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Aneutronic Fusion Propulsion

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The **Defense Intelligence Reference Document** provides nonsubstantive but authoritative reference information related to intelligence topics or methodologies.

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Contents

Figures

Tables

Aneutronic Fusion Propulsion

Introduction

Space exploration is limited by existing propulsion technology. Up to now, chemical rockets have been used to reach low-Earth orbit, the Moon, and the outer regions of the solar system. Chemical rockets can use either solid or liquid fuel. Regardless of the type of fuel, their design is similar to that shown in Figure 1. Oxygen is combined with hydrogen or a hydrocarbon fuel in a combustion chamber where high temperatures and pressures cause the exhaust to be ejected through a supersonic nozzle to provide thrust to the rocket. The momentum of the fuel ejected through the nozzle provides the force or thrust that accelerates the rocket forward.

There are many variations of chemical rockets, but they all suffer from the need to carry copious amounts of fuel. Other methods have been proposed to decrease the need to carry such a significant mass of fuel into space. Ion drives, for example, are used to provide the very low thrust required to maintain satellites in Earth orbit. The "fuel" that they carry is xenon gas accelerated by electric fields.

Nuclear fission propulsion has been proposed for space missions, and thermal nuclear fission reactor rockets were constructed and tested at the Nevada Test Site through Project Rover between 1956 and 1971.[1] In these rockets, a nuclear reactor provides heat to liquid hydrogen through nuclear fission and ejects the hydrogen gas through a Laval nozzle to generate thrust. While these rockets must still carry hydrogen fuel as a propellant, these rockets can provide more than twice the performance of chemical rockets by using heat through fission rather than reactive chemicals. The results of the 72 reactor tests conducted under Project Rover were very promising and culminated in the successful 12-minute test of the Phoebus-2A NERVA (Nuclear Engine for Rocket Vehicle Application) reactor that generated over 4 gigawatts of thermal power. One problem associated with nuclear fission rockets is radioactive contaminants. These contaminants in the exhaust make this technology impossible to use in launching payloads from Earth. Additionally, for applications in space, radiation protection must be provided for the crew by adding heavy shielding materials or by locating the crew as far as possible from the reactor propulsion system.

Nuclear fusion, as opposed to fission, provides another potential propulsion technology. In a fusion propulsion system, isotopes of light elements are fused together under extreme conditions to form heavier elements, releasing large amounts of thermal energy. This thermal energy can be used to heat liquid hydrogen to high temperatures and expand it through a Laval nozzle to provide thrust in a manner similar to that shown in Figure 1. Typically, isotopes of hydrogen and helium would be used in fusion propulsion systems. Deuterium is an isotope of hydrogen and can be separated from the hydrogen in water. Fusion reactions are difficult to initiate due to the high temperatures and pressures required. Thermonuclear bombs, for example, combine a fusion device with a nuclear fission bomb to provide the high temperatures required to initiate the fusion reaction. Regardless of the conditions required to induce nuclear fusion, the energy release is large. From propulsion standpoint, an advantage of fusion over fission is that for a given amount of thrust, the fusion reaction requires less fuel than either fission or chemical propulsion systems.

Fusion reactors using deuterium or tritium fuels are easiest to initiate; however, they generate significant amounts of neutron radiation. This is a hazard for the crew on a space ship, and there is a high probability that neutrons produced by fusion reactors would escape into space without providing much of their energy to a hydrogen propellant. Other fusion reactions using isotopes of helium and lithium will generate only charged particles, such as protons, that travel very short distances before giving up all of their energy as heat. These "aneutronic fusion" reactions take place without neutron production and decrease the need to carry large amounts of radiation shielding material for the crew. The energy from charged particles generated by aneutronic fusion can also be captured in conductive coils and converted directly into electricity. Aneutronic fusion promises to be an important mechanism for future space propulsion, although novel accelerator or laser systems must be researched and developed in order to initiate, sustain, and control the fusion reaction.

Another futuristic method of spacecraft propulsion involves the use of antimatter. Antimatter includes antiprotons, antineutrons, and positrons (anti-electrons). Although this propulsion process may be the most efficient, antimatter has some drawbacks. For example, antimatter is generated in only minute quantities at accelerator facilities around the world. Although it has been captured and stored, containment remains a problem. When antimatter combines with matter, it completely annihilates and converts to energy, which then can be converted into heat for a propulsion system. Antimatter reactions provide the greatest amount of energy per unit mass of any potential fuel, but the ability to generate significant quantities of antihydrogen or similar antimatter fuels at any accelerator facility is very limited.

The focus of this study is on aneutronic fusion propulsion. Integral to this study are the topics of fuel, rocket design, and the organizations that research aneutronic fusion development.

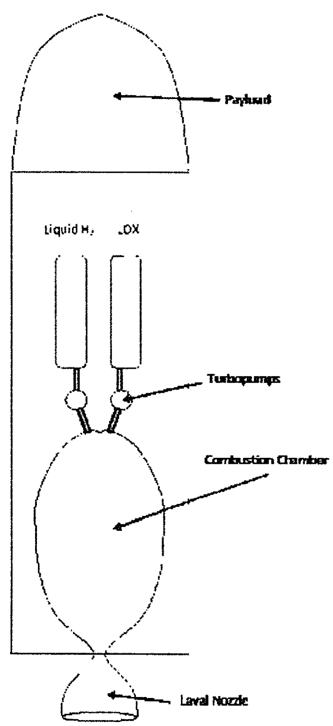

Figure 1. Liquid-Fueled Chemical Rocket.

Chapter 1: Theory

ROCKET PROPULSION

It is difficult to compare propulsion technology without talking about how objects are accelerated in space. Within Earth's atmosphere, aircraft use the air to generate lift and thrust. Propellers or turbofans move a mass of air rearward and Newton's second and third laws require that the momentum in this exhausted air is equal to a thrust in the opposite direction. In equation form, the thrust, F, is equal and opposite to the change in momentum over time.

$$\vec{F} = -\frac{d\left(m\vec{V}\right)_{exhaust}}{dt} \tag{1.1}$$

The momentum of the exhausted air is equal to the mass of air times its velocity and is provided by the propulsion system. The thrust can be used to accelerate a payload according to the following equation:

$$\vec{F} = m_{payload}\,\vec{a} \tag{1.2}$$

Here, thrust is equal to the payload mass times its acceleration.

This method of momentum transfer works well for aircraft operating within the Earth's atmosphere; however, operating in space presents special problems. Space is nearly a complete vacuum, and there is no air mass to accelerate, i.e., no "reaction mass" that can be accelerated and exhausted at high speeds. In space, the reaction mass is carried by the rocket in the form of propellant mass, which is expended as the rocket accelerates.

$$\vec{F} = m\,\vec{a} + \frac{dm}{dt}\vec{V} \tag{1.3}$$

In this equation, the thrust is provided by the momentum ejected from the rear of the rocket, but the total mass of the rocket is decreasing as the fuel is burned up and as propellant is lost. Examining equation 1.3, we see that there are two ways to increase rocket thrust. The first is to increase the mass flowrate, dm/dt, typically measured in kg/s (if mass flowrate is given in kg/s, then thrust, F, is given in newtons to maintain consistency). Unfortunately, this requires carrying increasing quantities of fuel. For flights to Mars, the outer planets, or to other star systems, it would not be possible to carry such large quantities of propellant.

A second choice would be to increase V, i.e., the velocity of the ejected propellant reaction mass. There is an upper limit, however, to how fast we can eject the propellant. In his Special Theory of Relativity, Albert Einstein demonstrated that no object that has any mass when at rest can be accelerated beyond the speed of light or 2.998×10^8 m/s in a vacuum. Einstein's relationship between an object's mass (m), its velocity (v), and the speed of light, (c) is given in equation 1.4:

$$m = \frac{m_o}{\sqrt{1 - \frac{v^2}{c^2}}} \qquad (1.4)$$

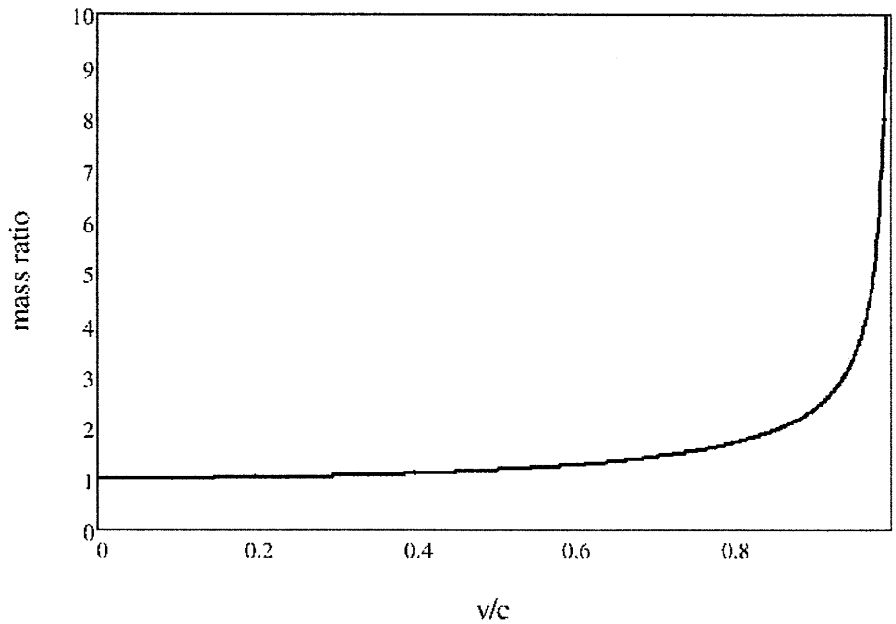

Figure 2. Mass Ratio (m/mo) Increases as Objects Approach the Speed of Light.

Equation 1.4 is plotted in Figure 2; we see that as an object's velocity approaches light speed its mass approaches infinity. Coupled with this, we see that as mass approaches infinity, the energy required to move the mass also approaches infinity. Thus, it would take an infinite amount of energy to accelerate an object to the speed of light. Equations 1.2 and 1.3 indicate that the best propulsion system would use the least amount of propellant but exhaust it at the highest possible velocity. Therefore, the rocket engine that has the highest exhaust velocity requires that the rocket be the least massive or carry the least amount of propellant. Unfortunately, this combination corresponds to the minimum efficiency in terms of rocket power. The point here is that for spaceflight to anywhere other than near destinations, our present rocket technology is insufficient.

Specific Impulse

To compare various propulsion systems and their fuel, rocket efficiency can be represented by the amount of momentum that can be obtained per unit weight of the propellant that is used. This is defined as the "specific impulse" (I_{sp}) and is measured in units of seconds:

$$I_{sp} = \frac{\Delta(m\, V_{exhaust})}{\Delta(m\, g_{earth})} = \frac{V_{exhaust}}{g_{earth}} \tag{1.5}$$

Here, earth's gravitational acceleration, g_{earth}, is 9.81 m/s^2. As described earlier, the best propulsion system is typically one that has the highest possible exhaust or propellant velocity. High specific impulse, or correspondingly high exhaust velocity, also produces low energy efficiency.

Table 1: Specific Impulse for Various Rocket Engine Types

Engine Type	V_e (m/s)	I_{sp} (s)
Saturn V Rocket, 2nd and 3rd Stages	4,130	421
LH_2/LOX Liquid Fuel		
Solid Rocket	2,500	255
Best Chemical Rocket Tested	5,320	542
F_2/Li/H_2 Chemical Rocket		
Nuclear Thermal Rocket	8,340	850
Ion Thruster	29,000	3,000
VASIMR	290,000	30,000

The efficiency of a rocket can be defined as the ratio of rocket thrust to the power required to generate the thrust. The resulting equations follow:

$$Power = \frac{dE}{dt} = \frac{1}{2}\left(\frac{dm}{dt}\right) V_e^2 \tag{1.6}$$

$$Thrust = \left(\frac{dm}{dt}\right) V_e \tag{1.7}$$

$$\eta = \left(\frac{Thrust}{Power}\right) = \frac{2}{V_e} \tag{1.8}$$

In choosing a rocket engine, as the specific impulse (I_{sp}) or the exhaust velocity (V_e) increase, the corresponding efficiency (η) decreases. The specific impulse for various fuels varies widely as shown in Table 1.[2, 3]

Tsiolkovsky Rocket Equation

For a spaceflight to Mars or other body, the exhaust velocity affects the time of flight and the amount of fuel that is needed to change the velocity of the spacecraft. The change in velocity (ΔV) can be expressed in terms of the initial mass of the rocket ($m_{initial}$, rocket + propellant) and the final total rocket mass (m_{final} rocket only):

$$\Delta V = V_{exhaust} \ln\left(\frac{m_{initial}}{m_{final}}\right) \tag{1.9}$$

The mass of propellant used to generate thrust is given by:

$$m_{propellant} = m_{initial} - m_{final} \tag{1.10}$$

$$I_{sp} = \frac{V_{exhaust}}{g_o} = \frac{T}{\dot{m} g_o} \tag{1.11}$$

$$m_{final} = m_{initial}\, e^{\Delta V / V_{exhaust}} \tag{1.12}$$

$$\Delta V = g_o\, I_{sp}\left[\ln\left(\frac{m_{initial}}{m_{final}}\right) - \frac{1}{R}\left(1 - \frac{m_{final}}{m_{initial}}\right)\right] \tag{1.13}$$

$$t = \frac{m_{initial}}{\dot{m}}\left[1 - e^{-\Delta V / V_{exhaust}}\right] \tag{1.14}$$

In these equations, R is the thrust-to-weight ratio and t is the time required for an engine burn to produce a desired ΔV. These are the standard equations used for rocket engine performance.

COMPARISON OF SPECIFIC IMPULSE FOR VARIOUS ROCKET DESIGNS

Chemical Rockets

Chemical rockets burn solid or liquid propellant. The exhaust gas exits the rocket through a Laval nozzle and generates thrust. Figure 1 provided the outline of a liquid-fueled rocket using liquid hydrogen as the fuel and liquid oxygen (LOX) to combust the fuel. Unlike turbofan and RAM engines, rockets are not airbreathing and must carry their own oxidizer.

The Laval nozzle is a principle component of chemical rockets; its design is based on compressible fluid flow theory.[4] In general, the nozzle is made up of contoured convergent-divergent cross sections. Conical cross sections are also sometimes used. Its purpose is to transform pressure energy into kinetic energy. Nuclear fusion rockets may also make use of Laval nozzles by heating up a liquid propellant and ejecting it as a supersonic gas. In subsonic flow, fluid can only be accelerated by decreasing the cross-sectional area of the duct section that it is traveling through, as in a Venturi tube. Once the velocity in a fluid reaches the speed of sound (Mach 1), the fluid can continue to accelerate only if it is expanded. The Laval nozzle combines a converging section where the flow is subsonic, a throat where the flow is accelerated to sonic speed (Mach 1), and a diverging cone where the flow is accelerated to supersonic speed. The performance of a rocket is based on its thrust, where $T = (dm/dt) \times V_{exhaust}$, and by maximizing the exit velocity, the thrust reaches a maximum. The pressure of the combusting gases in the combustion chamber directly affect the amount of thrust that the rocket can achieve.

Whether a rocket is propelled by gases from combusting propellant or by gases heated through a nuclear fission or fusion reaction, two equations determine the thrust of the Laval nozzle. The maximum mass flow rate through the nozzle can be computed in terms of the nozzle area (A_{throat}) the combustion or heated gas pressure (p_o), and the heated gas temperature (T_o).

$$\left(\frac{dm}{dt}\right)_{maximum} = \frac{p_o A_{throat}}{\sqrt{T_o}} \sqrt{\frac{\gamma}{R}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \qquad (1.15)$$

$$V_{exhaust} = \sqrt{\frac{2\gamma R T_o}{\gamma-1}\left(1-\left(\frac{p_{exit}}{p_o}\right)^{\frac{\gamma-1}{\gamma}}\right)} \qquad (1.16)$$

In these equations, R is the gas constant of the propellant gas and γ is a thermodynamic property of the gas called the ratio of specific heats. These equations make it possible to compute the maximum thrust generated by a propellant gas through a Laval nozzle based on the pressure and temperature of the gas in the combustion chamber or heating tank.

Ion Drives

Ion thruster electrical propulsion provides a convenient and efficient method of generating thrust. A gas that is easily ionized, such as xenon, is carried onboard as a propellant. The voltage difference between an electrode and a metal screen accelerates xenon ions toward the screen and out the back of the spacecraft, generating thrust. The specific impulse of this kind of drive is about 3,000 seconds. It is relatively common for satellites to use ion drives, generating minute forces measured in millinewtons, to maintain orbit. Solar energy and radioactive decay are possible sources of electric power for satellites in Earth orbit. In deep space, fusion or fission reactors could provide electrical power. However, once the xenon propellant has been expended, the ion drive is no longer useful.

Ion drives include the VASIMR (Variable Specific Impulse Magnetoplasma Rocket) designed by the Ad Astra Rocket Company in Webster, Texas. This system uses two RF radiowave antennae to couple energy into an ionized gas that is used for propulsion in space. While ion drives are often used to help maintain orbit for satellites circling the Earth, the VASIMR technology has been proposed for use in moving payloads throughout the solar system. The specific impulse for this technology is cited as 5,000 seconds compared to ~3,300 seconds for typical ion drives.[5]

Photonic Propulsion

Photons of visible light, infrared radiation, or x-rays can produce thrust through momentum transfer, where the momentum of each photon is given by $p = h/\lambda$ (h = Planck's constant, λ = radiation wavelength). Photonic propulsion has been explored by Y. K. Bae Corporation (http://www.ykbcorp.com) who holds a patent on a photonic laser thruster. These drives generate no contaminants and require a source of electricity to produce photons. Their photonic laser thruster (PLT) uses an active resonant optical cavity formed between two mirrors on a pair of spacecraft to generate thrust. Photonic drives would be viable on fusion or fission-powered spacecraft if their power output were used to generate electrical power that could provide light.

RADIATION SHIELDING

Radiation shielding will be important for astronauts traveling to the Moon, to the other planets, and to other star systems. Radioactive particles and cosmic rays left over from the big bang, radiation from supernovae, x-ray emissions from black holes, and a constant flux of energetic protons from our own sun all contribute to the radiation dose received by humans in space.

Radiation levels are typically measured in sieverts (Sv), expressing the amount of energy deposited in human tissue from radiation. One sievert is equivalent to 1 joule of energy absorbed for every kilogram of tissue.[6, 7] An older unit, the rem (Roentgen equivalent, man) is still in common use: 1 rem = 0.01 Sv. Sieverts are now the international standard unit.

The energy absorbed is strongly related to the amount of radiation damage done to the tissue. On Earth, the magnetic field of the planet helps to shield people from most of the effects of radiation from the sun, but cosmic radiation and terrestrial sources of radiation (granite, potassium, radon gas) all contribute to an annual background dose that everyone receives. The average annual dose of radiation in the United States is about 2.5 mSv from background and another 1.0 mSv from other source, such as dental x-rays, commercial jet flights, and radiopharmaceuticals. The total annual dose in the United States is approximately 3.5 mSv (millisieverts) per person.

In space, away from the protection of the Earth's magnetic field, the radiation dose increases substantially to about 250 mSv per year. The radiation dose in space is continuous, and the effects of being in space for extended periods of time may be cumulative. As a comparison, 2,000 mSv of radiation in an acute dose can cause significant medical problems and 5,000 mSv is usually fatal. Leukemia and other forms of cancer are possible for people exposed to chronic doses of radiation at the levels encountered in space.

The logical conclusion would be to carry radiation shielding into space to protect the astronauts. The problem is that shielding is typically heavy and expensive. Four types of radiation must be shielded:

1. Gamma Rays (γ)
   These are energetic forms of electromagnetic radiation (photons) and tend to penetrate most materials. High-density metals, such as iron, lead, and uranium are usually used to shield gamma rays.

2. Beta Particles (β^+, β^-)
   These are electrons or positrons, the antimatter counterpart to electrons. They are emitted by the radioactive decay of certain isotopes and through nuclear fission. Because these are charged particles, they are fairly easy to stop with minimal shielding.

3. Neutrons (n)
   These uncharged particles are generated by nuclear fission and fusion. They may penetrate metals, yet they can be slowed down until they decay in light materials that contain hydrogen or carbon. Typical shielding material includes water, paraffin wax, and polyethylene blocks.

4. Heavy Charged Particles (p, α)

   Ions are atoms that have one or more of their electrons stripped from their outer orbital. Due to their positive electric charge, ions are generally easy to stop within any kind of material, unless the ions are very energetic. Typical ions include protons, which are ionized hydrogen atoms, and alpha particles, which are ionized helium nuclei. Cosmic radiation includes heavy ions emitted by exploding supernovae and may include ions as heavy as iron nuclei at extremely high energy.

Long-duration spaceflights will require copious amounts of water for the crew, and water can be used to provide some shielding from neutrons for the astronauts. Shielding material for gamma rays presents a weight problem. Lead is one of the best shielding materials for gamma, but at a cost of about $10,000/lb to launch material into space, lead shielding is expensive to use.

The International Space Station and other spacecraft designed for long-term human habitation usually have a small area that is heavily shielded to prevent excessive radiation exposure to the crew during solar events.

In addition to the dangers of natural sources of radiation in space that can endanger human health and safety, the propulsion techniques of nuclear fusion and fission generate large fluxes of radiation. Neutron production is of special concern because neutrons can penetrate metals and the structural material of space habitats.

The general equations that govern radiation shielding can help develop spacecraft designs that will minimize radiation exposure. The intensity of gamma rays will attenuate according to the following equation:

$$\phi(r) = \phi_{initial}\, e^{\mu r} \qquad (1.17)$$

In equation 1.17, the flux of gamma rays or neutrons, given in particles per unit area per unit time, is represented by $\Phi(r)$; $\Phi_{initial}$ represents the initial flux without the shielding; and μ is the linear attenuation coefficient, a function of the gamma ray or neutron energy and the type of shielding material. The thickness of the material is represented by r. The radiation flux decreases with distance since photons or radioactive particles typically expand outward through a spherical area of $4\pi r^2$ as shown in Figure 3. Equation 1.18 shows the relationship between total attenuation, particle flux, and radiation exposure.

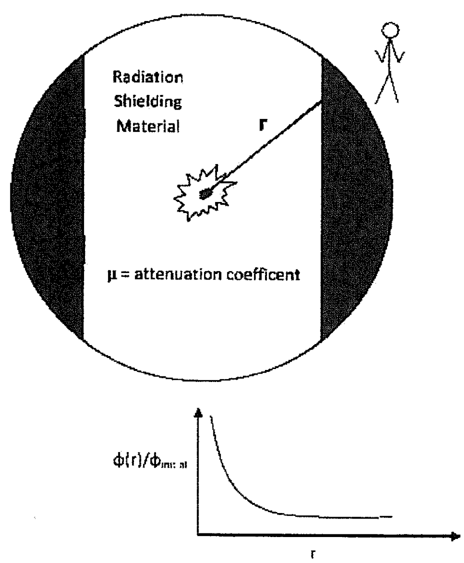

Figure 3. Spherical Radiation Shield Surrounding a Point Source.

$$\phi(r) = \phi_{initial} \frac{e^{-\mu r}}{4 \pi r^2} B(\mu r) \tag{1.18}$$

The radiation flux is inversely proportional to the square of the distance from a point source of radiation, such as a nuclear rocket engine. It also decreases through any intervening radiation shielding material. The last term in equation 1.18, B(μr), is called the "buildup factor"; it represents the process of reradiation following atomic collision with shielding material, thus contributing to the total radiation dose. This secondary radiation is a problem for all spacecraft since cosmic radiation impacting the spacecraft structural material can produce a cascade of secondary particles that can irradiate the crew.

A standard technique to decrease the radiation exposure to the crew on a spacecraft using nuclear fusion as an energy source will be to locate the crew as far away from the engine as possible and place as much liquid hydrogen or other light shielding material between the crew and the engine as designs allow. A simpler solution would be to use nuclear fusion schemes that do not generate neutrons. These are the so-called "aneutronic fusion" propulsion techniques.

SUBATOMIC PARTICLE MASS, VELOCITY, AND ENERGY

Atoms are composed of a small nucleus containing neutrons and protons, along with electrons orbiting the nucleus in shells. The atomic number (*Z*) is equivalent to the number of protons or electrons in a stable atom.[8] The atomic mass number (*A*) is the total number of neutrons and protons in the nucleus. The number of neutrons (*N*) can be found by subtracting *Z* from *A*. Atoms or nuclei are represented by a standard nomenclature based on *A* and *Z*.

$${}^{A}_{Z}Atom$$

Since chemical properties are governed by how many electrons circle the nucleus, *Z* defines the element and atoms with the same value of *Z*, but differing numbers of neutrons are referred to as "isotopes" of the same element. Some common isotopes of hydrogen are shown below:

$$\begin{array}{ll} hydrogen & {}^{1}_{1}H \\ deuterium & {}^{2}_{1}H, or\ {}^{2}_{1}D \\ tritium & {}^{3}_{1}H, or\ {}^{3}_{1}T \end{array}$$

Subatomic particles, such as *α*, *β*, and neutrons, have a mass described in atomic mass units (amu). One amu is defined as the mass of one atom of carbon-12, and it roughly represents the mass of one neutron or proton. In terms of amu, the mass of various particles are included in Table 2. Due to relativistic effects, particle mass increases as the velocity of the particle approaches the speed of light, and because of special relativity, the mass of particles listed in the table is the "rest" mass corresponding to a particle that is not moving.

Table 2: Rest Mass of Various Subatomic Particles

Subatomic Particle	Particle Name	Mass (amu)
α	alpha	4.001506
β	beta	0.000549
η	neutron	1.008665
p	proton	1.007276
D	deuterium	2.014102
T	tritium	3.016049
U-235	uranium	235.0439

Gamma rays, or photons, have no rest mass and only move at the speed of light ($c = 3 \times 10^8$ m/s). Photons do have an effective mass since their momentum is given by $p = mc = h/\lambda$ where h is Planck's constant ($h = 6.626 \times 10^{-34}$ J·s) and λ is the wavelength of the photon.

Particles also have energy, given by $E = mc^2$. Mass (m) was defined in equation 1.4.

Particle or photon energy is usually expressed in terms of electronvolts (eV). Typical powers of eV are also used, including keV (1,000 eV) and MeV (1 million eV). For reference, 1 eV = 1.602×10^{-19} joules.

NUCLEAR FISSION ROCKETS

During the Cold War, the United States and the USSR developed designs for intercontinental ballistic missiles to carry nuclear weapons. Conventional rockets used highly reactive chemicals and, as an alternative power source, the use of nuclear fission reactors was explored. Project Rover, supervised by the U.S. Atomic Energy Commission and the U.S. Air Force, developed specialized fission reactors with hydrogen propellant. A number of nuclear rockets were built and tested at the DOE Nevada Test Site (NTS) Area 25 in the 1950s. Nuclear fission reactors require a "moderator" to operate. The moderator slows down neutrons generated by fission and absorbs their energy. Hydrogen is nearly the perfect moderator and was chosen as the moderator and the propellant in the construction of the NERVA (1) rockets under Project Rover. Figure 4 shows the main components of a nuclear fission rocket.

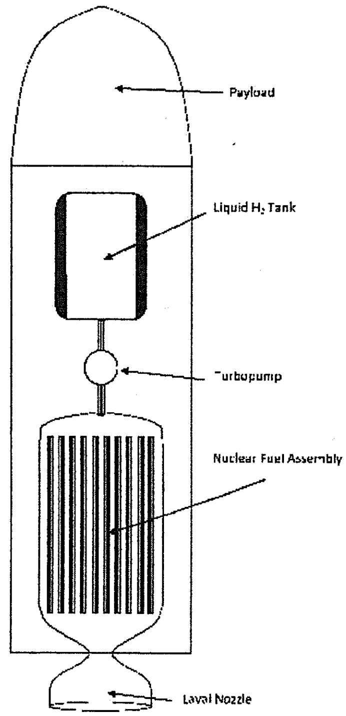

Figure 4. Nuclear Fission Rocket Design.

Nuclear fission rockets had numerous problems. The fission of uranium-235 emits about 200 MeV for every nucleus that undergoes fission. Approximately 11% of this energy is in the form of neutrinos and is unrecoverable. Approximately 4.8 MeV shows up as kinetic energy in the two or more neutrons that are created for every fission. At least one neutron must be absorbed by another U-355 nucleus and cause fission in order for a chain reaction to be sustained. Most of the energy goes into the kinetic energy of large fission fragments that are created by the breakup of the U-235 nucleus. Fission products are highly radioactive and may be ejected out with the rocket exhaust. Neutrons pose a radiation hazard to any human close to the rocket when it operates. In the tests of the NERVA series of rockets, on at least one occasion, pieces of radioactive material were ejected over a small region of the Nevada Test Site and had to be manually retrieved.

On the positive side, the NERVA rockets created large amounts of thrust, and the energy within the reactor was more than sufficient to send its payload to the desired location in the USSR. This prompted scientists to consider the use of thermal fission reactors for use in space exploration, although the persistent problem of radiation exposure to the crew remained unresolved.

Two classical designs were proposed. In one design, a reactor would be constructed as shown in Figure 4, and liquid hydrogen propellant would be passed through the reactor to create a supersonic exhaust and to provide thrust. The hydrogen fuel would be located between the reactor and the crew to serve as a radiation shield for neutrons produced during fission. The spacecraft would be elongated to move the crew as far away as possible from the reactor, taking advantage of the $1/r^2$ attenuation of radiation with distance from a source.

In a second design, a nuclear reactor would be used to generate electricity onboard a spacecraft. The electrical power would provide energy for life support and much of the reactor output could be used to power an ion drive where high voltages would accelerate an ionized gas (usually xenon) to generate thrust. The thrust generated by ion drives is typically small (millinewtons), but continuous acceleration could provide enough velocity to reach Mars or the outer planets.

Nuclear reactors have been used on spacecraft in the past, although their use is controversial. On 24 January 1978, for example, the Cosmos 954 Soviet spy satellite, complete with onboard plutonium-fueled nuclear reactor, crashed into the Arctic region of Canada.[9] The cleanup cost the Canadian government over U.S. $6 million, half of which was reimbursed by the USSR. The launch of a reactor into space always poses the danger of problems related to an accidental reentry that could cause significant hazards to populated areas.

Chapter 2: Nuclear Fusion Rocket Design

CLASSIC NUCLEAR FUSION SCHEMES

Nuclear fusion, which powers the Sun and the stars, begins with the collision of two lightweight atomic nuclei to create two new particles with the release of energy. As an example, if two specific isotopes of hydrogen (tritium and deuterium) were to collide, the reaction would produce a neutron plus an alpha particle (ionized helium nucleus).

$$ {}_{1}^{2}D + {}_{1}^{3}T \rightarrow {}_{0}^{1}n + {}_{2}^{4}He + 17.6\,MeV \tag{2.1}$$

The 17.6 MeV of energy is split between the kinetic energy of the neutron (14.1 MeV) and the helium nucleus (3.5 MeV) based on conservation of energy and conservation of momentum. The kinetic energy is eventually converted into heat in a fusion reactor. The 14.1-MeV neutron will penetrate far into lead or steel shielding and can cause considerable material damage. The ionized helium nucleus, however, will not go very far through any material without being absorbed and dissipating its energy as heat. There is a novel way to capture the energy from the ionized nucleus. As shown in **Error! Reference source not found.**, a magnetohydrodynamic (MHD) generator can b e used to harness the energy from the helium ions and convert it directly into electricity. The electricity could be used to power an ion drive on a spacecraft or provide power for life support. Equation 2.2, known as the Lorentz force equation, illustrates which parameters are involved and how they are related:

$$\vec{F} = e\,(\vec{V} \times \vec{B}) \tag{2.2}$$

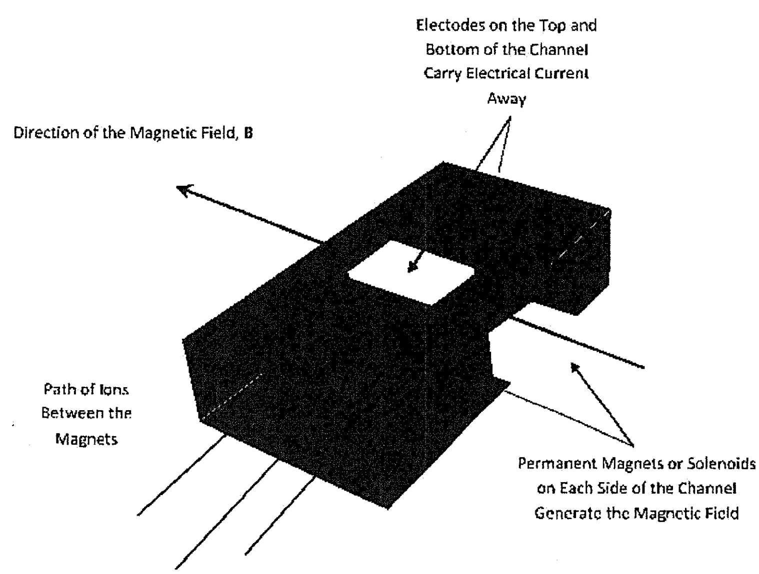

Figure 5. Schematic Design of a Magnetohydrodyanamic (MHD) Generator.

The velocity (V) of the ions interacts with the magnetic field (B) and forces positively charged ions to move downward in the channel to an electrode where they impart an electric current. The ion charge is given in the equation as *e*. MHD generators have been proposed for highly efficient generation of electricity from the combustion of coal, for example. On a spacecraft, MHD generators can generate power from both ions and electrons, which deflect in opposite directions due to the magnetic field.

Even if the ion energy cannot be converted directly into electricity, neutrons or ions can be used to heat up a propellant gas to provide thrust. Hydrogen gas would be the most efficient propellant for fusion reactions producing neutrons because the neutron energy is easily absorbed through collisions with the hydrogen nuclei.

Propulsion fusion reactors, however, still generate radiation, including neutrons, which pose a health hazard for the crew of any spacecraft. By carrying hydrogen propellant and locating the crew as far away as possible from the fusion reactor, some degree of shielding is possible.

While fusion reactors have the potential to produce incredible amounts of energy from relatively inexpensive fuel (deuterium, tritium, helium-3), the problems of initiating, controlling, and sustaining the fusion reaction remain unsolved.

FUSION INITIATION METHODS

There are many possible fusion reactions that extend all the way up from hydrogen to the actinides (uranium). In each case, the two ions that "fuse" must collide to form a new nucleus that rapidly decays with the release of fusion energy, as shown in Figure 6. Both ions, however, are positively charged and tend to repel each other due to Coulombic repulsion:

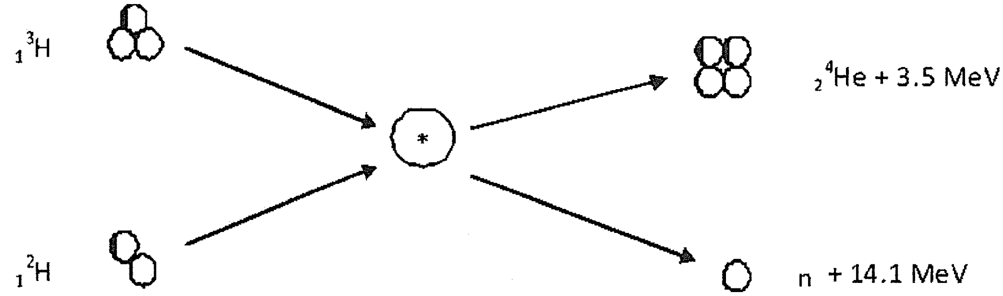

Figure 6. Nuclear Fusion of Deuterium and Tritium.

The Sun emits vast amounts of thermal energy through the fusion of hydrogen isotopes; it overcomes Coulombic repulsion through the high pressures and temperatures that exist in its interior. High temperatures create high ion velocities and high-velocity collisions are more likely to cause two ions to fuse together.

Controlled fusion reactions are difficult to achieve due to the temperatures required to initiate the process. The reactions that occur at the lowest temperatures are listed in Figure 7, including the D-T reaction which was discussed earlier.

${}_{1}^{2}\mathrm{D} + {}_{1}^{3}\mathrm{T} \rightarrow {}_{0}^{1}\mathrm{n}$ [14.1 MeV] + ${}_{2}^{4}\mathrm{He}$ [3.5 MeV]

${}_{1}^{2}\mathrm{D} + {}_{1}^{2}\mathrm{D} \rightarrow {}_{0}^{1}\mathrm{n}$ [2.45 MeV] + ${}_{2}^{3}\mathrm{He}$ [0.82 MeV]

${}_{1}^{2}\mathrm{D} + {}_{1}^{2}\mathrm{D} \rightarrow {}_{1}^{1}\mathrm{p}$ [3.02 MeV] + ${}_{1}^{3}\mathrm{T}$ [1.01 MeV]

${}_{1}^{2}\mathrm{D} + {}_{2}^{3}\mathrm{He} \rightarrow {}_{1}^{1}\mathrm{p}$ [14.7 MeV] + ${}_{2}^{4}\mathrm{He}$ [3.6 MeV]

${}_{1}^{3}\mathrm{T} + {}_{1}^{3}\mathrm{T} \rightarrow 2 \times {}_{0}^{1}\mathrm{n} + {}_{2}^{4}\mathrm{He}$ + [11.3 MeV split between the neutrons and helium]

Figure 7. Low Temperature Fusion Reactions.

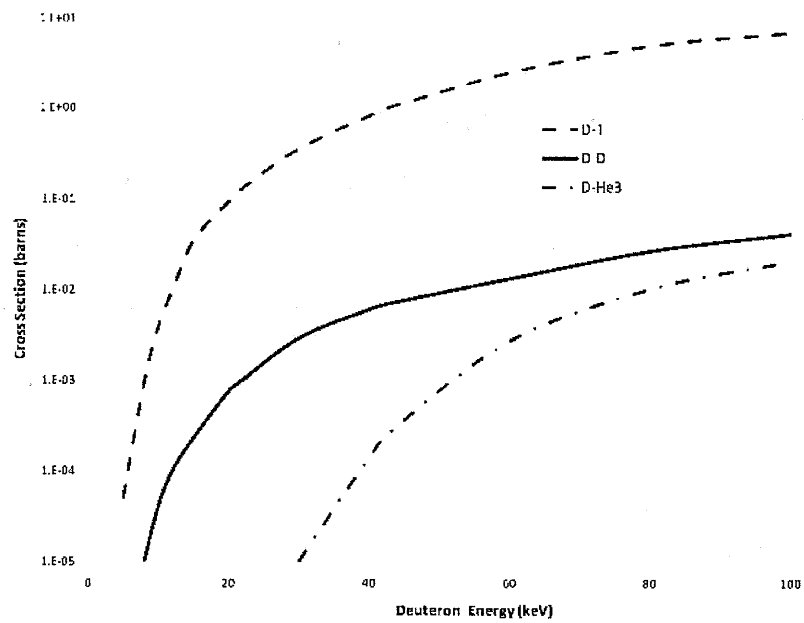

Figure 8. Fusion Ignition Energies for D-T, D-D, and D-He3.

Figure 8 shows the probabilities of these reactions occurring, expressed in units of barns (1 b = 10^{-28} m^2). The D-T reaction becomes increasingly probable as the energy of the deuterium nucleus (deuteron) reaches about 5 keV. In terms of temperature, this equals about 10 million degrees kelvin. At 10 keV (100 million degrees kelvin), the two D-D reactions listed in Figure 7 become more probable and D-He3 fusion becomes viable at 30 keV (300 million degrees kelvin). There are several ways to achieve these temperatures in a controlled manner. For example, Edward Teller and Stanislow Ulam developed a design for a fusion, or thermonuclear bomb, that used a plutonium fission atomic bomb to reach the ignition temperature for fusion. Deuterium is the most useful fuel for low-temperature fusion reactors, and there is a limitless supply available by centrifuging ordinary tap water to separate out heavy water (D_2O).

Because of deuterium's availability, a strong incentive exists to develop manageable ways to initiate nuclear fusion, concentrating on the fusion schemes outlined in Figure 6;

these methods are discussed below. Fusion reactors for the production of electricity have been a goal for over 50 years, yet no method has yet achieved "break even," where the amount of energy generated by fusion exceeds the energy required to initiate the fusion process. Fusion methods are often compared based on their ability to "break even."

GRAVITATIONAL CONFINEMENT

To initiate fusion, ions of hydrogen or its isotopes must be heated to high enough temperatures to increase the likelihood of a fusion reaction occurring during a collision. Another method is to increase the pressure of an ionized gas to a point where the number of collisions increase with an enhanced possibility of a fusion collision. This is the mechanism that stars employ to initiate fusion; for example, if the object were completely composed of deuterium, the minimum mass needed to generate gravitational pressures sufficient to initiate fusion would be equivalent to the mass of the planet Jupiter.

MAGNETIC CONFINEMENT FUSION (MCF)

Deuterium and other ions follow lines of magnetic flux, and tokamaks have been used to form a magnetic field in the shape of a torus to contain a plasma containing ions for fusion. Tokamaks contain powerful electromagnets that generate the magnetic field. Secondary electromagnets induce an electric current into the plasma to heat it to ignition temperature (ohmic heating). Other methods have been employed to heat the plasma, including the introduction of radiofrequency energy, magnetic compression, and neutral beam injection.

INERTIAL CONFINEMENT FUSION (ICF)

The Teller-Ulam thermonuclear bomb was an example of inertial confinement where x-ray radiation pressure from a fission explosion is used to compress a mixture of deuterium and tritium to initiate fusion.

The National Ignition Facility in Livermore, California, is an example of a laser-based ICF system. In this facility, a 287,000-lb, 10-meter-diameter target vacuum chamber is equipped with a small metal cylinder, or holraum, that contains a 2-mm pellet of D-T gas or "ice." An assembly of powerful lasers simultaneously fire 4 megajoules of infrared energy into a device that converts this energy into ultraviolet (UV) energy. The UV energy impacts the holraum, generating x-rays and rapidly heating the holraum. This induces an implosion that creates extremely high pressures and temperatures in the D-T pellet, initiating nuclear fusion. Less than 10% of the initial energy is imparted to the holraum. This is a pulsed system where multiple holraums and pellets would be required to sustain energy output.

Other methods can be used to momentarily confine a plasma containing deuterium and tritium to initiate fusion. For example, instead of lasers, ion beams, electron beams, and conventional explosives could be employed. Several systems based on electron accelerators have also been used.. The Farnsworth-Hirsch fusor and the Polywell are examples of two tabletop devices used to demonstrate fusion.

Another accelerator design is called the Dense Plasma Focus (DPF), where a pulsed accelerator drives a magnetic field within a diffuse mixture of deuterium and tritium gas to the top of an anode. When the moving magnetic field reaches the top of the anode, it collapses and generates a magnetic pinch for a fraction of a second that has high enough temperatures to generate fusion in the diffuse gas. The production of neutrons in D-T fusion can be on the order of 10^{13} neutrons. While this production may seem high, if this pulsed system were fired 10 times in 1 second, and all of the energy of the electrons and ions could be captured, the energy production would amount to only 280 watts.

MUON-CATALYZED FUSION

This method, sensationalized by Steven Jones at the University of Utah in the 1980s, makes use of the fact that certain material crystal shapes (hexagonal close pack, or HCP) tend to "hide" atoms of hydrogen in the interstitial space between atomic planes in the crystal. By diffusing deuterium into the crystal through electrolysis, fusion could be achieved. The famous scientist Sakarov observed this phenomenon as a way to account for the presence of He-3 in platinum. Platinum, palladium, and titanium are the materials that were used most often to demonstrate this technique. Initiating fusion by this method has been very poor.

CAVITATION (BUBBLE) FUSION

In water, vapor bubbles are produced when pressures drop below 2,300 pascals (~2% of atmospheric pressure) through a process called "cavitation." When these cavitation bubbles collapse, they produce high temperatures and pressures for a short period of time. Cavitation has been shown to release enough energy to pit ship propeller blades. In addition, heavy water (D_2O) and deuterated acetone have been used to demonstrate that cavitation can cause particles from fusion. Unfortunately, to date, the performance of cavitation fusion systems has been low.

ROCKET DESIGN USING FUSION ENERGY

While nuclear fusion releases large amounts of energy for a minimal quantity of fuel, initiation of the fusion reaction means that fusion ignition dictates the design of the system. Possible spacecraft designs include pulsed nuclear explosions with impact plates or sails; plasma confinement methods that generate charged particles used directly for propulsion; and confinement methods that heat a propellant, like liquid hydrogen, to be ejected through a Laval nozzle.

Chapter 3: Aneutronic Nuclear Fusion Schemes

Up to now, the fusion schemes described have the lowest fusion initiation temperatures ranging from 10 million kelvin to about 300 million kelvin. Most of the energy released from the fusion schemes in Figure 7 also release more than 80% of their energy in neutrons. Neutrons are difficult to shield and present a safety concern for the crew of a fusion-powered spacecraft. Unlike charged particles, their energy cannot easily be converted into electricity using magnetohydrodynamic generators and they cannot be focused into a propulsion beam to generate thrust. As a result, aneutronic fusion schemes have been explored for possible use in space propulsion. The schemes with the lowest temperature threshold are highlighted in Figure 9.

$${}_1^2D + {}_2^3He \rightarrow {}_1^1p\ [14.7\ MeV] + {}_2^4He\ [3.6\ MeV]$$

$${}_1^2D + {}_3^6Li \rightarrow 2 \times {}_2^4He\ [11.2\ MeV,\ each]$$

$${}_1^1p + {}_3^6Li \rightarrow {}_2^3He\ [2.3\ MeV] + {}_2^4He\ [1.7\ MeV]$$

$${}_2^3He + {}_3^6Li \rightarrow {}_1^1p + 2 \times {}_2^4He + 16.9\ MeV$$

$${}_2^3He + {}_2^3He \rightarrow 2 \times {}_1^1p + {}_2^4He + 12.86\ MeV$$

$${}_1^1p + {}_3^7Li \rightarrow 2 \times {}_2^4He\ [8.6\ Mev,\ each]$$

$${}_1^1p + {}_5^{11}B \rightarrow 3 \times {}_2^4He + 8.7\ MeV$$

$${}_1^1p + {}_7^{15}N \rightarrow {}_2^3He + {}_6^{12}C + 5.0\ MeV$$

Figure 9. Aneutronic Fusion Schemes

Deuterium is readily available by centrifuging water, and protons are ionized hydrogen atoms. Helium-3, however, is very rare on earth, although quantities of it exist in lunar regolith due to ion impact on the Moon from the Sun. Over one million tons of helium-3 is estimated to exist on the lunar surface. Removing the helium-3 schemes does shorten the table, and one of the most attractive schemes uses boron-11. Boron is readily available on earth and 80.1% of naturally-occurring boron is boron-11.

A consistent method of comparing each fusion scheme is based on how difficult it is to initiate fusion. In 1955, John D. Lawson established a standardized measurement of the performance of each fusion scheme based on the conditions required to initiate or ignite fusion. Three terms occur in his performance number, referred to as the "Lawson criteria." The triple product includes the plasma density (n_e), the energy confinement time (τ_E), and the plasma temperature. Lower values of the Lawson criteria indicate better fusion ignition performance.

The Lawson criteria for D-T fusion is 34; this figure of merit is only 0.43 for the first aneutronic fusion scheme, D-He3. Two of the best performing schemes are p-Li6 at 0.005 and p-B11 at 0.014. The ion temperatures required for both of these schemes are 800 keV and 300 keV, respectively, much higher than the 50 keV required for D-T neutronic fusion.

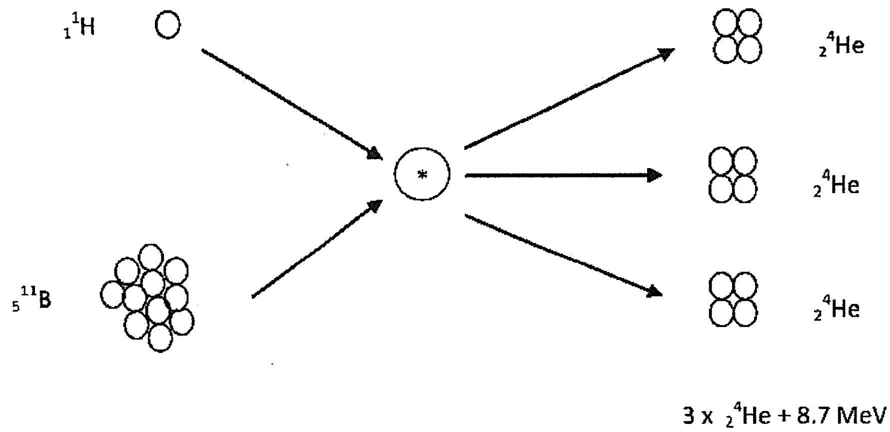

Figure 10. The Fusion of Hydrogen-1 and Boron-11 Produces Three Alpha Particles

Fortunately, both lithium-6 and boron-11 are readily available, while tritium must be manufactured due to its 12.6-year halflife. Lithium-6 represents 7.5% of all lithium on Earth. Lithium is mined at Silverpeak, Nevada.

Another concern in choosing an effective aneutronic fusion scheme is bremmstrahlung, or "braking radiation." This term refers to the x-rays emitted as electrons pass through metals and interact with electrons in the outer shells of the metal atoms. In order to ignite a fusion reaction, the gases must be heated to the point where they ionize and form a plasma. Electrons stripped from the ions in the plasma will interact with the walls of the chamber that house the plasma and bremmstrahlung x-rays will result. Bremmstrahlung is a parasitic process that decreases the temperature of the plasma and reduces the chance of fusion. While the two favored fusion schemes, p-Li6 and p-B11, can generate significant bremmstrahlung losses, there are techniques proposed using electromagnets to direct both electrons and ions to minimize x-ray production.

Chapter 4: Antimatter Propulsion

Although the focus of this report is aneutronic fusion propulsion, another possible propulsion technology involves the use of antimatter. Antimatter is created in certain nuclear reactions and minute quantities have even been collected from particle accelerators and stored for a short time in magnetic bottles. Antimatter has the highest energy density of any material known. When particles of antimatter and matter collide, they completely annihilate and convert their mass into energy according to Einstein's famous equation, $E = mc^2$.[10]

There are various terrestrial sources of antimatter. Positrons are created spontaneously from high-energy gamma rays as they decay. Any gamma ray with an energy of more than 1.022 MeV can decay by pair production where an electron and a positron are generated. A positron is the antimatter counterpart to an electron and carries a positive charge. Due to the difference in charge between electrons (β-) and positrons (β+), they can be separated by magnetic fields and the positrons stored.

Certain radionuclides decay through the emission of an antiproton, a negatively charged antimatter counterpart to a proton. If antiprotons are collected and combined with positrons, stable atoms of antihydrogen are produced. Antihydrogen has been created and stored in magnetic bottles. Up to 10^{12} antiprotons have been successfully stored for days at a time. Antihydrogen can also be potentially chilled to form liquid antihydrogen or "ice" to use as a rocket fuel. The specific impulse for antimatter rockets (I_{sp}/c) are 1 for electron-positron annihilation and 0.60 for proton-antiproton annihilation. For nuclear fusion, I_{sp}/c is only 0.119, followed by 0.04 for nuclear fission.

Antimatter could be used to heat up a propellant gas and expel it through a Laval nozzle to generate thrust. If liquid hydrogen is carried onboard the spacecraft, the electrons and protons in the hydrogen can be annihilated by the antimatter to generate power. Annihilation products can also be reflected or directed by magnetic fields to be ejected as exhaust from the rocket to generate thrust. Antimatter is seen as the only fuel that can potentially accelerate rockets to near the speed of light, providing the potential for human flight to neighboring star systems.

Chapter 5: Aneutronic Fusion Propulsion Projects

As discussed above, several techniques are currently being explored by research groups and private companies to employ nuclear fusion for space propulsion. Their efforts over the past 60 years have resulted in three classes of fusion drives, which are representative of magnetic, inertial, and antimatter schemes. These include magnetic confinement fusion (MCF), inertial confinement fusion (ICF), magnetized target fusion (MTF), inertial electrostatic confinement (IEC), and antimatter-catalyzed fusion applications.

Magnetic confinement fusion employs an electromagnet system that forces ions in a plasma to follow a toroidal-shaped magnetic field. Tokomaks and spheromaks employ this method and, between 1987 and 2004, the NASA Glenn Research Center developed the concept for Discovery II vehicle designed to deliver payloads to Jupiter and Saturn in a 4- to 6-month journey.

The simplest methods for fusion propulsion tend to use pulses from the detonation of nuclear devices. Other methods are based on the ejection of a propellant gas or ions to generate thrust.

NUCLEAR PULSE PROPULSION

In this method, nuclear explosions are used to provide rocket thrust. The explosions act upon a steel pusher plate attached to the rear of the rocket and shock absorbers cushion the impact to the crew and payload. General Atomics first proposed this technique in the late 1950s under Project Orion.[11, 12] With a maximum specific impulse of 100,000 seconds, this is one of the few fusion technologies that can be built with existing technology. Radiation exposure to the crew and the high period of acceleration induced by this propulsion system poses significant problems, yet a mission to Mars could only take 4 weeks using this technology instead of the 12 months required for conventional chemical rockets.

Project Orion led to Project Daedalus in the 1970s, pioneered by the British Interplanetary Society for missions to nearby stars.[1] In this design, a D-Li6 or D-He3 pellet would be imploded and the exhaust materials directed by an electromagnetic field to provide thrust for the rocket. The pellet would be ignited by multiple lasers that would strike the pellet and ablate the outer surface to generate a large implosive force.

A concept known as "Medusa" was developed in the 1990s that employed a large "sail" ahead of the payload. Fusion explosions between the payload and the sail would carry the payload forward. Specific impulses of as high as 100,000 seconds were possible.

Project Longshot, a conceptual spacecraft explored by the U.S. Navy and NASA in the 1990s, would have employed an electromagnetic funnel and ICF to power a rocket

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[1] Project Deadalus, led by Alan Bond, was a 5-year design study undertaken by the British Interplanetary Association between 1973 and 1978. The study focused on designing an unmanned, interstellar probe. Specifications were that the probe must use current (or near-term) technology and be able to reach its destination within a human lifetime. The probe's chosen destination was Barnard's Star (5.9 light years away), estimated to take 50 years at speeds up to 12% of the speed of light. The major stimulus for the project was Friedwardt Winterberg's ICF concept.

using D-Li6 fuel pellets. The estimated travel time of this system to Alpha Centauri was 100 years at an average velocity of about 0.5% of the speed of light.

OTHER ANEUTRONIC ROCKET DESIGNS

Antimatter-Catalyzed Fusion

In the 1990s, Pennsylvania State University worked on a fusion rocket design that employed antimatter to catalyze fission reactions in uranium. As a comparison, in order to make a nuclear fission bomb for space propulsion, approximately 12 kg of uranium-235 is required to generate the three critical masses required. Using antimatter, this can be achieved with gram-quantities of uranium.

Magnetized Target Fusion

Plasma guns are used instead of lasers to generate heat in a low-density fusion fuel mixture confined by magnetic fields. The fuel is rapidly compressed to ignite fusion. The NASA/MSFC HOPE (Human Outer Planets Exploration) Group estimates that this propulsion system could transport payloads to Jupiter within about 300 days.

Ion Drives

The VASMIR engine is a highly efficient ion thruster that uses an RF resonant cavity to accelerate ionized argon or xenon gas as a propellant. One concept is to generate electricity from aneutronic fusion by capturing the energy of the emitted ions in a magnetohydrodynamic generator. The electricity would then be used to power the VISMIR ion drive.

This direct conversion drive could capture useful energy from aneutronic fusion or from D-T fusion which is easy to ignite, but loses about 80% of its energy to neutrons. The neutrons can be used to generate secondary ions through impact on a target and the ion energy can be collected in the MHD generator.

COMMERCIAL DEVELOPMENT

In addition to teams from universities and national laboratories, several companies have been formed to develop aneutronic fusion propulsion systems. Several are discussed below.

1. EMC2 Fusion Development Corporation

   A prolific designer and author, Dr. Robert Bussard has explored inertial electrostatic confinement fusion as used in the Farnsworth-Hirsh Fusor.[13, 14, 15, 16, 17] He and his colleagues formed EMC2, a private company based in Santa Fe, New Mexico, to test components of a practical fusion drive. Their work has been funded by DARPA, NASA, and the U.S. Navy.

   Outlined in Figure 11, his QED (charged particle electric discharge engine) is based on the Farnsworth-Hirsch Fusor, an ion accelerator patented in 1968. This accelerator works through the use of spherical electrodes that force ions toward the center of a spherical chamber by Lorentz forces. By injecting preheated ions of deuterium and helium-3 or boron-11 into the fusor core, the resulting fusion heat and particles are collected by an electron beam generator that heats hydrogen. The hydrogen is used as a propellant gas that is exhausted through a Laval nozzle to generate thrust.

The Farnsworth-Hirsch Fusor is a proven technology that is used in tabletop experiments to demonstrate nuclear fusion. This device is an example of inertial electrostatic confinement (ICF). Scaling this device up to production of ions for a propulsion system is a major task for EMC2 and Dr. Bussard.

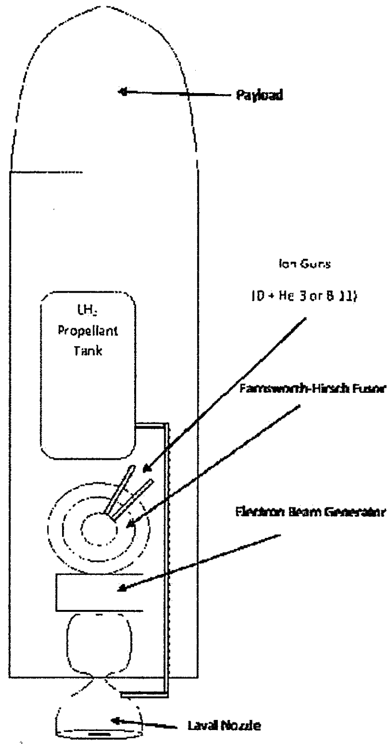


Figure 11. QED Rocket Design by Dr. Robert Bussard and EMC2.

2. ESA Advanced Concepts Team

   The European Space Agency (ESA), an international research consortium, has assembled their Advanced Concepts Team (ACT) to develop space propulsion systems based on nuclear fusion in open magnetic confinement. This system, an example of magnetic confinement fusion, uses gas dynamic mirrors (GDM) to constrain an ion plasma.

3. JPL, Rocketdyne, Rockwell

   Design of an inertial confinement fusion source for manned missions to Mars was conducted for this joint project where a magnetic thrust chamber was to be used to minimize contact between the plasma and the walls of the thrust chamber. With a 100-ton payload and a total vehicle launch mass of 6,000 tons, this spacecraft would deliver manned missions to Mars in 100 days.

4. Crossfire Fusor

   The Crossfire Fusor is as example of an inertial electrostatic confinement fusion (IEC) concept device combined with magnetic confinement. It was developed and patented by Dr. Moacir Ferreira (http://www.crossfirefusion.com). He has expanded his work to include the development of an electrodynamic space thruster, also based on the Farnsworth-Hirsh Fusor. This design uses aneutronic fusion along with superconducting electromagnets to help confine the ion plasma. An electron gun and an electric field are used to capture energy from the ions generated by fusion and to convert the resulting power into electricity. The use of the superconducting electromagnets eliminates the need for spherical electrodes. Hydrogen combined with Li-6, He-3, or B-11 would serve as the fusion fuel. This aneutronic concept device would theoretically allow interstellar travel to Alpha Centauri to take only 3 years.

Chapter 6: Speculation on Research Needs Over the Next 30 Years

What are the technological needs in space propulsion over the next 30 years (and beyond)? In 1961, Arthur C. Clarke observed, "The short-lived Uranium Age will see the dawn of space flight; the succeeding era of fusion power will witness its fulfillment."[18] Although the dawn of the uranium age occurred in the middle of the twentieth century, spaceflight is still in its infancy.

Early pioneers envisioning the technology that could propel humankind to the stars included the Austrian engineer Eugen Sanger, who in 1953 proposed the use of antimatter annihilation to generate photons for the creation of rockets that could approach the speed of light.[19, 20] The propulsion technology chosen for space exploration depends very much upon the mission. For example, flight from the surface to low-Earth orbit requires considerable energy to break free of the Earth's gravitational field, yet the duration of the flight is short. Space travel to the nearest stars will be of long duration and will be strongly influenced by the type and quantity of fuel available for extended journeys.

There are many different propulsion systems proposed for space exploration. The systems listed below involve propulsion through the transfer of momentum to the spacecraft through ejection of a propellant, where the propellant is a gas (ion drives), combustion products (chemical rockets, nuclear thermal), high-energy particles (fusion drive, antimatter drive), or photons (Bae drive).

- Chemical rocket, liquid fuel.
- Ion drives (VASIMR, PTI, and others).
- Bae photon drive (laser system).
- Stationary laser systems.
- Solar sails.
- Fission rockets:
  - Pulsed.
  - Thermal reactor with ion drive.
  - Thermal reactor with propellant and Laval nozzle.
- Fusion drives:
  - D-T fusion.
  - Aneutronic fusion.
  - Bussard (proton and boron-11).
  - Antimatter catalyzed.

- Antimatter drives:
  - Antimatter/fission.
  - Antimatter, propellant and Laval nozzle.
  - Antimatter, electrical generation, ion drive.
  - Antimatter, electrical generation, photon drive (Sanger).
- Speculative technologies:
  - Heim graviphoton drive.
  - Black hole energy source.

To look at the role of fusion propulsion over the next 30 years and beyond, we can envision four kinds of missions: surface to LEO (low-Earth orbit); LEO to Mars; LEO to Saturn; and LEO to Alpha Centauri A, B, or C. While technical hurdles will certainly be at the forefront for each mission, safety factors and fuel concerns will also contribute to the optimal propulsion technology chosen.

SURFACE TO LOW-EARTH ORBIT (100 MILES)

The energy required to move one kilogram of mass into LEO 100 miles above the surface of the Earth is about 30 MJ (8.5 kW-hr). The energy required to move this same mass from LEO to lunar orbit significantly smaller, yet the transit time can be very long. Chemical rockets, such as the Saturn V, have successfully launched satellites and the Apollo missions into earth orbit using RP-1 and LOX (liquid oxygen), along with LH2 (liquid hydrogen) in the second and third stages).

Proximity to the Earth's surface requires propulsion systems that are safe to the population and to the environment. The Rover Project in the 1950s explored the use of nuclear fission NERVA (Nuclear Engine for Rocket Vehicle Application) rockets, but ejection of radioactive debris made these rockets untenable for use on Earth. Fusion and antimatter systems suffer the same problem. Chemical rockets will continue to move humans into local space until another technology is available. Given sufficient technical and financial support, additional systems may be explored over the next 30 years:

- **The Space Tether**: This involves a carbon nanotube tether that connects a spaceport on the Earth's surface to a station in geosychronous orbit above the equator. Carbon nanotubes are extremely strong, yet fibers of sufficient length to fabricate into a tether are not yet available. This is an active area of research (http://www.spaceelevator.com) with scientific progress presented at regular conferences. Cargo and passengers would be moved into LEO using an elevator attached to the tether.

- **SSTO (Single Stage to Orbit)**: Multistage rockets are now used to attain Earth orbit since most of the energy expended by the rocket is used to lift the rocket and its fuel. The space shuttle is based on an earlier design by Eugen Sanger in 1930s

Germany called the Silvervogel that was intended for use in suborbital bombing of distant targets. The shuttle requires expendable rockets to attain orbit. Several efforts are underway to manufacture aircraft that can attain orbit with less cost and environmental damage as the current rocket technology. While the Spaceship One and Spaceship Two designed by Scaled Composites and Virgin Atlantic can carry passengers into space, they lack the energy to propel a payload into orbit at the required 17,000 miles per hour. The Boeing X-37 is designed to carry unmanned payloads into orbit, yet still requires an Atlas V rocket to launch. The DARPA/USAF Falcon is designed for hypersonic flight at Mach 6, far short of the Mach 23 or so required for orbit. Through the use of RAM jets and hybrid systems (air breathing/rocket), the goal of SSTO is achievable over the next 30 years.

LEO TO MARS (34 TO 249 MILLION MILES)

Chemical rockets have been used to launch probes to Mars with great success. The transit time is typically 9 months, each way. Aerobraking in the Martian atmosphere is used to slow down the vehicles, resulting in a considerable savings in fuel. For human flight to Mars, the transit time must be as short as possible to minimize radiation exposure from cosmic sources, including the proton flux from the Sun. The specific impulse of chemical rockets is low; I_{sp} = 421 seconds for the last two stages of the Saturn V, for example. Ion thrusters are also existing technology and can generate much higher specific impulse (3,000 seconds for xenon electrostatic drives to 30,000 seconds for VASIMR). Ion drives, however, typically generate very low thrust.

A high performance Hall effect ion drive with I_{sp} = 8,000 seconds generates only 2.5 newtons of thrust, for example, which is enough to accelerate one kilogram of mass at 0.25 g, where g = earth's gravitation acceleration. This drive requires 140 kW of electricity to operate and a supply of xenon gas as a propellant. For a probe having the mass of the International Space Station (370 metric tons), we can use equation 6.1 to calculate the time required to transit to Mars with our Hall effect ion drive.

$$t = \sqrt{\frac{2\,d\,m}{F}} \qquad (6.1)$$

In this equation, t is the transit time, F the thrust, d the distance, and m the mass of the object to be accelerated at a constant rate. Results show that it will take at least 4 years to make this transit. The use of multiple drives may decrease this time.

For manned flights to Mars, an estimated transit time of 30 days would be considered appropriate in order to minimize radiation exposure to the crew. For this scenario, 10,000 Hall effect ion drives would be needed along with 1.36 gigawatts of electrical power, slightly more than the power generated by a single reactor at the San Onofre Nuclear Power Plant. An alternative ion drive design is the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) developed by Franklin Chang-Diaz in 1977. These systems use hydrogen, argon, or neon gas and generate 1 newton of thrust for 100 kW of power. The VX-200, a 200-kW VASIMR engine, will be tested on the International Space Station in 2011 or 2012.[21]

Chemical rockets and nuclear electric propulsion can be used to reach Mars; both are based on existing technology. A third candidate is nuclear thermal propulsion. Rockets of this design were tested at the Nevada Test Site and were intended to launch payloads from the Earth's surface. With I_{sp} = 850 seconds, the performance more than doubled that of typical chemical rocket designs. The largest NERVA rocket tested generated 867 kN of thrust using liquid hydrogen propellant. NERVA rockets were proposed for the Manned Mars Mission using a tethered cabin to protect the crew from reactor radiation. The NERVA project was cancelled in 1972.

LEO TO THE MOONS OF JUPITER AND SATURN (460 TO 940 MILLION MILES)

Project Prometheus, 2003-2005, concentrated on nuclear electric and nuclear thermal propulsion for unmanned missions to the moons of Jupiter. For manned flight, the nuclear thermal systems based on NERVA still provide high thrust, reasonable values of specific impulse, and a technology that requires no major breakthroughs in order to be achieved. For manned flights, tethered systems will likely be necessary to minimize radiation exposure to the crew from the reactor. For the next 30 years, nuclear thermal propulsion can be used to explore locations throughout the solar system based on new engineered designs with no unresolved scientific hurdles.

Fusion reactors or fusion propulsion can be developed for missions throughout the solar system, but there are many unresolved issues in their use. The fusion propulsion technology that may show promise in the far-term are pulsed propulsion systems. These concept designs include large sails or collectors that absorb the energy from thermonuclear explosions initiated at a specific distance from the collector. Each explosion generates a pulse that accelerates the vehicle forward. Design challenges include protection of the crew from the radiation of the nuclear blast, cushioning the crew from the incredible "jerk" or change in acceleration that occurs during each blast, and the design of a suitable collector.

LEO TO ALPHA CENTAURI (4.22 LIGHT-YEARS OR 24.8 TRILLION MILES)

Alpha Centauri contains three of the closest stars to our solar system. Alpha Centauri A and B are binary stars orbiting one another, yet each one is approximately the same size as the Sun. Alpha Centauri C, or Proxima Centauri, is the closest at 4.22 light-years and is a red dwarf. There is a limited possibility that Alpha Centauri has Earth-like planets.

Rockets optimal for flights to these stars and destinations of similar distance would require high specific impulse propulsion. Depending on other mission requirements, the thrust may be kept low since the application of a small, but continuous thrust over a long period of time leads to high velocities. Since aerobraking may not be possible, the spacecraft can accelerate for half the trip and must decelerate for the second half. Spacecraft acceleration can be low, and most designs for human flight focus on a continuous acceleration of 1 g (Earth gravity) to provide optimal crew conditions.

Chapter 7: Conclusions

Among the various aneutronic fusion propulsion technologies developed, Robert Bussard and his colleagues appear to have the best developed proposals. All nuclear fusion designs rely on ignition of the fusion reactions that will consume less energy than is produced by fusion. This hurdle is significant and has thwarted the ability for fusion reactors to generate commercial electricity.

Antimatter engines are a more promising technology, since the technique to harvest and store small amounts of antihydrogen already exists. Antimatter is a denser form of energy than fusion fuels and presents the possibility of creating a rocket that approaches the speed of light relative to Earth. The major hurdles to antimatter propulsion include the production of commercial quantities of antihydrogen and the safe transport of antimatter from the earth's surface into space.

Appendix A: Relativistic Rockets

Since the application of a constant acceleration for a long period of time can lead to very high velocities, these spacecraft may reach relativistic velocities where $V > 0.5\,c$ (speed of light). At these velocities, time dilation and Lorentz contraction can be significant.[22] Special Relativity can be used to compute these effects based on the Lorentz factor, γ, as shown below:

$$\gamma = \frac{1}{\sqrt{1 - \left(V/c \right)^2}} \qquad \text{(A.2)}$$

Specific impulse for relativistic rockets is usually expressed in dimensionless form:

$$\frac{I_{sp}}{c} = \gamma \left(\frac{v_{exhaust}}{c} \right) \qquad \text{(A.3)}$$

Treating Earth as a nonaccelerating reference frame, time intervals measured on a rocket traveling at a velocity with respect to Earth will be "dilated" according to the following equation:

$$\Delta t_{earth} = \gamma\, \Delta t_{rocket} \qquad \text{(A.4)}$$

Time intervals measured by the crew on the rocket will be longer than the interval measured on Earth. The ratio of time measured on the rocket to time measured on earth follows the graph in Figure 12. When a spacecraft reaches 86% of the speed of light, their "clock" will run at half the speed of a clock located on earth.

For a constant acceleration, equations for rocket performance can be written in terms of the following variables:

t	=	time measured on the rocket
t'	=	time measured in the rest mass frame (Earth)
D	=	distance traveled
a	=	acceleration
c	=	speed of light
V_{final}	=	final rocket velocity at rocket time t'

$$t' = \frac{c}{a} \sinh\left(\frac{a\,t}{c} \right) = \sqrt{\left(\frac{D}{c} \right)^2 + \frac{2\,D}{a}} \qquad \text{(A.5)}$$

$$D = \frac{c^2}{a} \left[\cosh\left(\frac{a\,t}{c} \right) - 1 \right] = \frac{c^2}{a} \left[\sqrt{1 + \left(\frac{a\,t'}{c} \right)^2} - 1 \right] \qquad \text{(A.6)}$$

$$V_{final} = c\, \tanh\left(\frac{a\,t}{c} \right) = \frac{a\,t'}{\sqrt{1 + \left(\frac{a\,t'}{c} \right)^2}} \qquad \text{(A.7)}$$

$$t = \frac{c}{a} \sinh^{-1}\left(\frac{a\,t'}{c}\right) = \frac{c}{a} \cosh^{-1}\left(\frac{a\,D}{c^2} + 1\right) \tag{A.8}$$

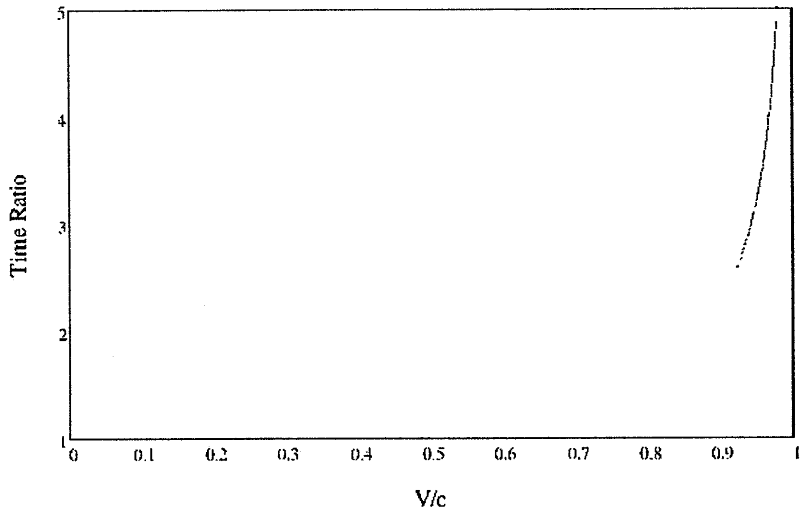


Figure 12. Time Dilation at Relativistic Velocities.

The Tsiolkovsky rocket equation is important as it relates the change in the mass of a rocket due to fuel consumption in order to generate a desired *ΔV*, or velocity change:

$$\Delta V = I_{sp} \ln\left(\frac{m_{initial}}{m_{final}}\right) \tag{A.9}$$

For a relativistic rocket, velocity is affected by time dilation resulting in the relativistic rocket equation:

$$\Delta V = c \tanh\left(\frac{I_{sp}}{c} \ln\left({m_{initial}}/{m_{final}}\right)\right) \tag{A.10}$$

Through any propulsion method, kinetic energy must be added to the rocket through reaction mass (propellant) in order to accelerate the rocket to its final velocity. Since mass changes with velocity, we will need to use Einstein's equation to determine the kinetic energy required to accelerate the rocket to a final velocity based on its rest mass, m_o.

$$E = m\,c^2 = KE + m_o\,c^2 \tag{A.11}$$

$$KE = m\,c^2 - m_o\,c^2 = m_o\,\gamma\,c^2 - m_o\,c^2 \tag{A.12}$$

$$KE = m_o\,c^2\,(\gamma - 1) \tag{A.13}$$

Appendix B: Aneutronic Fusion Rocket

For travel to the stars, aneutronic fusion combines a high specific impulse of I_{sp}/c = 0.119 (ideal), compared to a maximum possible of 1.0, with minimal radiation to the crew. The Bussard fusion propulsion system is an example of this design and uses the Farnsworth/Hirsch electrostatic confinement method to initiate fusion of hydrogen and boron-11.[23] The specific impulse of this design is reported from 1,500 to 6,000 seconds requiring 4.5 to 8 gigawatts of power from the fusion reactor. In this design, 0.078% of the mass converted into energy actually goes into thrust with the remaining energy converted into heat and gamma rays. For a long-duration space flight, the specific impulse of the fuel source must be very high since a great deal of fuel is consumed over time, but the thrust required is relatively small.

To explore the needs for high I_{sp}, we can envision a flight to Proxima Centauri, a distance of 4.22 light-years. The maximum acceleration that the crew can survive is assumed to be 1 g (earth gravity). As the vehicle accelerates away from Earth, relativistic effects described through equations A.5 to A.10 become important. The clocks on the rocket appear to be moving slower than the clocks on Earth, the rest mass frame. During this mission, the rocket is assumed to accelerate for the first 2.11 light-years to its maximum velocity. At this midpoint in its journey, the rocket turns around and decelerates at the same rate until it reaches Proxima Centauri.

Typical questions about the mission:

- How long will the journey take (in terms of both Earth clocks and rocket clocks)?
- How much fuel is consumed?
- What maximum velocity is achieved?

The answers to these questions are dependent upon:

- The distance to the star.
- The mass of the rocket payload, engine, and fuel.
- The effective specific impulse of the engine, when all inefficiencies are included.

For the trip to Proxima Centauri, the minimum duration flight is affected by how close to the speed of light the ship can travel. Unfortunately, the higher the maximum speed, the greater mass fraction of fuel required. This is shown in Figure 13. If the fuel is assumed to be no more than 50% of the initial mass of the rocket, for example, the maximum speed that could be attained is limited to 8% of the speed of light for the ideal fusion drive (I_{sp}/c = 0.119).

The following equation is used in the figure:

$$\frac{V_{maximum}}{c} = \tanh\left(-\frac{I_{sp}}{c}\ln\left(1-\frac{\Delta m}{m_{initial}}\right)\right) \qquad \text{(B.14)}$$

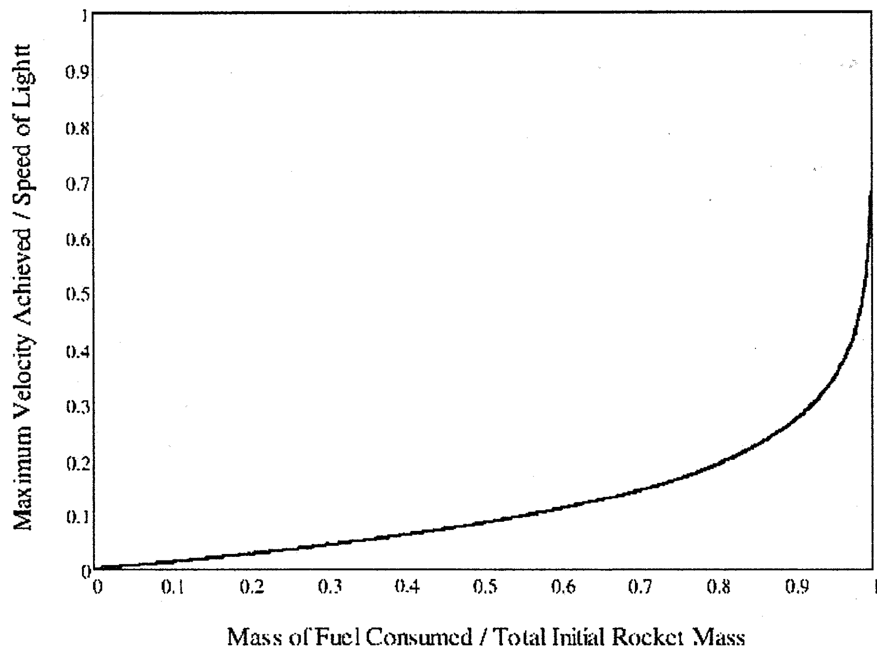


Figure 13. Maximum Achievable Velocity Versus Fuel Usage.

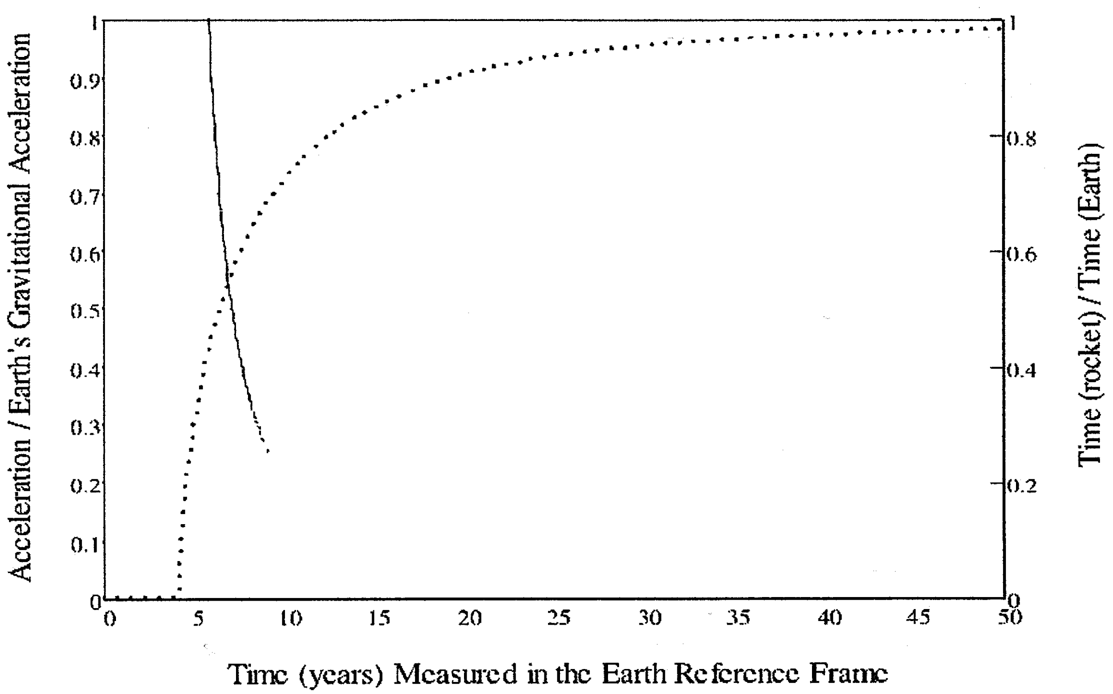
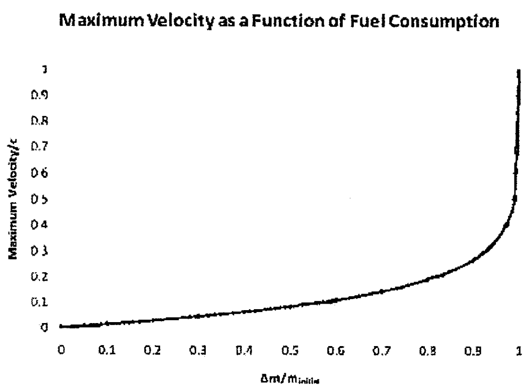


Figure 14. Acceleration and Rocket "Clock" Ratio versus Mission Time on Earth.

Another item to consider is the value chosen for the constant acceleration of the spacecraft. We cannot exceed 1 g for crew safety, yet higher accelerations mean shorter trips to the stars. Figure 14 shows how much time is required for the trip (one way) based on the required acceleration. These equations are independent of the specific impulse of the rocket. The mission cannot be less than 4.22 years in duration, since the spacecraft cannot exceed the speed of light. If a 10-year mission were chosen, the fuel usage would be tremendous, but the vehicle could attain an acceleration of 0.20 g. At this acceleration, time on the rocket would pass at 72% of the rate of time on Earth.

To predict the amount of fuel required for the ideal fusion drive, the Bussard Aneutronic Propulsion system, weighing 14 tons, is assumed to be coupled to a craft the same mass as the International Space Station. By assuming a very gradual acceleration of 0.001 g, the trip will take about 127 years attaining a maximum velocity of 6.5% of the speed of light. Even at this modest acceleration, 85% of the initial mass of the spacecraft will have to be fuel/propellant. The Mathcad spreadsheet used to predict these values is included in Appendix D as the "Relativistic Rocket Worksheet." Figure 15 shows the opening page of the worksheet. Any text in red can be modified to predict performance with different drives, vehicle mass, or distance traveled.

Relativistic Rocket Calculator					
Values in Red May be Changed by the User					
A. Define the Mass of the Rocket and the Engine					
1. Payload Mass	370,000	(kg)			
2. Engine and Fuel Mass	12,700	(kg)			
3. Total Rocket Mass	382700	(kg)			
B. Define the Specific Impulse of the Engine					
1. Specific Impulse	3639143.731	(s)			
2. I_{sp}/c	0.119				
C. Define the Distance to the Star					
1. Distance	4.22	(lightyears)			
2. Distance	3.99246E+16	(m)			
D. Define the Maximum Acceleration					
1. Acceleration/g	0.001				
2. Acceleration	0.00981	(m/s^2)			
E. Compute the Time Required for the Mission					
1. Mission Time (Earth Time)	4036935068	(s)	=	128.0104	(years)
2. Mission Time (Rocket Time)	4034009639	(s)	=	127.9176	(years)
F. Calculate the Velocity at the Midpoint					
1. Velocity at Midpoint	19758174.9	(m/s)			
2. Velocity/c	6.6%				
G. Calculate the Energy Required					
1. Lorentz Factor	1.002175889				
2. Energy from Fuel	1.49888E+20	(J)			
H. Calculate the Mass of Fuel Required					
1. Delta-V	19758174.9	(m/s)			
2. Mass Ratio (final/initial)	1.74E+00				
3. Final Mass	2.20E+05	(kg)			
4. Mass of Fuel Consumed	3.26E+05	(kg)			
5. Fuel Mass/Initial Rocket Mass	85.1%				



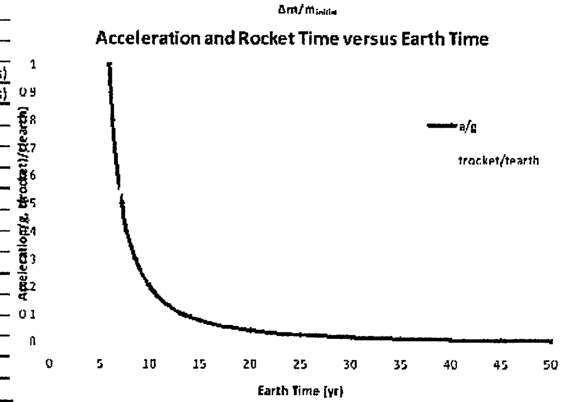


Figure 15. Spreadsheet for Sample Mission to Alpha Centauri.

Table 3: Specific Impulse for Selected Drives

Specific Impulse for Selected Drives		
	Isp/c	Isp (sec)
Chemical Rocket (Stages 2,3, Saturn V)	0.000014	421
Hall Effect Ion Drive	0.000082	2,500
VASIMR Ion Drive	0.000196	6,000
Nuclear Fission Drive	0.040000	1,223,242
Bussard Aneutronic Fusion Drive	0.000196	6,000
Ideal Fusion Drive (p --> He)	0.119000	3,639,144
Antimatter, proton/antiproton	0.600000	18,348,624
Antimatter, electron/positron	1.000000	30,581,040

The performance of the Bussard Aneutronic Drive used in the example actually has a much lower specific impulse as indicated in Table 3. Considerable work will be needed to design an aneutronic drive that can approach the maximum theoretical value of $I_{sp}/c = 0.119$. Research challenges in the development of aneutronic drives should be studied over the next 20 to 30 years and include the following:

- **Fusion Initiation:** Reliable fusion of p + ^{11}B has only been demonstrated in a laboratory setting using a picoseconds laser in 2005 by V. S. Belyaev in Russia. The particle energies required to initiate p-B fusion are 300 keV, which corresponds to about 3.3 billion degrees C. For comparison, the easiest fusion reaction to initiate is D-T which requires only 66 keV or 730 million degrees C. D-T fusion is still difficult to initiate in the laboratory, and the energy generated by D-T fusion still exceeds the energy required to initiate the process with the exception of thermonuclear devices. Work on inertial confinement fusion, electrostatic confinement, magnetic confinement, laser ablation, and other techniques are under investigation at laboratories around the world and reliable, efficient fusion initiation devices will be developed over the upcoming 30 years.

- **Materials:** New materials will be required to survive the temperatures and radiation within a fusion propulsion system ignition chamber and nozzle (if used). These materials must effectively stop the leakage of gamma rays from fusion production and x-rays emitted through bremmstrahlung due to electron impingement on the chamber walls. Materials development should be a major focus for research.

- **Generation of High-Tesla Electromagnets:** Powerful electromagnets will be required to direct positively and negatively charged fusion products into generating thrust or for direct conversion into electricity. Superconducting magnets are viable, although they will be located near the fusion reactor—high temperatures and gamma radiation will heat and embrittle the material. Work will be needed to create magnets capable of generating 10 T magnetic fields.

Appendix C: Antimatter Annihilation Rocket

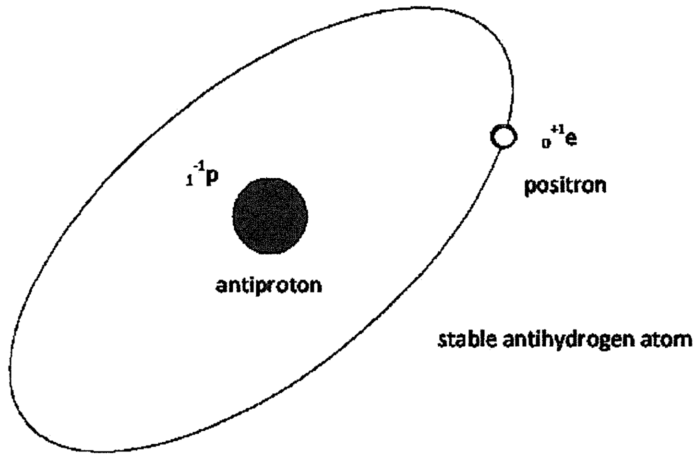


Figure 16. Antihydrogen Atom.

Using data from Table 3, the only propulsion system that can generate higher I_{sp} than fusion will be due to antimatter annihilation. By using the Relativistic Rocket Worksheet in Appendix D, it is possible to decrease the time to reach Proxima Centauri to only 18.5 years by accelerating at 0.05 g to reach 43% of the speed of light. By using antihydrogen, two annihilation mechanisms are possible:

- Electron-positron annihilation releases one energetic gamma ray (1.022 MeV) or, in the presence of a nucleus, two 0.511-MeV gamma rays. There is no effective way to reflect gamma rays, but they can be absorbed with suitable shielding and their energy converted into heat. Research into designs that convert gamma ray heat into propulsion or electrical power should proceed over the next 10 to 20 years.

- Proton-antiproton annihilation releases charged and neutral pions, which decay after about 0.026 microseconds into charged muons and neutrinos. The charged pions can be used to directly generate thrust or to make electricity if they are directed by electromagnets. Unfortunately, 40% of the pions will be neutral and quickly decay into gamma radiation, which are lost from the system or absorbed in the rocket chamber wall and generate heat. Muons also decay into charged particles (electrons and positrons), along with neutrinos. Neutrinos and antineutrinos, along with their energy, are lost from the system. Novel rocket designs that capture gamma radiation with a tungsten insert allow the waste heat to be used to accelerate a propellant, such as hydrogen, to generate additional thrust. This system was proposed by Robert Frisbee and Ulrich Walter and deserves further study.[24] Efficient ways to redirect the energy of gamma rays into thrust should be a major focus of research.

Antimatter propulsion is fairly straightforward since ignition is not a problem. By mixing hydrogen with antihydrogen, annihilation begins immediately. Antimatter propulsion has two major hurdles that are currently under investigation at CERN and at the Brookhaven National Laboratory.

- **Antimatter Generation:** Only minute quantities of antimatter have ever been produced. Antiprotons are produced in accelerators and in some radioactive decay schemes. CERN has had an active program since 2000 in antimatter detection and collection.[25] Studies of antimatter production will continue during the upcoming decade due to their importance as a dense storage medium for energy and for their use in particle physics experiments. Current patents should help decrease the costs of production of antihydrogen. Three programs have been part of the CERN Antimatter Factory:

  - **ASACUSA**: Antiprotons were directed through helium to generate atoms of helium-2 with antiprotons replacing the orbiting electrons.
  - **ATHENA**: An antiproton beam was fired through positrons generated from the decay of Na-22. To generate the antiprotons, a proton synchrotron is used to collide protons on an iridium surface. Antiprotons produced in the collision are directed with electromagnets into an antimatter decelerator and captured. By 2002, ATHENA made 106 antihydrogen atoms in this way. The estimated cost of generating antihydrogen using current technology is about $65 million/gram.
  - **ATRAP**: This device used a Penning trap to combine cold antiprotons and positrons to create antihydrogen.

- **Antimatter Storage:** Penning traps and Penning-Malmberg traps have been used to contain antihydrogen for several weeks using a combination of RF and magnetic fields.[26] Further research into antimatter storage will lead to the ability to transport and store nanogram or microgram quantities of antimatter.

Speculative Technologies: The Heim Quantum Theory

Burkhard Heim was a theoretical physicist that explored a new theory to link quantum mechanics and the Theory of Relativity.[27] He postulated that time and distance are quantized and that matter and energy can be described in terms of 12 dimensions. His worked was followed by the Extended Heim Theory from Walter Droscher and Jochem Hauser.[28] The Heim Theory is able to predict, with a high degree of accuracy, the mass and charge of almost all subatomic particles. New particles, such as the neutral electron, are also predicted. The relationship of his work to space propulsion involves the prediction of a quantum gravity force mediated through graviphotons created from the interaction of matter and virtual particles. Droscher and Hauser have proposed the use of graviphotons to provide propulsion in space with no ejection of matter to generate thrust.

There are few peer-reviewed articles on Heim Quantum Theory, and physicists disagree with the formulation of the theory and its results. Nevertheless, this would be the first method that would not require the transfer of momentum by ejecting mass to generate thrust. The Heim Working Group and the work of Droscher and Hauser should be followed for possible application to spacecraft.

Appendix D: Relativistic Rocket Worksheet

Estimate of the Performance of an Intersteller Relativistic Space Vehicle

1. Define the Specifications for the Rocket

   a. Rocket mass

   $m_{payload} := 370 \cdot 10^{3} \cdot kg$ *Assume the same mass as the ISS with a crew of 6.*

   $m_{engine} := 14 \cdot ton$ $\quad m_{engine} = 1.27 \times 10^{4}\,kg$

   $m_{rocket} := m_{payload} + m_{engine}$ $\quad m_{rocket} = 3.827 \times 10^{5}\,kg$

   b. Specific impulse for the engine

   $I_{sp} := 0.119 \cdot c$

   $\frac{I_{sp}}{c} = 0.119$

2. Define the Requirements for the Mission to Alpha Centauri

   a. Assume that the rocket will accelerate halfway to Alpha Centauri at 1 g (earth gravitational acceleration), and will decelerate during the last half of the trip at the same rate.

   $a := \frac{g}{1000}$ $\quad a = 9.807 \times 10^{-3}\,\frac{m}{s^{2}}$

   $ly := c \cdot 365 \cdot 24 \cdot 3600 \cdot s$

   $D := 4.22 \cdot ly$ *Distance to Proxima Centauri in lightyears.*

3. Compute the Rocket Performance

a. Time required to reach Proxima Centauri in earth time (inertial reference frame) and in rocket time..

$$t_{earth} := 2\cdot\sqrt{\left[\frac{\left(\frac{D}{2}\right)}{c}\right]^2 + 2\cdot\frac{\left(\frac{D}{2}\right)}{a}} \qquad t_{earth} = 127.903\,yr$$

$$t_{rocket} := 2\cdot\frac{c}{a}\cdot\mathrm{acosh}\left[a\cdot\frac{\left(\frac{D}{2}\right)}{c^2} + 1\right] \qquad t_{rocket} = 127.81\,yr$$

b. Peak velocity.

$$V_{midway} := c\cdot\tanh\left[a\cdot\left(\frac{\frac{t_{rocket}}{2}}{c}\right)\right] \qquad V_{midway} = 1.975\times10^{7}\,\frac{m}{s}$$

$$\frac{V_{midway}}{c} = 6.587\,\%$$

c. Compute the required kinetic energy that must be supplied by the fuel.

$$\gamma := \frac{1}{\sqrt{1-\left(\frac{V_{midway}}{c}\right)^2}}$$

Lorentz factor at the midway point (peak velocity).

$$\gamma = 1.002$$

$$KE := 2\cdot m_{rocket}\cdot c^2\cdot(\gamma - 1) \qquad KE = 1.497\times10^{20}\,J$$

d. Compute the mass of fuel that must be consumed by the rocket to complete the one-way trip.

$$\Delta V := V_{midway} \qquad \frac{\Delta V}{c} = 0.066$$

$$mass_{ratio} := e^{\left(\frac{c}{I_{sp}} \cdot \operatorname{atanh}\left(\frac{\Delta V}{c}\right)\right)} \qquad mass_{ratio} = 1.741$$

$$m_{final} := \frac{m_{rocket}}{mass_{ratio}} \qquad m_{final} = 2.198 \times 10^{5}\ \mathrm{kg}$$

$$\Delta m := 2 \cdot \left(m_{rocket} - m_{final}\right)$$ *Mass of fuel consumed.*

$$\Delta m = 3.257 \times 10^{5}\ \mathrm{kg}$$

$$\frac{\Delta m}{m_{rocket}} = 85.111\%$$

Appendix E: Endnotes

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