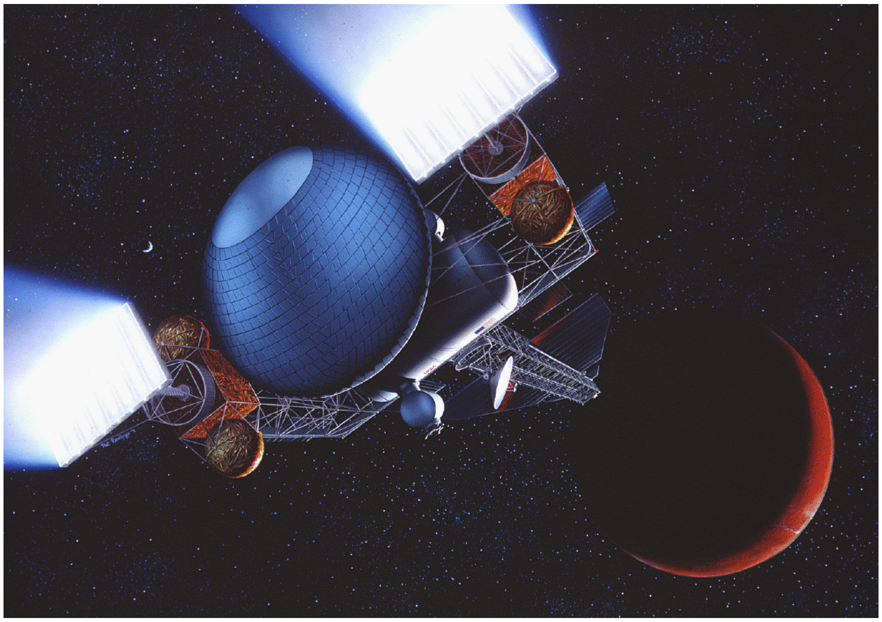
Advanced Fusion For Space Applications



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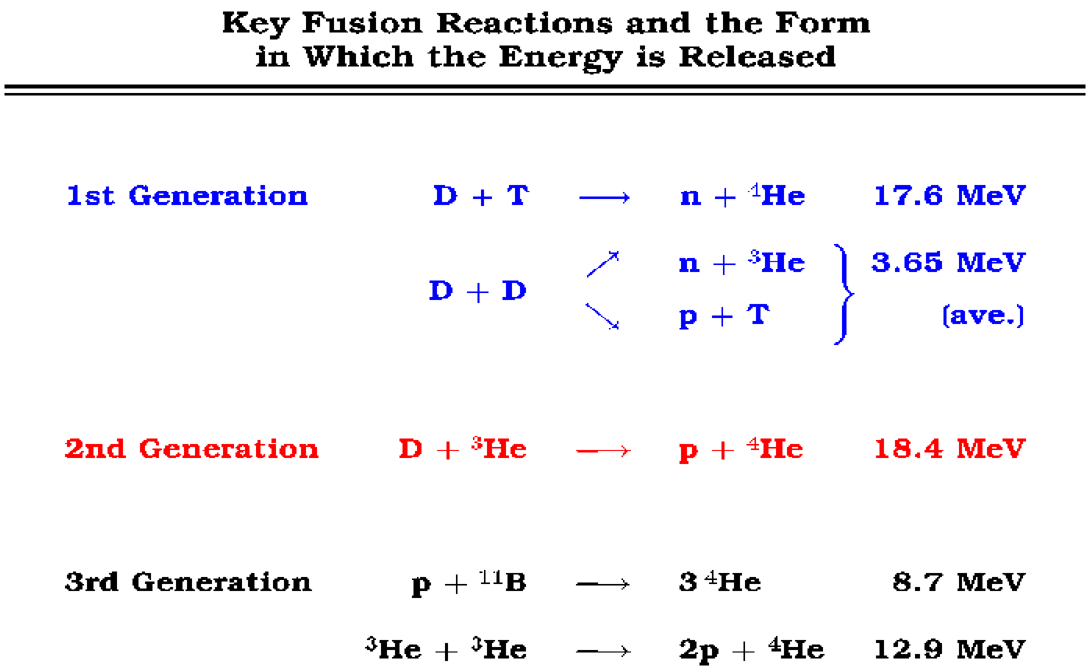
Introduction

As long as we have dreamed of expanding our race beyond the planet Earth, it has been apparent that a high-power, low mass energy system would be needed. The ratio of power to mass is essential in determining how fast a rocket can get to where it's going, and it's mass determines how much it costs to launch. Today, there are two choices for such power systems, nuclear fusion, and antimatter annihilation. While antimatter possesses much higher power density than fusion, it is difficult and expensive to make in large quantities on earth. You would not be able to make it on board a spacecraft, since the energy cost of generating antimatter far exceeds the return. Furthermore, antimatter is inherently dangerous, as a loss of containment means almost certain destruction for anything around it. For these reasons, it is important to look very seriously at the application of advanced fusion technologies.

Ever since nuclear fusion has been considered for space power, it has been clear that standard deuterium-tritium (D-T) fusion reactors would have some fundamental limitations. The first of these limits is that 80% of D-T fusion energy is produced in the form of neutrons. This means a lot of neutrons at high energy, which pose a large problem when trying to shield a payload. Since neutrons penetrate matter very easily, they require a lot of shield mass, and the reactor requires a neutron-safe container. The second limit is that in order to use these neutrons for electric power generation, their energy must first be converted to heat, and then be transferred to a Carnot-cycle limited device. Currently, the best Carnot engines for space power can produce 25% efficiency, but a price is paid for this because they are very massive. Still another difficulty, is that tritium is not readily available anywhere in the known universe. Therefore, if you wish to have an unlimited fuel supply, you need to have mass-expensive breeding blankets and extraction devices. These limitations can all be overcome, but at the penalty of making a very massive rocket. This creates a discrepancy with the fundamental goal of the nuclear rocket, and that is to generate a low mass, high power system.

The answer to this problem lies in advanced fusion. For the purposes of this paper, advanced fusion means to burn advanced fuels in advanced reactor configurations. Work done as of late on the fusion of fuels other than D-T has shown promising results. In particular, the fusion of two ^{3}He atoms, and the fusion of a deuterium with a ^{3}He atom are of interest. Figure 1 shows the D-T and advanced fusion cycles:



Key Fusion Reactions and the Form in Which the Energy is Released

1st Generation	$D + T$	$\longrightarrow$	$n + {}^4He$	17.6 MeV
	$D + D$	$\nearrow$	$n + {}^3He$	3.65 MeV
		$\searrow$	$p + T$	(ave.)
2nd Generation	$D + {}^3He$	$\longrightarrow$	$p + {}^4He$	18.4 MeV
3rd Generation	$p + {}^{11}B$	$\longrightarrow$	$3\,{}^4He$	8.7 MeV
	${}^3He + {}^3He$	$\longrightarrow$	$2p + {}^4He$	12.9 MeV

Figure 1—Fusion reactions

These reactions produce little or no neutrons, and most of their energy is released in the form of charged particles. Charged particles require very little shielding, and can be converted directly into energy without the use of a Carnot engine. Direct conversion is very effective, and has demonstrated efficiencies of over 70%[2]. Still another advantage of direct conversion over high efficiency Carnot engines is that there are no moving parts, so maintenance is kept to a minimum. Further, ^{3}He fuel is found all throughout the universe and the reactor could be refueled at any number of locations such as the moon.

Applications

This strong argument for advanced fusion forces one to consider the applications for such a power supply in greater detail. There are 4 major regimes of application for high power and energy density systems in space: near-earth missions, base-settlement missions, interplanetary missions, and interstellar missions. Advanced fusion is preferable for almost all of them, with the exception of low power space satellites and possibly lunar bases.

Near Earth Applications

First consider the application of near earth missions. This refers to any applications in which the reactor will orbit the earth. Few advanced fusion power reactor designs are mass effective below a few hundred mega-watts, although an innovative new fusion device being researched at the University of Wisconsin, the University of Illinois, and other places is rapidly up and coming for low power generation. This would be a remarkable device for all satellite power systems requiring less than 100 MW, as it's mass is low, and it is very safe. This fusion reactor uses a technique called inertial electrostatic confinement (IEC), which will be talked about in more detail later.

High power satellite applications come primarily from the military, specifically weapons platforms. The need for high power was looked at heavily as part of the strategic defense initiative (SDI) in the early 1980's under President Reagan. An example of the power levels needed for various weapon types are listed in figure 2.

Weapons Platform	Power Required
Free Electron Lasers	300 MW
Neutral Particle Beam	500 MW
Electromagnetic Launchers	500 MW

Figure 2—Power needs of SDI defense weapons

These were determined to be vital systems for a ballistic missile defense system, but the power levels required to operate them are not achievable with standard space power systems today. Even though the weapons will not need to expend this power continuously, there are no solar platforms that can deliver this power for a long enough time to hold off an attack. Thermal fission systems are not good for weapons systems, since continuous startup and shutdown can poison the reactor, and make it unusable. Fast fission reactors require their coolant to be expelled when generating at these power levels, a problem which leads to the satellite being unable to see clearly. Once again, fusion systems may have the answer. Preliminary studies have been done on a burst mode D-^{3}He advanced reactor that can deliver 1000 MW$_e$ for up to 600 seconds. This device, called a tandem mirror, will be talked about in detail later. As you can see, this reactor is capable of producing the power required for strategic defense satellites, and sustaining it for a fair length of time. Such a system could be used to protect hundreds of millions of lives.

As research needs in space grow, it will become important to test high power experiments in scientific space labs. While a fission reactor or solar panels are suitable for the international space station, the time will soon be upon us where we need a high power space station. High-energy experiments in space could be used to explore the very origin of the universe, or help us come up with new ways to warp space and travel through it. For these experiments, advanced fusion is preferred once again for its low mass, low radiation, and high output characteristics.

Still another application for a fusion system in earth orbit would be an orbital transfer vehicle, capable of moving satellites up and down in their orbits. Such a system would require 10's of MW of electric power, and a low mass vehicle would be far more effective. For this reason, the high power density of an advanced fusion reactor is desired.

Base-Settlement Missions

Soon, we will expand our civilization to other bodies within our solar system. Since these new colonies will be far from the resources on the Earth, they will need to be self-sufficient. In order to insure this, a power system will be needed that has high output, is safe, and can be refueled without supplies from Earth. About 1 MW of electric power is needed to start a fully operational lunar base. To do this on Earth, a typical power plant burns oil or coal, but these materials will not be available on other worlds. Even the nuclear fission systems of earth pose difficulties to distant colonies. There will not be enriched uranium readily available, facilities will be needed to deal with the radioactive waste, and there is a chance of meltdown due to unforeseen events on a new world. Solar power is a poor option. On the moon, the lunar night lasts 14 days. On other planets, solar intensity falls off as $1/r^2$ so it becomes less effective further out.

It is important to note, however, that fission reactors are considered to be a strong alternative power source for a small lunar base because the technology has already been developed, and is trusted, despite the other complications that may arise. Furthermore, the moon is not so far away that transporting uranium, or even a new reactor would be exceptionally difficult. ^{3}He fusion, overcomes all these problems. On the moon, for example, there is a large amount of ^{3}He in the regolith, deposited by the solar wind, which can be extracted by heating the regolith to 700 °C. This is quite easy to do since the regolith has a very low specific heat. Lunar ^{3}He supplies are estimated to be 1,000,000 metric tonnes, and one kilogram fused in an advanced fusion reactor at 70% conversion efficiency produces 11.4 MW-y of energy[10]. Further, with the technology available today, it is estimated that a lunar miner could extract 33kg of ^{3}He per year. While obtaining the ^{3}He, the miner also would extract necessary volatiles for life, such as water, oxygen, nitrogen, hydrogen, and methane[10], so the mining operation for fuel would give you other necessities required to survive. When burning ^{3}He, the only byproducts are hydrogen and ^{4}He. These are safe, and can be released into the atmosphere with no harmful effects. From a safety standpoint, all advanced fusion systems have no chance of criticality, because the reaction is not self-sustaining, but requires power input and fuel flow to continue. Finally, as a comparison with solar power, a fusion reactor can always be running, and there is no need for complicated and massive energy storage systems.

Most of the emphasis in the discussion has been limited to application on the moon, but on further worlds, the need for advanced fusion power grows even greater. An extremely safe, self-sufficient system is required to keep the colonists on distant planets from relying on shipments of fuel from their home world, which could take years to get there.

Interplanetary Missions

When traveling from planet to planet, it is preferable to keep the journey as short as possible, especially for manned missions. With chemical rockets (minimum energy), the optimum path to Mars requires a journey of 9 months. This can have serious physiological and psychological repercussions on the astronauts involved. Even worse, journeys to other planets often take years or more depending on how far out you go. In order to shorten these journeys, a spacecraft that can generate a high exhaust velocity and a lot of thrust per unit mass is required. Fission rockets are strongly considered to be a possible solution to this problem, but even they cannot generate near the thrust power per kilogram of an advanced fusion system. Figure 3 compares the thrust to weight ratio of some different types of propulsion systems.

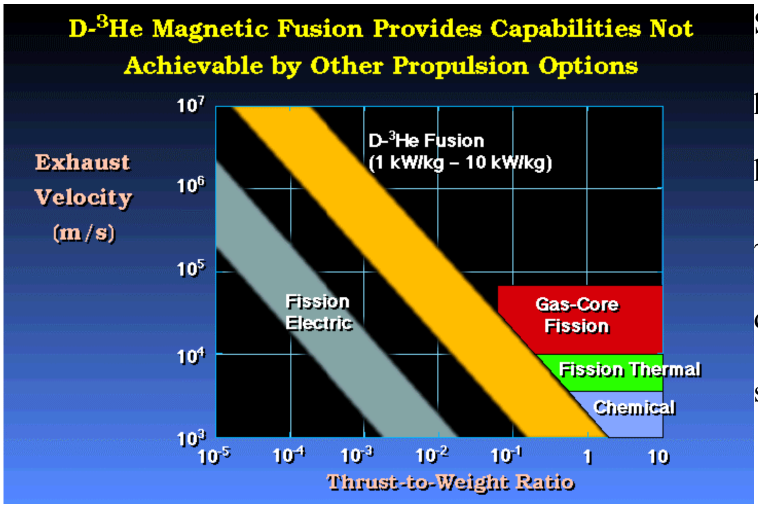


Figure 3—Thrust to weight ratios of different fusion systems

Since direct conversion fusion power systems provide the highest power per unit mass ~1-10kW/kg, they are most desirable for this application, specifically D-^{3}He.

The reason D-^{3}He is used instead of straight ^{3}He, is because the energy density of D-^{3}He is higher (for the lunar base, fuel mass was not as important). Electric power could be used to accelerate a propellant to high velocity ~10^5-10^6 m/s. This would allow a lot of momentum to be imparted to the rocket, with very little mass flow. Figure 4 shows the trip times to Mars and Jupiter with a D-^{3}He fusion system.

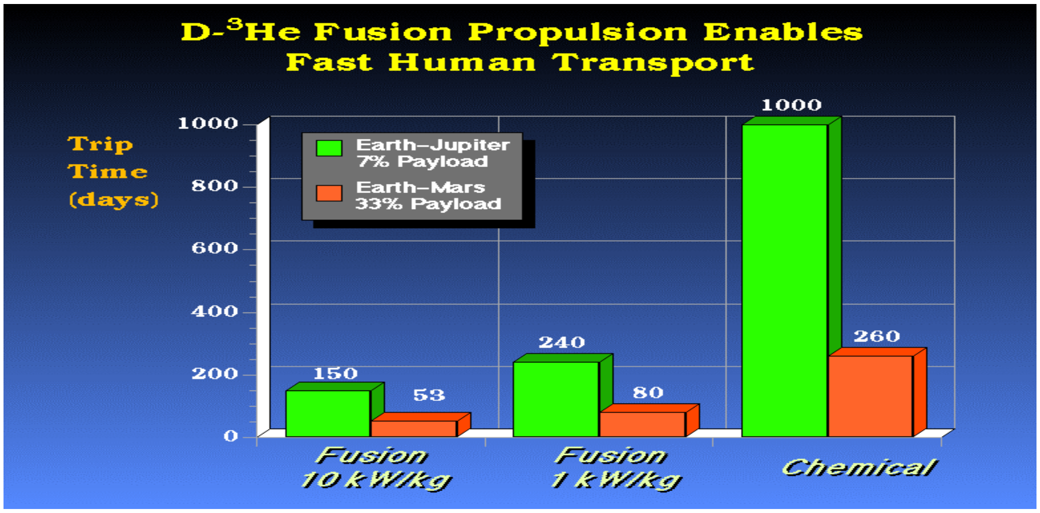


Figure 4—Earth to Mars and Earth to Jupiter trip times

In addition to producing thrust for the spacecraft, a D-^{3}He power system also produces electric power for all of the ships non-propulsion requirements, eliminating the need for a separate electric power generation system. The development of a D-^{3}He rocket could be a huge step towards opening up the solar system to mankind. To quote a colleague, Dr. John F. Santarius at the University of Wisconsin: "I confidently predict that, as the train functioned in opening the American West, D-^{3}He magnetic fusion will open the Solar-System frontier."

Interstellar Missions

Similar to the interplanetary missions, a very high power to mass ratio will be needed if humans are ever to reach the stars within a lifetime. These rockets would operate similarly to the interplanetary missions, but would have a small modification. When suitable velocity is reached, it may become beneficial to directly exhaust the reaction products of the fusion reaction. An interstellar mission could take place under the following protocol. A spacecraft is launched into orbit by conventional rockets to escape the gravity of the Earth. From here, it is stocked, and the fusion system powered up. A load of several kilograms of ^{3}He is brought to the craft from the moon so that it will have plenty of energy for the voyage. At this point, the fusion reactor increases its output to activate the electric field generators that will accelerate the stored propellant out the engine. This burn continues until the spacecraft reaches 1% the speed of light, at which point the electric thrusters are disengaged, and the fusion reactor opens up to outer space. The reaction products from the D-^{3}He reaction, shooting out at over 30 million m/s now propel the craft, and will continue to accelerate it until it reaches about 10% the speed of light.

For these systems, an even higher power/weight ratio is needed than for the interplanetary missions. In order to carry the large payloads that would be needed for interstellar travel, the fusion system should have power densities near 10MW/kg. It is predicted for a rocket with 250 metric ton payload, that a journey to the nearest solar system, Alpha Centauri (4.2 lt-yr away) could be completed in about 40 years using D-^{3}He propulsion[11] at these levels. This will take technology beyond what can be seen today, but given a good enough reactor, D-^{3}He has the required energy density.

An unmanned system could be made to Alpha Centauri in approximately 100 years with a more reasonable power density. A 10kW/kg D-^{3}He reactor could transfer a small payload with some of the configurations discussed in this report.

Power systems other than antimatter and fusion cannot even be considered for interstellar travel unless there is a way to slow down the human aging process. Fission and D-T fusion require too much shielding and waste handling to have low enough mass, and chemical systems cannot burn for so long. If there is an effective way, however, to contain and capture the energy from antimatter annihilation, it could surpass fusion energy densities by far, and be a distant future means of propulsion. The inherent danger of antimatter explosions and inability to store antimatter with today's technology force us to consider advanced fusion the only option for the near future.

Advanced Fusion Configurations

Now that the need for advanced fusion has been established, it is worthwhile to take a look at some of the systems that are under development today. Every system cannot be covered, but the details of a few that are considered promising will be explored. These are the spheromak, the tandem mirror, the field reversed configuration, and the IEC.

Spheromak

A spheromak is essentially a tokamak in which the center hole has been removed. The primary magnetic field is generated by a current conducted through the plasma, and the vertical field is generated by poloidal field magnets. Figure 5 shows a picture of a spheromak.

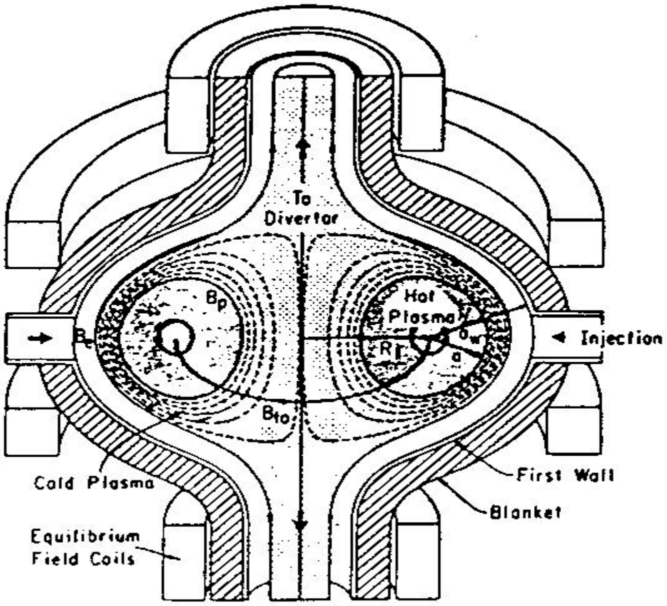


Figure 5—Spheromak Cross Sectional View

While the spheromak suffers some of the same troubles as a tokamak in terms of confinement, it offers the possibility of higher plasma temperatures, and high specific powers. A good spheromak should be able to produce the 10kW/kg required for fusion propulsion if a high enough plasma temperature can be reached, however this only applies to high mass, high output systems.

Spheromak research was funded heavily from the late 70's to the late 80's and has mostly tapered off today due to large funding cuts. In this time, plasma temperatures of 400eV were achieved with a magnetic field strength of 3 T. The plasma heating and magnetic field were achieved by a 1 MA toroidal plasma current. The spheromak was not sufficiently researched in its short tenure and is now being looked at again by many researchers across the country.

Tandem Mirror

The tandem mirror is another magnetic confinement system where the plasma is confined by a solenoidal "bottle". At the ends of the bottle are magnetic mirrors with applied electrostatic potentials to reduce wall loss. In order to use the tandem mirror for propulsion, one of the ends can be biased with a lower potential than the other, which would cause the high-energy plasma to leak out. Particles exiting this mirror would fall down a 1 MeV hill and thus exit the reactor at very high speed. A picture of the tandem mirror is shown in figure 6:

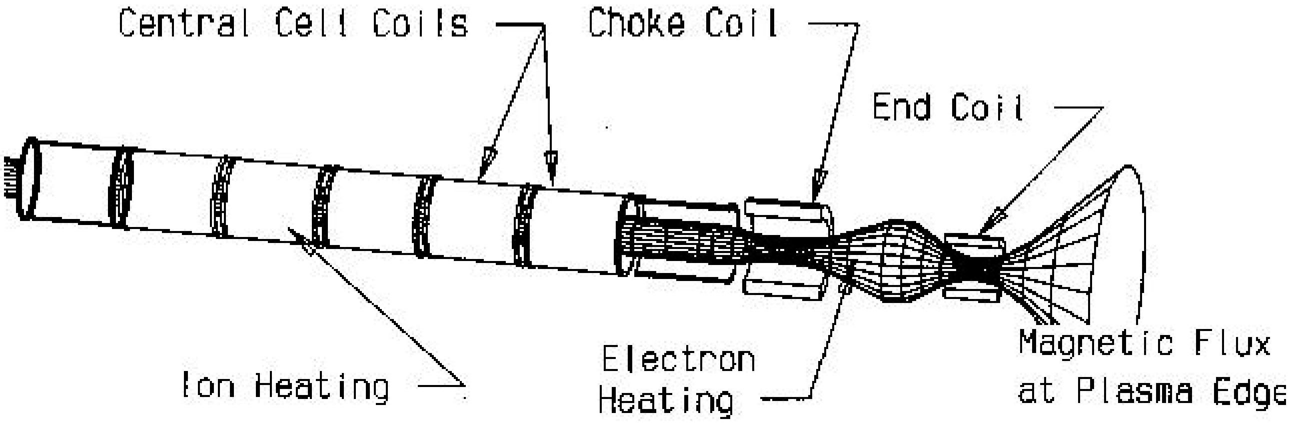


Figure 6—Tandem Mirror Propulsion Reactor

The tandem mirror has a lot of experimental data today, and aside from a few glitches, works quite well. It should be able to obtain high enough plasma temperatures for D-^{3}He, and is very good for directed thrust. Its specific power is about 1kW/kg, which although is not as high as some systems is still very attractive for propulsion. Large mass devices are needed to get this specific power though, and at low power levels, it would produce far less kw/kg. Other characteristics of the tandem mirror are that it can be stacked with additional segments for greater power output, and can easily be used for burst mode applications. It is a high output design, and cannot be used for low power application effectively. A hypothetical tandem mirror fusion propulsion system would produce nearly 2 GW of fusion power at an ion temperature of 105 keV of which 1500 MW would be thrust power. The mass of this system would be about 1250 tonnes, which leads to a specific power for this large configuration of 1.2kW/kg. Tandem mirror work is taking place in the U.S. and Japan at the TMX-U and GAMMA-10 reactors, respectively.

Field-Reversed Configuration (FRC)

Perhaps one of the most promising prospects for advanced fusion reactors is the field-reversed configuration. This reactor has a very high stability and offers the potential for direct conversion. It confines a fusion plasma in a central toroidal region with magnetic mirrors at the ends of the toroid. Similarly to the tandem mirror, one of these mirrors could be weaker, allowing high velocity particles out one end. A schematic of the FRC design is shown in figure 7:

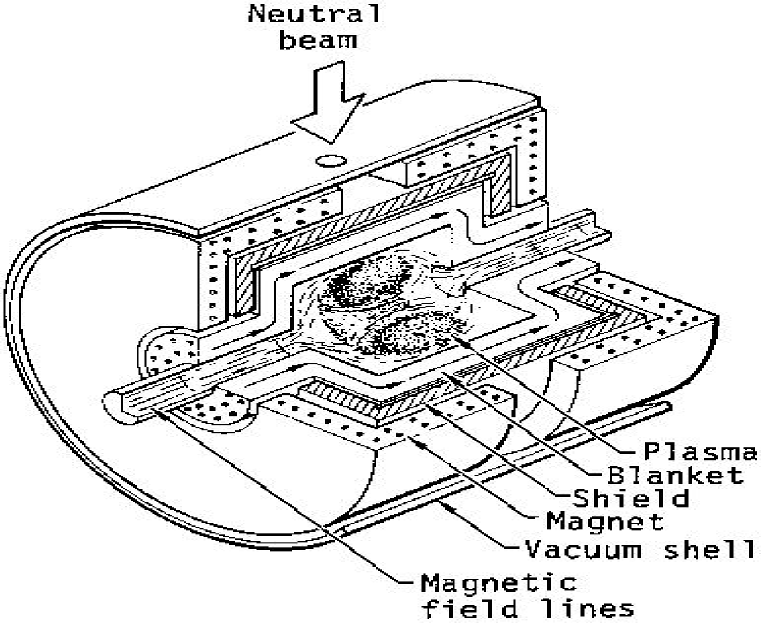


Figure 7—An FRC reactor with neutral beam port

FRC concepts are being worked on even now to minimize the system mass. The neutral beam port on the top of the schematic is a modification so that a neutral beam could be used to create and maintain the plasma, which may decrease the mass of the reactor since other means of ionization would be unnecessary. This configuration has the potential for a high specific power relative to many magnetic confinement systems , at ≤5 kW/kg. A large system mass and power output is needed before this power payout comes out, so it is less effective at low powers. Another beneficial property the FRC has is direct thrust capability in the same way as a magnetic mirror. Studies are being conducted on FRC at the University of Wisconsin—Madison, as well as other universities, and institutions. This idea is promising and will probably see a lot of research in the future.

Inertial Electrostatic Confinement (IEC)

The concept of IEC has existed since the late 1960's when it was invented by Philo T. Farnsworth. Recently, however, people have started to realize that it may be useful as more than just a low flux source of charged particles. In fact, it may prove to be useful in a number of fields, including charged particle production, medical isotope production, and the burning of advanced fuels as a fusion reactor.

IEC devices work on a very simple concept compared to the magnetic reactors. There are no magnets involved in the simplest IEC, as electrostatic forces are used to confine the plasma. Ions are produced at some radius outside an inner grid, which is biased with a large negative voltage. This causes the ions to accelerate toward the grid and oscillate around it with fusion relevant energies. As they collide with other ions they fuse with them, and release their respective reaction products, which have plenty of energy to escape the confinement. These reaction products can then be used to generate electricity and/or thrust. A picture of an IEC thruster is shown in figure 8:

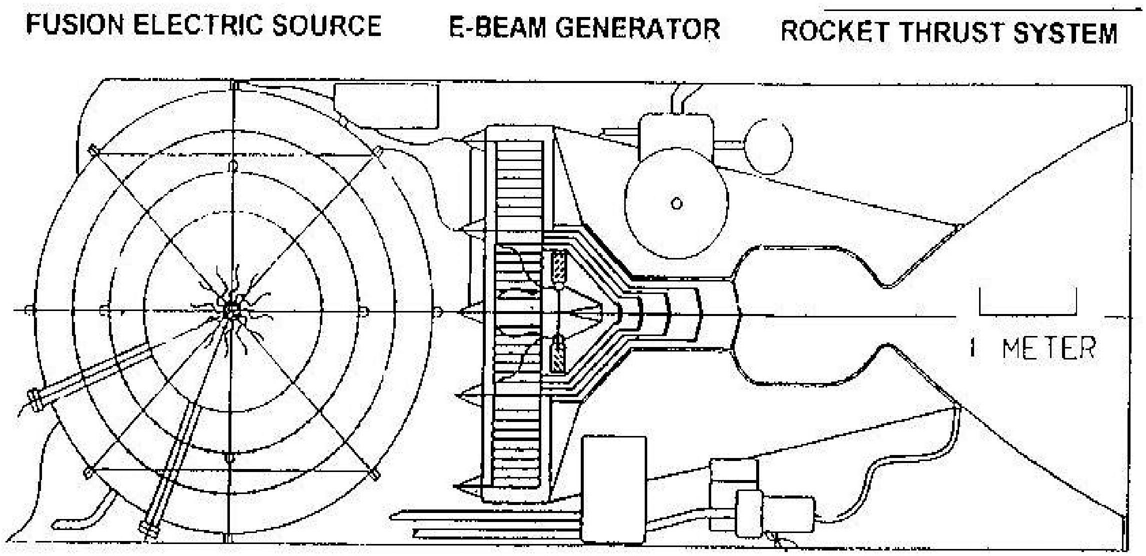


Figure 8—An IEC powered thruster

IEC devices have the advantage of not needing extremely heavy magnets for the plasma confinement, which makes them very low mass and compact. Since they are not thermally heated devices, it is easy to obtain fusion relevant energies by operating at low pressures, and accelerating the particles under a high voltage electrostatic field. This makes it very easy to get the ions to high velocity, and may be the only system in the near future that has the potential to fuse a ^{3}He plasma. IEC has some problems with whether or not it will be able to ever reach the fusion rate levels required for power generation. Since it depends on low pressure operation, only small numbers of particles will get accelerated by the field, and only those at high energy can fuse. Also, at high power levels if the inner grid is made from solid matter, it has the potential to melt. Ideas to replace the inner grid with an electron cloud are currently underway, however, and could pave the way of the future for fusion power. Further, IEC devices could probably generate up to 10kW/kg on almost any power scale of 1 MW or above.

Analysis of Systems

Having completed the discussion regarding the need for application of advanced fusion systems, and examined some of the configurations available, the next step is to discuss which configurations may be suitable for which applications

For most near Earth applications, it is necessary that a low to moderate power source be used. For these, the IEC is the only reasonable reactor, because the other three configurations require a high mass to produce low powers. In the case of some high power military satellites, however the tandem mirror may prove useful high power burst mode production. If the IEC could be perfected, it would replace fission reactors and solar panels entirely in space, which would result in increased safety on the fission side, and decreased drag and mass on the solar side.

For base-settlement missions, it is important, but not vital to have a settlement be self-sufficient. If self-sufficiency is required, it is in turn required that a fusion reactor capable of burning advanced fuels be developed. For this application, a high power version of the IEC would be an ideal fusion system. It is quite possibly the only reactor talked about that would be able to burn ^{3}He straight, which results in the production of completely benign materials, and energy. It is the system that requires the least shielding (no neutrons) and is simple and easy to work on. A colony on the moon, for example could fuel itself if transport ships from Earth became unavailable. The other fusion systems are so high output that they would be overkill for any initial colonies on other worlds. If large settlements developed, a use could be found for higher power output fusion reactors, but in the beginning the need will not exist. Fission reactors seem more feasible for a small colony on another world if an IEC system or something comparable in terms of plasma temperature is developed.

Interplanetary travel has a higher dependence on the specific power of the reactor used. It is necessary for an interplanetary rocket to produce on the order of 1-10kw/kg of reactor mass. These levels can be achieved by burning a D-^{3}He mixture at high power levels. The best systems for these high power densities are the magnetic systems discussed, and possibly a very high power IEC system if the technology ever developed. Both the tandem mirror, and the FRC configurations, would be appropriate, since the spheromak has had less work done on the application to space needs. That is not to say the spheromak could not be useful with more work, however. Figure 9 summarizes the characteristics of a hypothetical tandem mirror and FRC spacecraft burning D-^{3}He:

Parameter	**FRC**	**Tandem Mirror**
Specific Power (kW/kg)	1.3	1.2
Fusion Power (MW)	500	1960
Thrust Power	330	1500
Neutron Power Fraction	0.019	0.025
Total Mass (tonnes)	250	1250
Length (m)	9	113

Figure 9—System parameters for FRC and Tandem Mirror configurations

This shows that with present technology, the tandem mirror is not competitive with the FRC in specific power until it reaches a very high mass. For that reason, the tandem mirror would most likely be used for large vessels, whereas the FRC would be capable to move smaller and larger vessels. Another point is that FRC mass may be decreased substantially as the reactor improves, and its specific power may eventually dominate the tandem mirror.

For interstellar travel, it is absolutely essential to have a very high specific power. None of the configurations discussed here can deliver the kind of specific power needed for a manned mission to cross the stars in a lifetime. The closest is the FRC, which would have to be improved a few orders of magnitude to be useful. The reason this is the case is because such a huge amount of fuel is needed to accelerate the large mass in an interstellar mission. FRC or magnetic mirror configurations may be useful, however, in sending an unmanned mission to a nearby star. The journey to alpha centauri with a low payload probe system might take about 100 years with a 10kW/kg fusion power system.

Summary

In order to expand beyond the planet Earth, the establishment of a nuclear fusion system that can burn advanced fuels is absolutely necessary. It may even be necessary to maintain the national security of the United States, and the safety of the entire world from a ballistic nuclear missile attack. Advanced fusion is a safe, efficient, and nearly unending supply of power for the future of mankind.

Research and experiments are underway today at many universities, institutes, and national labs to deliver to this promise to the world. Devices such as the spheromak, tandem mirror, FRC, and IEC will provide us with the key to unlocking safe fusion power. Even if they are not the reactors we will use in the future, the experiments performed on them will provide us valuable insights into the next generation of fusion systems. This research must continue and be expanded if we want to continue to explore our universe.

References

1. J.F. Santarius, “Magnetic Fusion for Space Propulsion: Capabilities and Issues,” ANS Topical meeting on Nuclear Technologies for Space Exploration, 16-19, August 1992
2. G.L. Kulcinski and J.F. Santarius, “Advanced Fuels Under Debate,” Nature, Vol. 396, 24-31, December 1998
3. J.F. Santarius, “Magnetic Fusion for Space Propulsion,” 10th Topical Meeting on the Technology of Fusion Energy, 7-12, June 1992
4. J.F. Santarius, “Generic Magnetic Fusion Rocket Model,” Journal of Propulsion and Power, Vol. 14:4, 519-524, 1998
5. J.F. Santarius, “Could Advanced Fuels Be Used with Today’s Technology?,” Journal of Fusion Energy, Vol. 17:1, 33-40, 1998
6. J.F. Santarius, “Lunar ^{3}He, Fusion Propulsion, and Space Development,” Second Symposium on Lunar Bases and Space Activities of the 21st Century, 5-7, 1988
7. J.F. Santarius, “FRC Power Plants – A Fusion Development Perspective,” U.S.-Japan Workshop on the Physics of High-Beta Fusion Plasmas, 1998
8. J.R. Roth, “Space Applications of Fusion Energy,” Fusion Technology, Vol. 15, 1375-1394, 1989
9. G.H. Miley, “Advanced Fuel Concepts and Applications,” IAEA-TC, 392/36, 1981
10. T.M. Crabb, “Synergism of ^{3}He Acquisition with Lunar Base Evolution,” Lunar Bases & Space Activities in the 21st Century, Astronautics Corporation of America – Technology Center, 1988
11. R.J. Halyard, “Optimum Interstellar Travel Times for Pulsed Fusion Propulsion Systems,” J. Brit. Interplanetary Soc., Vol. 44, 377-384, 1991
12. G.L. Kulcinski, “SOAR: Space Orbiting Advanced Fusion Power Reactor,” UWFDM-722, Fusion Technology Institute, 1987
13. G.L. Kulcinski, “NEEP 602 – Spring 2000,” Course homepage for NEEP 602, http://silver.neep.wisc.edu/~neep602/SPRING00/neep602.html, 2000
14. G.L. Kulcinski, “Resources From Space” Course hompage for NEEP 533, http://silver.neep.wisc.edu/~neep533/neep533.html, 1999