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using a

Field Reversed Configuration Reactor

A New Technical Approach for Space Propulsion and Power

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SPACE FUSION ENERGY CONVERSION USING A FIELD REVERSED CONFIGURATION REACTOR

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ABSTRACT

Fusion energy offers many inherent features which would benefit space flight. If the technology had been developed such that fusion energy conversion were available for space use today, fusion energy would be providing increased safety, reduced flight operational costs, and space mission enabling capabilities. The fusion energy conversion design approach, referred to as the Field Reversed Configuration (FRC) -- when burning deuterium and helium-3, offers a new method and concept for space transportation which high energy demanding programs, like the Manned Mars Mission and planetary science outpost missions require. FRC's will increase safety, reduce costs, and enable new missions by providing a high specific power propulsion system from a high performance fusion engine system that can be optimally designed. By using spacecraft powered by FRC's the space program can fulfill High Energy Space Missions (HESM) in a manner not otherwise possible. FRC's can potentially enable the attainment of high payload mass fractions while doing so within shorter flight times. The time has arrived to initiate a space fusion energy conversion program and in particular to demonstrate the FRC potential for space. In addition to the aforementioned advantages, fusion provides an energy option to fission.

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INTRODUCTION

This paper articulates the future space mission requirements for high energy missions and the space program's propulsion and electrical power generation plans for meeting those requirements. Current propulsion R & D activities focus on the technology to gain one or two seconds in specific impulse in chemical propulsion systems. Therefore, the concern, in particular, is whether adequate measures are being taken to assure that future space mission propulsion and power needs will be met on a timely basis where the demand is anticipated to be for high energy levels.

Emphasis is placed on the theme that as the low energy space missions are completed, a requirement will develop for a high energy mission capability. That mission capability is not being pursued and could very well be a long time in developing. Yet that does not necessarily have to be the situation. Quantum leaps in the national space transportation infrastructure are possible by developing systems which have high specific power and impulse capabilities. It is the intent of the authors to bring forward some new thinking onto what they perceive as a space propulsion/power crisis that can be anticipated, but which can be circumvented by the use of an alternate energy source.

Energy requirements for space propulsion and electrical power will grow. The accomplishment of high energy missions of the type presented in this paper will not be easy to achieve. This class of high energy missions requires commitment now for the space program to realize timely benefits. The long lead time in bringing this striking new capability forward alerts us to the importance of commencing this challenging research early. Now is the proper time to assume the world leadership role in achieving a high energy capability for space use. The ultimate future for the continuation of advancements in space exploration and space science depends upon the development of that high specific energy capability. Space travel's economics will become severe, possibly to the extent of making high energy missions too costly to perform. That will inhibit our ability to press forward with more ambitious missions. Therefore, the initiation of a relatively modest investment now for a well-planned experimental test program, one designed to achieve a high energy space mission capability, constitutes a major investment opportunity for the future of the U. S. space program and a major challenge to address. This report recommends the use of fusion energy to perform the missions. Its potential offers such great dividends that it can not be ignored. It is a key element in the implementation of the "US National Space Policy" (ANOM89).

THE POWER OF SPECIFIC POWER

An analysis of future anticipated HESM (High Energy Space Missions), such as the Manned Mars Missions, shows serious shortcomings with the implementation of those missions particularly with regard to the chemical propulsion vehicle's performance, safety, economics, and environmental issues which can become involved with its repeated use for future exploration missions.

Manned Mars settlement, to be successful, will require two high power consumption functions: transportation logistics and local Martian electrical power, subjects which need to be more fully addressed. Since the 1960's, the focus on propulsion systems for Manned Mars Missions has been on chemical propulsion systems combined with aerobraking as the joint technological approach for meeting the mission's energy requirements. Some consideration was given to nuclear fission thermal propulsion, but the performance, operational simplicity, and safety issues detracted from its further consideration. There is recently renewed interest in nuclear thermal systems. Fusion energy has yet to be considered either as a propulsion system option or as an improvement over fission.

Also, there are 2 major applications of a high energy source for electrical power. A large electrical power capability will be important for Mars settlement enabling the utilization of local planetary resources which in turn will reduce the space logistic requirements. High energy levels will provide the space based power for the production of electricity for extraterrestrial settlement including habitat environmental conditioning and manufacturing. The technology to accomplish the utilization of local planetary resources is being pursued by the University of Arizona. It will provide the electrical power for beam power as a potential optional method for providing a cost effective space transportation propulsion logistics support capability. The requirements and methods for high electrical power generation on the planets is not a resolved subject.

The key for the accomplishment of the anticipated high energy space missions, whatever the application, is high specific power. The proper manner by which to address each of the aforementioned issues is through a total space systems engineering approach as discussed in this paper.

Manned space flight safety is achieved by faster trip times resulting in reduced hazard potential from exposure to galactic and solar radiation as well as adverse psychological and physiological effects that could result from long flight times in space. From the perspective of the space traveller, spacecraft having greater mass performance potential will obviously possess the capability to provide more safety features and protection from radiation as well as to provide for other safety features, increased design margin, and back-up flight systems. But from the aspect of safety to the Earth's population, the preference is to place the minimal mass into orbit. Minimal mass also reduces the impact to the environment and the overall economic impact of high energy space missions.

The problem is, how does one resolve these two counterbalancing forces? The solution is to develop high specific power energy conversion systems. High specific power systems, which only fusion energy is currently perceived as capable of delivering, will improve launch safety by minimizing the number of LEO launches. An optimization of mass to LEO also minimizes the energy requirements on Earth's resources that will be necessary to implement the missions. Also minimized are the atmospheric pollutants and the cost of future space flight operations and programs. Nuclear fission propulsion was examined in the 1960's as an option and considered not to be of benefit to the Manned Mars Mission as defined then. There will always be a question, too, of safety from the presence of a large NERVA category power source in Earth orbit and from the ground testing to qualify it. Nuclear electric propulsion does not appear to offer the performance advantage for the large payloads that the Manned Mars Mission requires. It still requires a reactor for power.

The most attractive option is fusion energy. But fusion energy has not been developed to a point where net power has been demonstrated. Even if it had been demonstrated, the experiment which is most likely to demonstrate fusion first is the tokamak. The tokamak is not a concept which can provide the performance necessary to realize the desired advantages. Its large magnet mass prohibits the low flight system mass required for space transportation flight. Instead a light weight concept such as a compact toroid, e.g., the FRC (Field Reversed Configuration), is considered to offer the greatest potential for development.

Properly developed, space fusion energy will revolutionize space travel. For example, if a flight weight propulsion system can be designed having a specific power of 1 kW/kg, the number of Shuttle launches to LEO to perform one Manned Mars

Mission could be reduced by a factor approximately 7 fold from that required by current chemical space propulsion systems. The flight time could be reduced to a total of less than 6 months whereas the chemical propulsion system will require 1 to 2 years total flight duration.

Space program resources must be directed toward those issues as a matter of top priority in undertaking an advanced mission development program. A program designed to test evaluate the FRC reactor burning D-^{3}He could be accomplished on an expedited basis with initial results anticipated within 5 to 10 years.

A High Energy Mission Requirement Exists

This paper first considers hypothesized high energy missions. The energy requirements to meet those missions were analyzed. The results reveal very significant benefits for science and solar system exploration that can be attained by fusion's presence. The practical applications of fusion all relate to large energy consumption missions, namely, those in the multimegawatt category and higher; fusion is not currently foreseen as a competitor to, nor a replacement for, the conventional low energy systems for the near term applications.

The thesis of this report is that (1) a high energy space mission capability needs development (Figure 1a and b) and (2) the Field Reversed Configuration magnetic confinement fusion reactor, burning deuterium-helium-3 is the optimal approach which should be pursued at the highest priority level to meet this need.

THESIS
HIGH ENERGY SPACE MISSION (HESM) CAPABILITY: MULTI MW'S TO GW'S • **Requirement for HESM exists:** - Manned Mars: - Science outposts including sample returns: outer planets, comets, asteroids, others - Oort Cloud/Stellar • **Technology lacking. Start R & D now since development will require time.** • **Space program's advancement hinges upon high energy conversion elements being made available for the NASA space transportation infrastructure.**

Figure 1a. Thesis.

Mission Beneficiaries from High Energy
High Performance Propulsion •**Systematic exploration of Mars, including manned exploration:** - Safety - Economics - Reliability - Logistics - Electrical Power • **Enables: scientific exploration of the entire solar system, interstellar space, and nearest stars.**

Figure 1b. Mission benefits from a high energy capability for space.

Improved crew safety results because of the reduced flight time, thereby reducing the crew's exposure to galactic cosmic rays plus other safety factors pertaining to reduced flight times as discussed later. High specific power systems, coupled with a variable high specific impulse capability, will reduce the launch load requirement over lesser energy intense systems, thereby reducing the quantity of mass which must be placed into low Earth orbit. Many 10's of billions of dollars savings in launch costs can be achieved over low performance systems in implementing a permanent presence program like manned Mars. Reliability gains must be incorporated into remote manned missions, like those to Mars. Reliability will be an ever increasing factor in the accomplishment of future science missions as the flight times become longer, the distances greater, and the mass demands increased for the conduct of more sophisticated missions, such as sample return missions. The brute force method of more redundancy and lower stress through higher safety factors exacerbates the mass-economy problem. New approaches that reduce moving parts and which inherently contain fewer or no parts that are subject to erosion must be incorporated into the flight systems as a new technical approach. A permanent presence of man on Mars will require space logistical support that will be enabled by the space program's capability to support flights there on a frequent basis but which will not be exorbitant in terms of flight costs. To achieve a permanent presence of man on Mars, more emphasis will be placed on self reliance which in turn will necessitate the use of the Martian planetary resources. Significant electrical power will be required to accomplish the manufacturing of the essential products there and to support life habitats. High electrical power technology must, therefore, become a part of the future space mission enabling infrastructure.

Thus, the objective of this paper is to address the concern regarding high energy needs for future space missions and to forward some new thinking on solutions. (Figure 2)

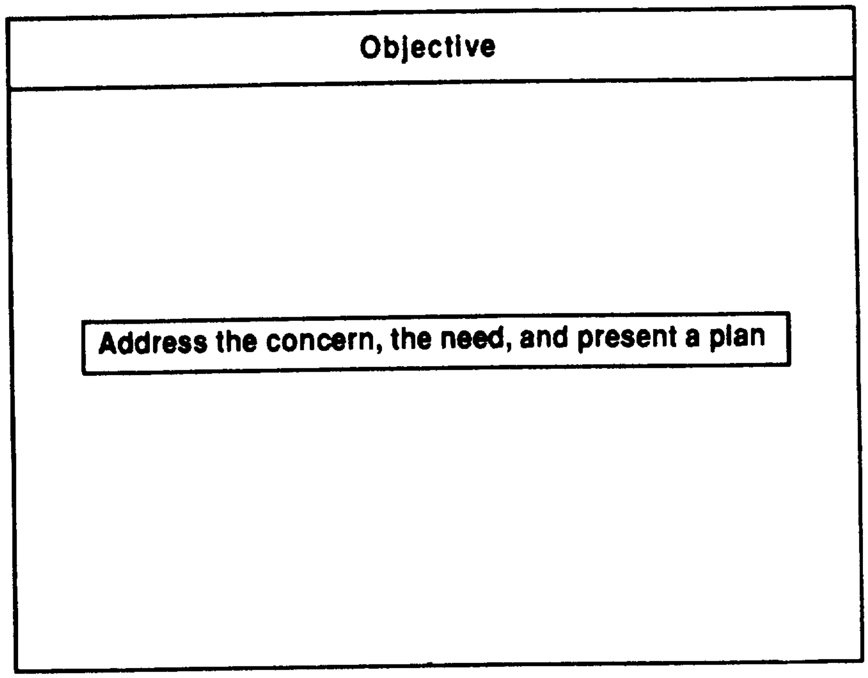


Figure 2. Objective.

The thesis is that a requirement exists for high energy mission capabilities which needs to be addressed. This paper thus examines the missions, system requirements, the basic method to address the system requirements, energy options, and relative advantages; and it recommends a particular energy approach and in particular, a design solution that appears to offer intrinsic advantages which meet space system requirements.

HIGH ENERGY MISSIONS

A few of the high energy missions that can be accomplished if fusion were available include: faster and therefore safer manned Mars missions, manned missions beyond Mars, in-situ stellar science, interstellar plasma science, understanding and mapping of the heliosphere, interstellar astronomy, Oort Cloud exploration and science, multiple planetary outpost missions using just one spacecraft as a launch platform on a single mission, comet/planet rendezvous with sample returns, polar solar science, faster trip times to the outer planets with more massive and better equipped science payloads, science missions to the inner planets, power generation for permanent manned and unmanned science outposts, remote planetary materials processing energy, plus others. Those missions determine certain fundamental system requirements, Figure 3. The calculations are based upon relatively low thrust, constant acceleration propulsion systems (FRI89).

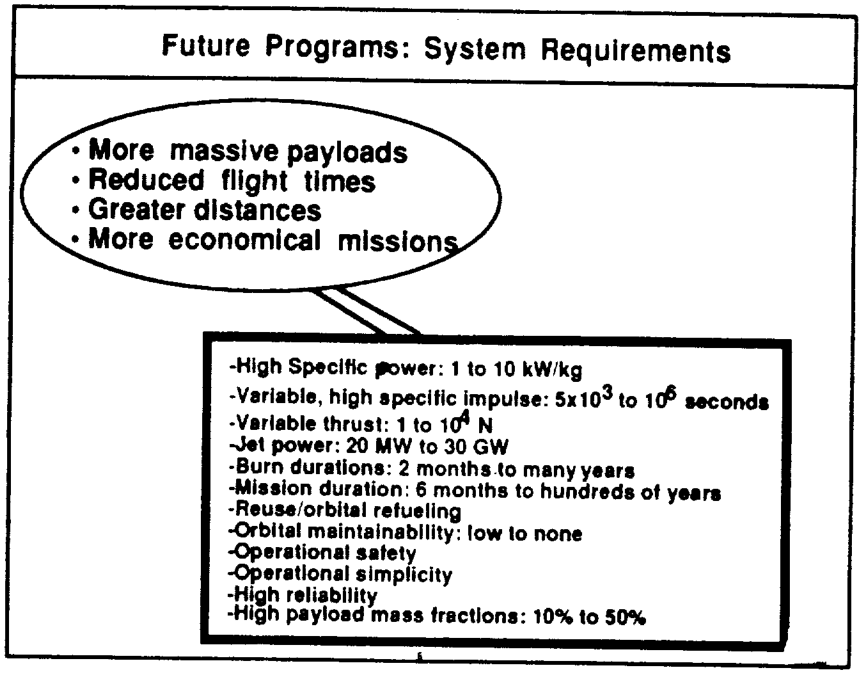


Figure 3. Flight system requirements for future programs.

Manned Mars Exploration Program

High specific energy propulsion and power systems particularly benefit the Manned Mars Missions. In addition to Mars, it is anticipated that large power levels will be required for lunar operations to perform mining, material processing, and life support functions. Figure 4a summarizes the key mission design data for future missions, manned and unmanned. A range of values is included showing data for a rapid trip as well as trip times offering economy of propellant and fusion vehicle size while still accomplishing the same mission objectives in a reasonable flight time. The flight time to deliver a 133 MT manned payload to Mars and to return a 61 MT payload to Earth can be accomplished in a trip flight time of 3 months each way with a space launch vehicle of moderate (~610 MT) initial vehicle mass in LEO (Low Earth Orbit) using a propulsion system having a specific power (designated as α_p where α_p = jet power/inert propulsion mass) of 1 kW/kg (Figure 4a and 4b) (FRI88).

Manned Mars Mission Parameters

ADVANTAGE OF HIGH SPECIFIC POWER + HIGH SPECIFIC IMPULSE

High Energy Performance for 133 MT out-bound payload, 61 MT return.

α_p, kW/kg	Flight time, years	M_o, MT	M_p, MT	γ, %	P_j, MW	<Isp>, seconds X 10^3	Δv, km/s
1	0.44 - 0.5	1041 - 613	681 - 335	12.8 - 22	227 - 145	9.4 - 10.6	98 - 90
10	0.18 - 0.5	1034 - 185	676 - 30	12.9 - 72	2255 - 227	18.9 - 35.8	196 - 90

α_p propulsion system specific power, kilowatts/kilogram
Flight time, years the total round trip time in flight exclusive of visit time at the destination
M_o initial mass in low Earth orbit
MT metric tons
M_p propellant mass in metric includes fuels plus diluent
γ payload mass fraction
P_j jet power
MW megawatts
<Isp> average specific impulse over the mission
Δv incremental velocity change

Reference: Alan Friedlander and Jim McAdams, Letter, dated October 13, 1988, Subject "Completion of Fusion Propulsion Analysis Support," SAIC, Schaumburg, IL

Figure 4a. Manned Mars mission performance using high energy propulsion.

That time could be reduced to a very attractive, short flight time of only approximately one month, provided that a propulsion system having a specific power of 10 kW/kg can be achieved and an initial vehicle mass of ~1,100 MT is placed into low Earth orbit. Refer to Figure 4b for the mission performance characteristic trend curves.

Manned Mars Initial Vehicle Mass

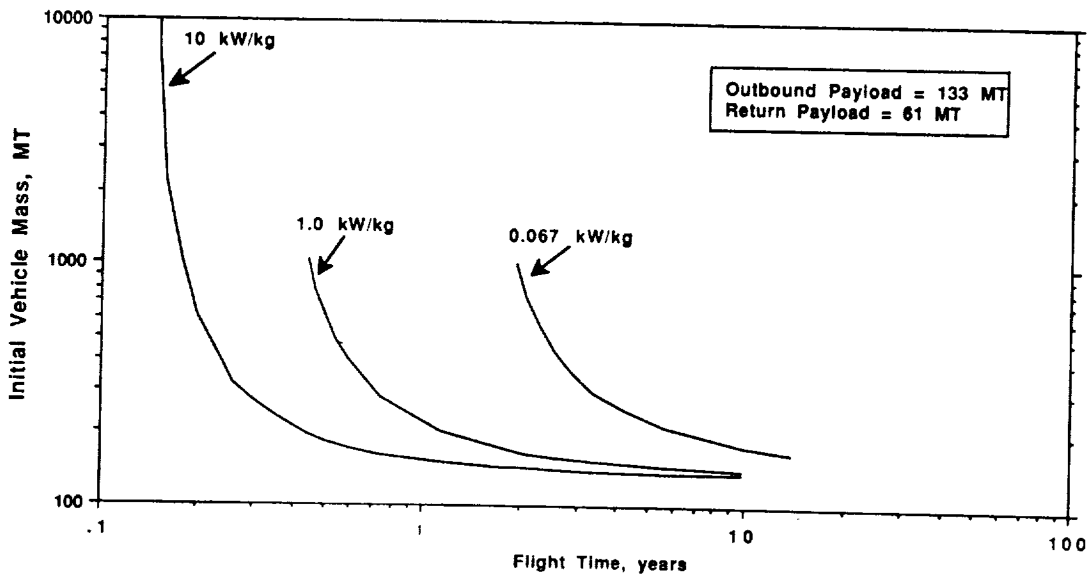


Figure 4b. Manned Mars mission performance using high energy propulsion.

To achieve the anticipated need for more massive payloads, quicker flight times, greater distances traversed, all at reduced costs, the suggested approach is to perform those missions by the development of propulsion systems that yield a high specific power, α_p=1 kW/kg to 10 kW/kg, at a variable high specific impulse (~10^3 - 10^5 seconds). The specific parameters, as specified in Figure 3 will be important to the HESM category.

The economy -- and safety -- goals are attained by substantially increasing the payload mass fraction as shown in Figure 4a. The Shuttle's mass fraction, for example, is low -- slightly greater than 1%. Economy of mission must ultimately be achieved in space as with commercial airlines or other successful transportation businesses, where the payload mass fraction is high. In current day wide body aircraft it is approximately 50%. The mission parameters shown cover a wide mission range, perhaps a full spectrum, of space mission requirements -- from manned Mars, to outer planetary sample returns, out to a rendezvous with Alpha Centauri. The value of high α_p to the manned Mars program is clearly illustrated by Figures 4a and 4b where the flight time, system performances, and masses required to conduct missions carrying 133 MT outbound and 61 MT inbound manned payloads are presented. The α_p of 0.067 kW/kg is considered a target for nuclear electric propulsion. Preliminary studies indicate that fusion can produce specific power performance in the range of 1 to 10 kW/kg, roughly an order of magnitude above the target for nuclear-electric.

A space logistics infrastructure is basic to the implementation of a viable permanent presence of man on Mars. It is difficult to conceive of a flight frequency less than 2 flights per year. But using current propulsion technology with consideration to its innate performance limitations, the Earth to LEO transportation requirements will be enormous. For example, if launched today using current space propulsion technology, an initial 1,000 MT mass in LEO for the Martian space vehicle would require the energy equivalent of ~37 Shuttle launches. Thus, each flight to Mars, assuming a $320M cost per Shuttle launch, the current cost number, will be at a price of $12B per flight. Larger launch vehicles will obviously reduce the number of launches, but an accurate total systems cost analysis must be accomplished before cost savings can be stated. A specific power of 1 kW/kg propulsion system would permit a 131MT outbound-61MT inbound payload to be sent to Mars using propellants placed into orbit by approximately 6 Shuttle launches, or for a 10 kW/kg system, only one Shuttle launch to deliver propellants to a reusable, space based fusion engine system.

> The resolution of high energy space transportation propulsion infrastructure resides not in the capability to launch greater vehicle mass from Earth to LEO and in performing developmental research that yields 1 or 2 seconds improvement in specific impulse. Instead, the space program will better benefit by the development of the technology which requires less mass being placed into LEO to accomplish the same mission, or better still, to accomplish the mission with a more massive payload, flown at higher speeds. That is, a space propulsion system having high specific power and variable high specific impulse is needed.

SCIENCE MISSION PERFORMANCE

While fusion may offer the greatest immediate mission enabling value to the space exploration program, and particularly to the safety of manned missions, fusion energy enables very interesting space science missions. The high energy science missions include soil sample return missions from the moons of the outer planets with **round trip flight times** varying from 1.6 years for Europa to 7.4 years for Charon (Figure 5).

Science Program Benefits

Sample return missions:
20 MT outbound; 10 MT inbound

Mission	t, years (Round trip)	M_o, MT	M_p, MT	γ, %	P_j, MW	<Isp>, seconds x10^3	Δv, km/s
	$\alpha p1 : \alpha p10$	$\alpha p1 : \alpha p10$	$\alpha p1 : \alpha p10$	$\alpha p1 : \alpha p10$	$\alpha p1 : \alpha p10$	$\alpha p1 : \alpha p10$	$\alpha p1 : \alpha p10$
Europa	1.56 : 1.56	320 : 32	243 : 6.8	6.3 : 63	57 : 50	17.7 : 64.1	209 : 209
Titan	2.99 : 2.56	74 : 29	36 : 5.3	27 : 68	18 : 40	26.2 : 81.2	196 : 223
Miranda	5.34 : 5.34	60 : 26	26 : 3.4	33 : 77	14: 27	35.7 : 118	233 : 233
Triton	5.85 : 6.85	108 : 27	62 : 3.8	19 : 74	25 : 30	35.1 : 130	314 : 283
Charon	7.42 : 7.42	81 : 27	41 : 4.1	25 : 73	19 : 32	40.5 : 137	317 : 317

Figure 5. Performance advantage of high specific power/specific impulse propulsion systems for planetary missions (FRI89).

Those times are for the round trip flight time, exclusive of the stay time for science gathering at the site. In the analyzed mission scenarios a very substantial 20 MT payload was flown to the planetary destination and a 10 MT payload returned to Earth where its precious cargo of extraterrestrial soil can be analyzed in depth.

The jet power required to perform such missions is much less than the more massive Manned Mars Missions. It is shown to range from 15 MW to 60 MW. The propulsion system performance is demanding, with the specific impulse ranging between 17,000 seconds and 140,000 seconds. The mission parameters and capabilities for outer planetary missions are summarized in Figure 5. Three separate asteroid visits at 1 AU distance can be quickly performed, i.e., in less than only 2 years using the same 20 MT outbound payload and 10 MT returned payload.

To complete a 10MT payload Oort Cloud rendezvous mission at 20,000 AU, a 700 MW power source operating a 1 kW/kg propulsion system will accomplish that mission in 120 years, while a 10 kW/kg specific power propulsion system completes the trip in 55 years, using a 7 GW reactor power output. The energies here are obviously of a magnitude that a new energy source is mandated. Fusion is a logical candidate, but serious R & D must begin now in view of the lead time required for such a development.

Our nearest stellar neighbor, Alpha Centauri, actually a 3-star system -- α, β, and Proxima -- at 4.3 light years distance, offers the greatest technical challenge. Alpha closely replicates our sun's characteristics, exhibiting nearly the same brightness properties and mass. But this is not really a mission for a specific power of 1 kW/kg reactor design which takes ~400 years for a 10MT payload fly-by mission, or slightly less, depending upon the initial vehicle mass. For a rendezvous mission, even a specific power system operating at 10 kW/kg requires ~290 years. Advanced system technology might be able to increase the performance capability to 40 kW/kg, thereby reducing the flight time to ~180 years. Because of the mission difficulty it is essential to commence technology development and planning for the mission early.

With fusion, unlike any other known energy source, we can commence consideration of these marvelous missions because of its innate compatibility with high energy mission vehicle system requirements.

VEHICLE SYSTEM REQUIREMENTS

The ability to perform the complete class of missions considered herein resides upon several key factors which serve as the basic high energy system mission architecture requirements, Table 1, for the next generation spacecraft which the United States space program should now be pursuing to assure a national space posture in the future.

Table 1. Future spacecraft energy system needs (SCH90).

1. the ability to develop a specific power system of 1 kW/kg, or 10 kW/kg in the case of the stellar mission;
2. the ability to produce sufficiently high thrust for a vehicle of this size and a variable specific impulse (10^4 to 10^6 seconds);
3. reliable propulsion and vehicle performance for months to many years (e.g., for as long as 50 years of continuous firing operation);
4. reactors ranging from 20 MW to 30,000 MW jet power production;
5. the ability to perform the missions safely from both the standpoint of public safety and flight safety.

The most severe requirements are established by the stellar mission. An orderly progressive reactor enhancement program build-up will ultimately allow NASA to proceed from the lesser demanding missions to the more difficult, for example, the 10's MW for unmanned science payloads to 100's MW for manned missions to GW's for stellar missions. The capability to meet the high energy mission specific impulse and thrust requirements imposed by the vehicle on the propulsion system are to be similarly developed.

PROPULSION SYSTEM REQUIREMENTS FOR HIGH ENERGY MISSIONS

From the mission and vehicle requirements we can determine the fundamental space vehicle propulsion system requirements for high energy missions. These are shown in Table 2 below (SCH90).

Table 2. Propulsion system requirements for high energy missions (SCH90).

- minimize propulsion system mass,
- meet long system life time requirements of years,
- provide a remote, reliable, and efficient space restart capability,
- use only radiation for cooling,
- be designed for the presence of a "free" continuous vacuum,
- provide power for variable propulsive thrust and specific impulse requirements,
- provide sufficient power also for the generation of electricity,
- operate in a low acceleration environment (low thrust and zero gravity),
- produce a very wide range of output power levels (throttable),
- be designed for long operational times - thrusting and quiescent despite a lack of ready access for maintenance.

Space propulsion system requirements can only be met by an effective space fusion research program, one which is conducted on a program priority reflecting the importance of fusion energy to the space mission architecture.

SPACE ENERGY OPTIONS

The available energy options for HESM and specific energy for each are compared in Figure 6. The greater than 7 orders of magnitude improvement in specific energy over chemical is the initial rationale for interest in fusion. The potential for high efficiency energy conversion and other properties, including safety, as discussed subsequently, make fusion a more desirable energy source for space propulsion than fission, the other high specific energy source shown. The authors considered matter-antimatter as another potential option but have serious reservations concerning its competitiveness with fusion and fission based upon the relative technology data bases at this time. Solar energy cannot serve as a high energy source that will meet the demands of the mission class considered herein.

Energy Options

ENERGY SOURCES: SPECIFIC ENERGY, J/KG	
Fusion ($D\text{-}^3He$)	3.5×10^{14}
Fission	8.2×10^{13}
Chemical	1.3×10^{7}

Figure 6. Specific energy for space energy options.

A comparison of the relative merits of the three energy sources and their estimated capability to meet those mission requirements presented earlier are shown in Figure 7. Except for the chemical systems these are subjective evaluations due largely to the undeveloped status of the nuclear energy systems for space.

Preliminary analyses and/or educated guesses. All require thorough analysis, design, and testing to validate whether the parameters can be met.

Desired Parameters and Values	Fusion	Fission	Chemical
High Specific power: 1 to 10 kW/kg	✔	<1	✔
Variable, high specific impulse: 5×10^3 to 10^6 seconds	✔	?	
Variable thrust: 1 to 10^4 N	✔	✔	✔
Jet power: 50 MW to 10 GW	✔	?	
Burn durations: 2 months to 50+ years	✔		
Mission duration: 6 months to 5 years for solar system missions	✔	✔	✔
Reuse	✔	?	✔
Low to no space maintainability:	?		✔
Operational safety	1	3	2
Operational simplicity	✔		✔
Cost effectiveness for high energy missions	✔		
High payload mass fractions: 10% to 50%	✔		

Figure 7. Comparisons of energy options.

SAFETY

Safety in the figure is ranked highest on a scale of 1 to 3 for the use of fusion, based upon the attributes listed in Figure 8.

<u>Attributes</u>:

Safety is a major motivation for the use of fusion for HESM.

- **Faster trips to Mars (~3 months one way).**
- **Decreases substantially the numbers of launches to LEO**
- **Propulsion braking, not aerodynamic braking on Mars mission.**
- **Non radioactive fuels.**
- **Absence of high speed components such as SSME turbines.**
- **Fuels do not chemically react with each other.**
- **Total energy content of plasma is very small.**
- **Absence of environmental impact on the Earth.**

<u>Issues</u>:

- **Activated materials from neutrons: resolve by minimizing neutrons + shielding**
- **Cryogenic fuel storage and magnetic cooling: resolve by standard design and safety practices**

Figure 8. Safety implications concerning the use of fusion energy.

Faster fight times minimize the hazards to the flight crew that occur from galactic radiation (reduced integrated dosage) and solar events (probabilistic occurrence), psychological effects from an extended time in a small confined space (without escape), and physiological deterioration from extended weightlessness periods. While all of these issues may have "workarounds," fusion offers significant advantages for reducing the concerns very substantially.

Where high energies are required in space, high specific power systems reduce the mass requirements and consequently the required number of launches to place the mass there. It is obviously safer to place the mass necessary for a Manned Mars Mission into LEO using 5 Shuttle launch equivalent flights rather than 37, for example.

Note that the high level of propulsion system performance permits the use of propulsive, not aerodynamic, energy transfer for braking maneuvers. That provides more flight operational options and greater tolerance to errors and is, therefore, considered as an inherently safer flight operational mode.

Although the neutron flux from the burning of fusion fuels is not anticipated at this time to be entirely eliminated, with the proper selection of fuels it can be reduced to the low value of approximately 1-2%. That aids the design process substantially but is still sufficiently high to activate structural materials and to require some shielding. Most importantly, however, is the avoidance of high level radioactive fission products.

It is important for the next programs to assure safety to ground handing personnel and to the public by the selection of fuels that eliminate radioactive elements. Public opposition concerning these matters is also eliminated.

Magnetic fields provide a very reliable and effective means of confining the fusion plasma and holding it where desired. Magnetic field lines direct the thrust particles. Wear and high kinetic energy components typically associated with conventional propulsion systems are therefore eliminated. For example, nozzle erosion and attendant hazards, as experienced with solid propellant motors, are eliminated as are those associated with high speed turbopumps.

The total energy content of the working "fluid," i.e., the plasma, is small at 10^{15} ions/cc. The primary hazard is termination of the reaction if the plasma should come into contact with the first wall. Damage to the reactor magnet is the worse case. The reactor is not going to "blow-up," in contrast to liquid and solid propellant systems which can occur when internal system divergences are experienced.

Deuterium can be extracted from sea water using solar energy if necessary, and ^3He can be mined on the moon. An option for obtaining ^3He is to breed it on each using a special accelerator-target facility.

The two primary fusion reaction hazards are the presence of neutrons and the use of cryogenic fluids. Other secondary hazards include stored energy in the magnetic fields and high voltages. The proper selection of fuels which minimize the neutron flux, combined with shielding, is the proper resolution of the neutron hazard. The other hazards are controlled by standard, well developed practices for working with cryogenics, static loads, and high fields/voltages.

Let us address the subject of fusion energy and propulsion and the means by which the authors suggest its advantages can be realized.

FUSION REACTIONS

In fusion reactions, under the right set of conditions, light weight nucleons join to form other nucleons; the products are referred to as fusion "ash." Some of the ash is burned in secondary reactions although this is usually a small contributor to the total fusion power. The conversion of mass to a specific quantity of energy is determined by the mass loss between the initial reacting mass and the residual rest mass of the reaction products in accordance with the equation, $E = mc^2$. The energy appears as kinetic energy of charged particles and/or neutrons depending upon the fuels selected for the reaction. The challenge in achieving controlled fusion has been in designing a satisfactory stable confinement scheme capable of containing the high temperature plasma (10^8-10^9 °K) sufficiently long that a net positive yield of energy results. The status now is that we have currently come to a point where the fusion energy production is very close to breakeven, only being down a factor of 3-5.

SPACE FUEL OF PREFERENCE

Of foremost importance is the selection of a proper fusion fuel pair for space use. The number of nature's elements which will fuse is indeed quite large. However, during the discussions on space energy fusion fuel applications we shall be concerned primarily with just three reactions, i.e., those listed in Figure 9a and 9b (group A).

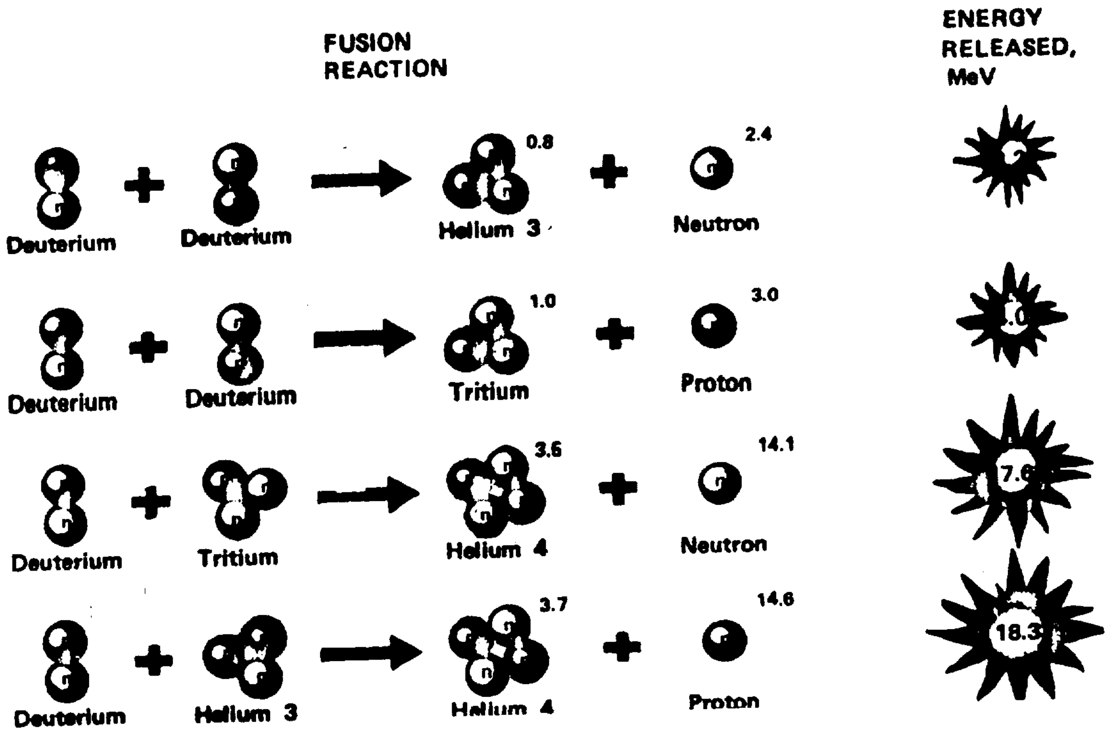


Figure 9a. Fusion fuels for space applications.

Fusion Reactions for Space Applications

A. The most important fusion reactions for space applications

1. $D + {}^3He$ = p (14.68 MeV) + ${}^4He$ (3.67 MeV) nearly aneutronic: D-D side reaction)

2. D + D = n (2.45 MeV) + ${}^3He$ (0.82 MeV) (50%)
   = p (3.02 MeV) + T (1.01 MeV) (50%)

3. D + T = n (14.07 MeV) + ${}^4He$ (3.52 MeV)

B. Other Desired (Aneutronic) Reactions (energetically very difficult)

4. $p + {}^{11}B$ = 3 ${}^4He$ (8.7 MeV total)

5. ${}^3He + {}^3He$ = 2p (5.7 MeV each) + ${}^4He$ (1.4 MeV)

Figure 9b. Fusion fuels for space applications.

Those listed in group B as purely aneutronic, i.e., without neutrons in the reaction products, are preferred; but these reactions are energetically very difficult to achieve, i.e., a high energy level is required to initiate the reaction to produce net power from the reacting elements. The net power gain is, therefore, very low by comparison.

As shown by Figure 10 the preferred fuel for space is deuterium-helium-3 where nearly all of the energy is present in the form of charged particles, 14.68 MeV protons and 3.67 MeV alpha particles. An assessment of advanced fusion energy for space applications, conducted by the Air Force Studies Board for the National Research Council, reached similar conclusions (MIL87). The confinement conditions required to burn it are less than an order of magnitude greater than the D-T reaction (and much less demanding than the other aneutronic reactions).

Fusion Fuel of Choice for Space

Deuterium - Helium-3

Advantages:

- **Charged particles as fusion products (ash) to permit direct conversion of energy into:**
  - thrust
  - electrical power
- **Permits the design of highly efficient thrust and electrical power conversion systems. These are not thermal conversion systems.**
- **Minimal neutron flux**
- **Non radioactive isotopes**
- **Fuel production does not require nor generate radioactive products**

Disadvantages:

- **More difficult to achieve reaction conditions**
- **^{3}He rare, requires lunar mining or breeding** (but, supply available for testing)

Figure 10. Space fusion fuel preference.

The D-^{3}He fuel cycle is particularly attractive and is preferred over other high energy sources since the charged particles can readily produce thrust by being propelled as magnetically controlled bleed off particles from the plasma through a magnetic nozzle. Note also that high specific power is made possible due to high β (i.e., the ratio of plasma pressure to magnetic pressure = 90%) and the replacement of heavy coils by plasma currents. That important parameter is, thus, made possible by a reactor capable of burning fuels whose reaction products are charged particles. Fortuitously, more than 95% of the D-^{3}He reaction's energy is present in the form of charged particles, namely, alpha particles and protons, the energy of which can be converted directly to propulsion and/or electrical power without the usual thermal and mass inefficiencies and losses associated with those systems. By the proper use of design parameters the neutron flux can be reduced to approximately 1-2% (CHA89). With regard to its availability, helium-3 can be mined on the moon and has been estimated to contain ~10^9 kg (WIT86), Similarly, it can be expected to be present on other airless bodies. It can be bred using proton acceleration onto lithium-6 or alternatively via the production and decay of tritium (MIL88). There is sufficient helium-3 available now on Earth for accomplishing a meaningful test program without lunar mining preceding a fusion program (KUL87).

To fuse nucleons, several conditions must be met. Sufficient kinetic energy must be imparted to the ions to overcome the mutually repulsive Coulomb forces and to penetrate their respective nuclei. Hence, a large quantity of energy is required to initiate fusion reactions. Whether or not two nuclei fuse is a statistical matter of nucleons colliding at the proper point of impact and with a sufficiently high energy (velocity) to result in nucleon penetration. The rate of reaction (Figure 11) is expressed by $<\sigma v>$ which is the average product of the fusion reaction's nuclear cross section area (σ), cm,^{2} and the relative ion velocity (v), cm/sec. It is referred to as the reaction rate coefficient. The product of the reaction rate coefficient with the energy per reaction determines the energy density.

Fusion Reaction Rate

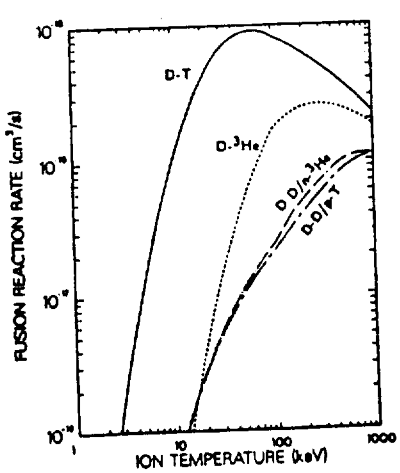


Figure 11. Fusion rate of reaction for selected fuels (SAN88).

The plasma, must be confined for an adequate time (τ), seconds, at a sufficiently high ion density (n), number of ions/cm^3, and at a sufficiently high temperature, T_i, to achieve burning. The confinement figure of merit of a plasma is measured by the confinement parameter $n\tau$ and temperature T_i, Figure 12.

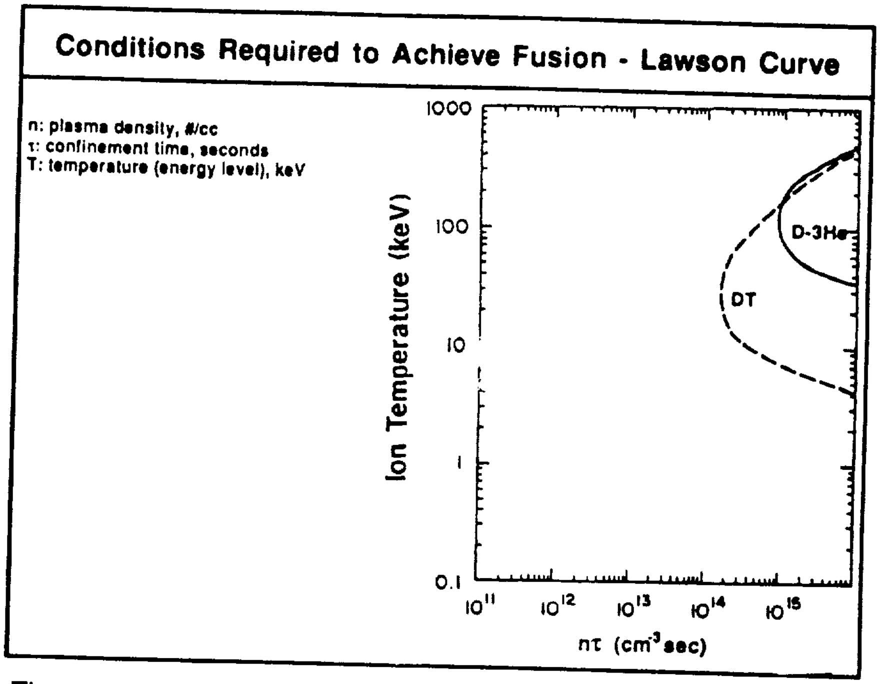


Figure 12. Lawson curve.

Figure 12 presents the Lawson criteria. The Lawson criteria defines the breakeven condition value of $n\tau$ required at a given temperature T_i. Breakeven is the point at which the total fusion output, if it were converted to electricity and reinjected, the reactor would self-sustain burning. This provides an excellent first estimate of these parameters, although Lawson made certain assumptions such as 33% energy conversion efficiency and 100% efficient heating of the plasma by fusion products.

Neutrons, as typical reaction products, are immediately lost from the plasma without a transfer of energy to the plasma. The charged fusion products, i.e., ions, are slowed by the background plasma, and their energy then serves to heat the plasma and any cold fuel input. When the product of fuel confinement time and fuel density ($n\tau$ product) is sufficiently large ($n\tau \geq 5\text{x}10^{14}$ cm^{-3}sec where $T_i = 10$ keV for DT and for D-^{3}He, $n\tau \geq 2 \times 10^{15}$ cm^{-3} sec where $T_i = 30$ keV, for example), the charged fusion product heating can balance plasma energy losses from conduction, convection, and radiation as bremsstrahlung and synchrotron radiation. When this condition occurs, the plasma is said to be ignited, and the burn can proceed without further input of energy from external auxiliary heating systems. The progress made over the past 25 years, Figure 13, shows an improvement of 7 orders of magnitude in the E_{out}/E_{in}, the value of which is rapidly converging on breakeven for the tokamak, the leader in the magnetic confinement experiments.

Progress

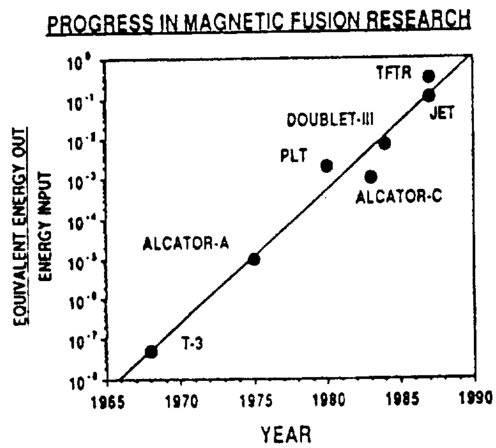


Figure 13. Progress made in energy production from fusion experiments (SAN88).

The status of several key experiments is shown later in Figure 25. The operational regimes for $n\tau$ and T have both been met individually by different experiments, although not at a level that satisfies both parameters, $n\tau$ and T_i, simultaneously.

Means of Accomplishment

There are three ways by which fusion can occur: magnetically confined plasmas, inertially confined plasmas, and gravitational (Figure 14).

Confinement Approaches

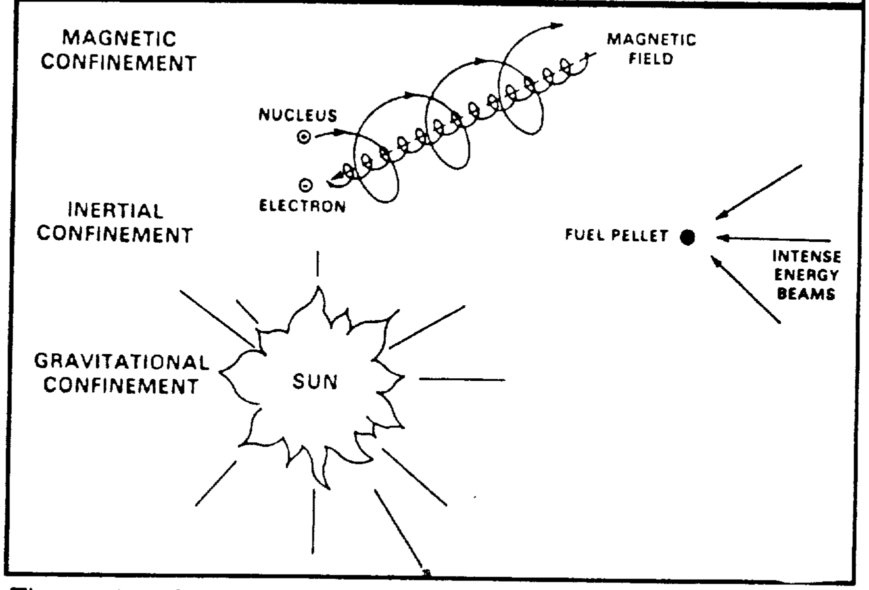


Figure 14. Means to achieve fusion.

Magnetic confinement, the focus of this report, has been researched the longest. The inertial confinement approach uses very high energy laser beams targeted at a small (~1 mm) pellet of fusionable fuels to reach the Lawson parameters under high densities for short periods of time. Efforts at demonstrating a cold fusion process (not presented on the figure) are under study or are uncertain, except for muon catalysis which is not a space option without a light weight accelerator. Figure 15 shows two magnetic confinement approaches, a simple magnetic mirror -- an open system -- and a simple torus -- a closed system. Plasma confinement is provided by magnetic force fields from magnet coil windings. The reactor suggested by this report, discussed next, uses principles pertaining to both, but without the extensive coil windings.

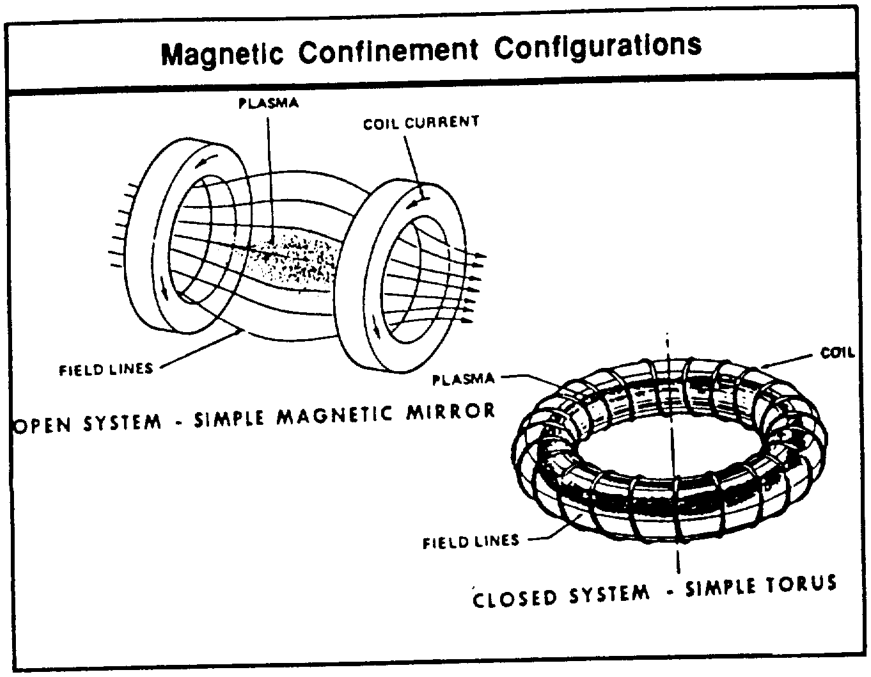


Figure 15. Basic magnetic confinement techniques.

FIELD REVERSED CONFIGURATION (FRC)

When considering the options for magnetic confinement for space we need to evaluate the capability of reactor design approaches that most closely meet space requirements, Table 3.

Table 3. Fusion Options and Comparative Evaluations (CHA89).

Parameter	Field Reversed	Tandem Mirror	Spherical Torus
Specific Impulse	○	○	○
Thrust (Power)	◓	○	○
Beta	○	◓	●
Power Density	○	◓	●
Thrust (Power)/Weight	○	◓	◓
Charged Particle Extraction	○	○	◓
Propellant Thermalization	○	◓	●

○ - Good ◓ - Average ● - Poor

Table 3 shows the Field Reversed Configuration (FRC), of the current magnetic reactor concepts considered applicable to space, to offer the optimal plasma confinement concept (Figure 16), hence the proposed approach of the authors.

Field Reversed Configuration

This paper discusses the design and operating principles of the magnetic confinement reactor known as the Field Reversed Configuration.

Its applicability to the space program is examined and shown to be potentially beneficial.

A FRC developmental plan is outlined.

Figure 16. FRC content.

The FRC's characteristic plasma ion flux is illustrated in Figure 17 by the arrows in the torus.

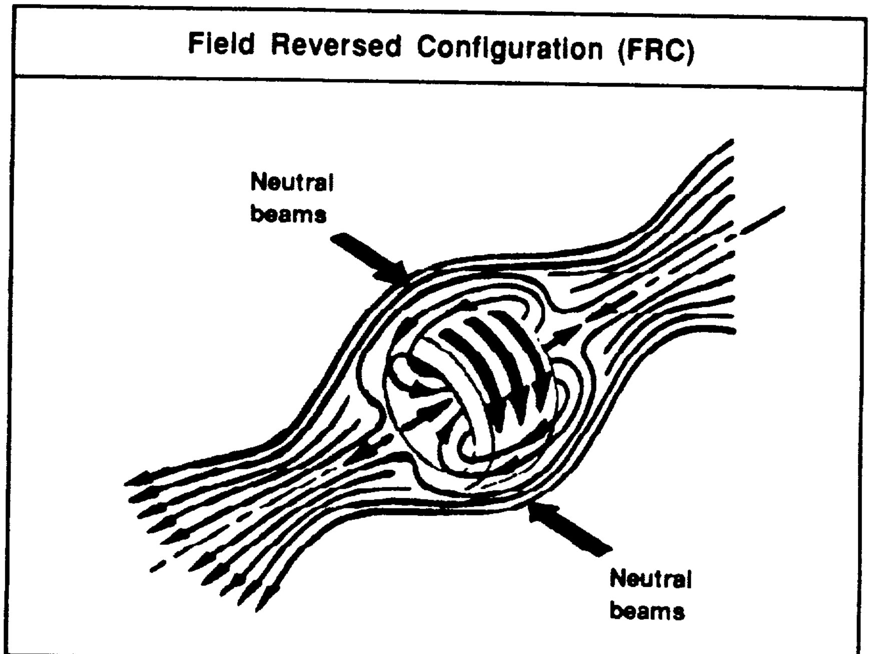


Figure 17. FRC plasma ion flux.

The FRC combines attractive features of both toroidal and linear systems. The closed inner field surfaces provide good confinement of the plasma. Yet, the linear topological nature of the external magnetic field lines would be conducive to the production of direct thrust.

The attractiveness of this machine stems from its high β good plasma confinement scheme, high power density, potential for steady state operation, and overall compact design. Plasma confinement is provided by the two end magnets and a reversed field which may be initiated and sustained by a number of methods. A toroidal current produces the confining magnetic lines of force which are in the poloidal direction (refer to Figure 18).

Field Reversed Configuration (FRC) Formation

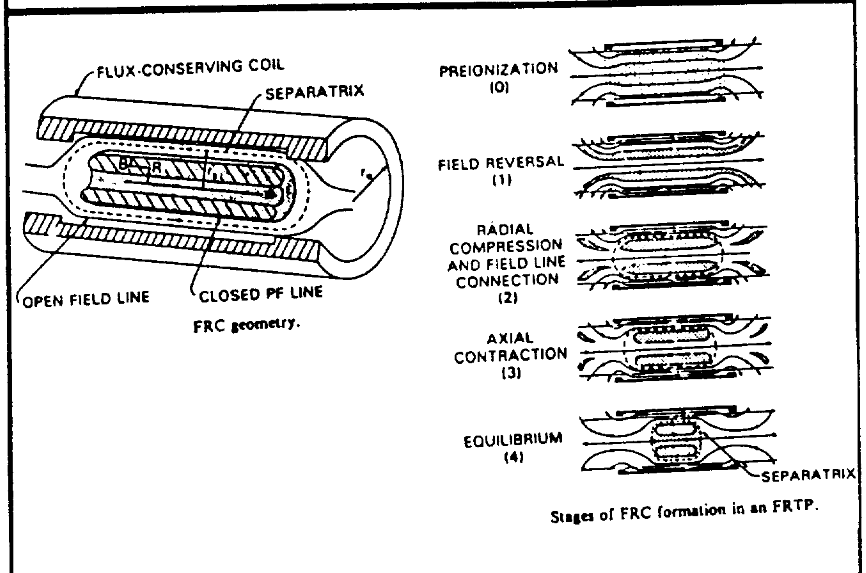


Figure 18. Plasma formation in an FRC (HOF86).

The FRC's advantage resides with the device's innate ability to contain the fusion plasma with a magnetic field generated by large internal currents that are produced without requiring magnetic coils linking the plasma. The plasma formation steps are shown in Figure 18.

One possibility for achieving ignition is to heat the fuel to the ignition temperature by quickly compressing the plasma with a rapid ramping of the plasma current and an increased magnetic field. Another is to inject a high energy neutral beam. The plasma fusion products heat the surrounding plasma, providing an attractive reactor energy balance.

The optimism for the FRC's performance as a viable reactor is indicated by the statement made by Dr. Tuszewski, one of the FRC scientists at the Los Alamos National Laboratory, in a paper presented at the Eighth Topical Fusion Meeting (TUS88). "The FRC is ideal for use of the D-^{3}He fuel cycle. Its high plasma beta and power density allow substantial reactivity, little radiation losses, and most of the fusion power in the form of 14.7 MeV protons. These charged particles can be diverted in the FRC edge layer towards electrostatic direct converters, resulting in very high plant efficiencies. These attractive features are illustrated in Table 2, where the approximate parameters of a 1 GW FRC reactor are compared for a pulsed D-T system such as CTOR and for a conceptual steady-state D-^{3}He system. One observes that the 14 MeV neutron production with D-^{3}He can be reduced by about a factor 100 compared to that of the D-T system. Another (possibly crucial) advantage of the D-^{3}He system is that gross FRC stability may be achieved at s ~ 10 with the help of high energy neutral beams, large-orbit protons, and possibly larger plasma elongations. This may not be the case for the D-T pulsed system at s ~ 30, in spite of the alpha particles."

Two terrestrial FRC experiments are in operation, one at Los Alamos and another at Spectra Technology in conjunction with the University of Washington. The FRC's fundamental advantages are presented in Figure 19.

FRC Advantages

- High Beta (ratio of plasma pressure to magnetic field pressure)
  - Burns D-^{3}He efficiently
  - High power density
  - Reactor mass minimization
- Linear topology + Thermalization of propellant → thrust + electrical power
- Allows direct conversion of energy

Figure 19. Inherent advantages of the FRC plasma confinement design.

The capability of the FRC to meet the space requirements as defined by Figure 3 is considered to be a good match. Thus, it appears to have very desirable inherent properties for the space application -- Figure 20.

FRC Status: Space Requirements Compatibility

Preliminary analyses and/or educated guesses. All require thorough analysis, design, and testing to validate whether the parameters can be met.

SPACE REACTOR PARAMETER GOAL	FRC PERFORMANCE AND RESEARCH STATUS			
	Meets	Does not meet	Unknown	Comments on FRC status
Specific Power	✓			Limited study. Requires design.
Thrust (a) low: 1 N to 10K N	✓			Limited conceptual work.
(b) medium: 10KN to 50KN			✓	Has not been addressed.
(c) high: 50KN to 500KN		?		Requires a large plasma volume.
Specific Impulse	✓			10^3 to 10^6.
Fuel Cycle			✓	Can burn D-^{3}He
Beta	✓			90%.
Ignition	✓			Needs design study. Requires testing.
Throttle capability	✓			Needs design study. Requires testing.
Plasma Stability			✓	Limited analysis. Burn experiments required - major issue.
Power Level	✓			~50 to 10 GW
Electrical Power Variability	✓			Requires design study.
Dual Mode Operation	✓			Requires design study.
Mass			✓	Requires design study.
Efficiency (P_{thrust}/P_{fusion})	✓			High.
Recirculation Power	✓			Low.
Modes of Operation	✓			Work will follow net power demonstration.
No (low) Neutron production	✓			<2%.
Failure Tolerance	✓			Requires design study
Space Environment	✓			Requires design study.

Figure 20. Compatibility of the FRC with space reactor design requirements (SCH90).

The evaluation must necessarily be considered as subjective due to the lack of any study or testing which will support the conclusions with data. Note that the key parameters, such as plasma stability, require further investigation, the basis for establishing a space fusion propulsion developmental plan.

Fusion Engine Design

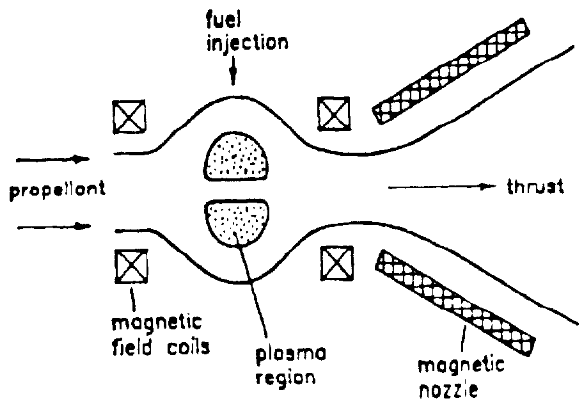
The FRC is ideally suited to propulsion by virtue of its external topology. Engine thrust is produced by the controlled release of a portion of the plasma, directed by a magnetic nozzle. One advantage of magnetic reactor designs is the absence of moving parts and of parts subjected to erosive wear. These are essential, inherent features to achieve the long life time operational requirements of the space program. The reactor is fueled by pellets which are injected into the plasma. Thrust and specific impulse are simultaneously controlled by the injection of propellant into the scrape-off layer. The thermalization of propellant is attained by heating from the plasma; the extent of thermalization is important to assure its efficient use. Plasma thrust is produced and controlled by the release of plasma and propellant along the axis through the external mirror magnets. A reactor of the power magnitude required by the manned programs would be characterized by the parameters as shown by Table 4 below (CHA89).

Table 4. FRC High Power Design Parameters.

Total power	0.5 GW
Plasma Volume	80 m^3
Elongation Factor	6
Ion Gyro Radius	0.01 m
Plasma Radius	1.5 m
Stability Factor	50
Propellant Addition	0 - 0.8 kg/s
Specific Impulse	10^6 - 10^3 seconds
Thrust	0.4-50 kN

Thrust for a fusion engine is produced directly by a magnetic nozzle at one end, accomplished by a field imbalance, Figure 21. The thrust and specific impulse are varied by changes in the propellant flow rate.

Fusion Engine Using a FRC Reactor

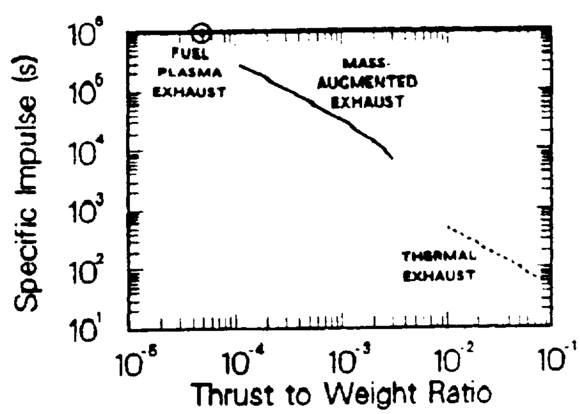


Reference Randy Chapman and George Miley "Fusion Space Propulsión with a Field Reversed Configuration," University of Illinois, 1988

Figure 21. Fusion engine design concept (CHA89).

Fusion propulsion performance is shown by Figure 22 for three operational modes: the highest, plasma only at 10^6 seconds; a variable range attained by the injection of a diluent; and a thermal conversion mode comparable to any thermal propulsion system. Thrust is increased as specific impulse decreases.

Fusion Propulsion Performance



Reference John Santarius, "Lunar ^3He, Fusion Propulsion, and Space Development," University of Wisconsin, 1988

Figure 22. Fusion engine specific impulse performance (SAN89).

The use of the magnetic nozzle and plasma entrapment makes this concept attractive because the plasma remains physically away from the wall.

TECHNICAL CONCERNS

The concerns that need to be addressed are shown in Figure 23.

FRC Concerns

- **Plasma stability at net power**
- **Plasma formation**
- **Demonstration of thermalization of propellant**
- **Insufficient data base**
- **Fuel burn efficiency**
- **Lack of program priority and urgency to develop**

Figure 23. FRC parameters requiring further and testing.

The FRC's limitations that need to be addressed are as follows (Table 5) (CHA89, SCH90):

Table 5. FRC limitations.

- Limited volume: Its size is considered to be volume limited based upon stability considerations. One approach taken to produce greater power is to provide a greater elongation factor. This consideration may be the ultimate limitation on the reactor size. Ions injected to orbit the plasma are anticipated to assist in the maintenance of plasma stability.
- Fuel efficiency: One important subject for investigation is the means to improve upon the fuel burn-up factor which is ~3%.
- Reactor plasma efficiency: Thermalization efficiency of the propellants, ash, and reaction products must be studied in detail.

Much of the concerns result from the fact that relatively little emphasis has been placed on the FRC. Consider the status as shown in Figure 24 which shows that the FRC resides in the least developed knowledge base.

Reactor Knowledge Base

Magnetic Confinement Concept Classification of Reactor Knowledge Base.

Well Developed	Moderately Developed	Less Developed
Tokamak	Advanced Tokamak Tandem Mirror Stellarator Reversed Field Pinch	Field Reversed Configuration Spheromak Elmo Bumpy Square Dense Z Pinch

Figure 24. Comparison of fusion experiment knowledge base (SCH90).

When we consider its demonstrated $n\tau T$ performance relative to ignition for other reactor experiments, the advancement is not nearly as great, largely due to the few FRC experiments built to date. (Figure 25) That chart, in essence, summarizes the FRC development risk.

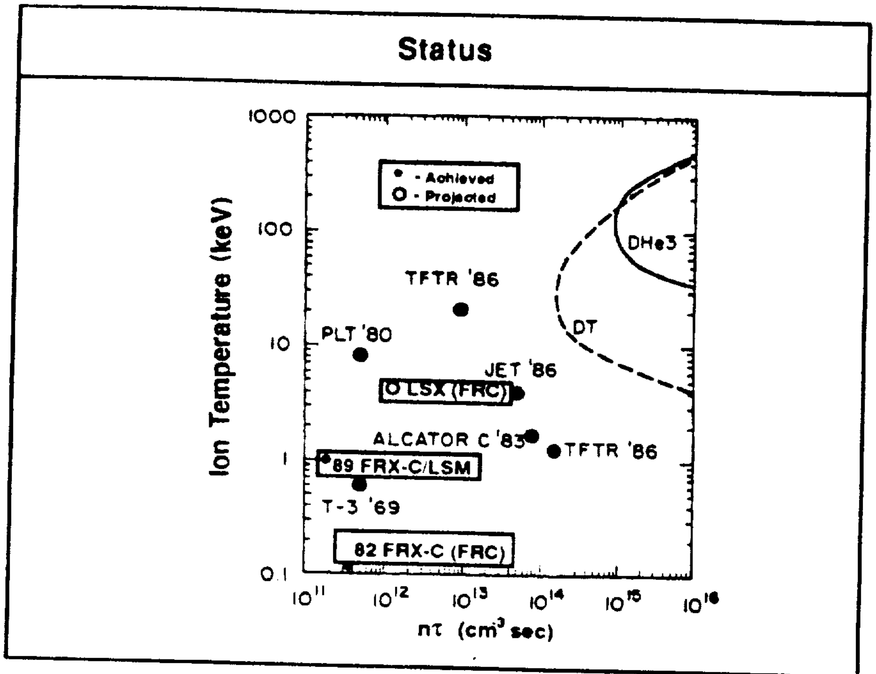


Figure 25. Status of fusion experiments relative to meeting burning conditions (SAN88).

SPACE VEHICLE SYSTEM ISSUES

Simultaneously with the development of the capability to produce thrust from controlled fusion is the ability to provide technology for the system capabilities that will satisfy the mass constraints necessary to achieve the specific power for these systems. Refer to Figure 26.

System Issues

- **Reactor space starts**
- **Thermal control**
- **Neutron flux**

Figure 26. Significant space flight fusion system issues that need to be addressed (SCH90).

The means to provide an in-space restart capability within specific power constraints constitutes fundamental supporting space fusion technology research. Yet no such research effort is being expended. Thermal control and neutron flux abatement are the other two key technology issues to make fusion energy practical. The selection of D-^{3}He as the space fuel is important in order to simplify the system engineering task and to minimize mass. The space restart technology is the most key topic in need of R&D consideration since large levels of energy will be stored aboard the spacecraft to restart the reactor. The production of highly effective, low mass, electrical power systems for space applications needs to be further researched.

COSTS

The status for program costing is shown in Figure 27.

Costs
• Funding for space fusion energy conversion = 0 $. • DOE total fusion funding for application to the production of utility company electrical power ~ $325M/annum. • FRC funding ~ $5M/annum. • Space fusion program of ~$100M/annum will provide a timely investigative program.

Figure 27. Program cost status/projections for space fusion research.

The best program approach is considered to be to design a series of large step, high risk FRC experiments aimed at quickly demonstrating a space fusion reactor capable of burning D-^{3}He. The plasma is believed to be capable of being heated to ignition using neutral beam injection and of being maintained stable by the beam flux. Experimental verification is required.

This empirical approach, by-passing the depth of understanding desired by a science program, is appropriate for an engineering developmental program and has, in fact, been a path successfully taken to implement prior inventions. This must be accepted as an expedited but high risk approach. The magnitude of the gain to space programs justifies the risk level and warrants the recommendation. It should be emphasized that the cost estimates are no more than educated estimated judgments to demonstrate plasma stability in an FRC. More definitive cost estimating needs to be performed.

SCHEDULE

The anticipated schedule for achieving fusion energy conversion for a FRC program is shown in Figure 28.

Schedule
• No space fusion energy program: ∞ time • At the current level of DOE funding: maybe 50-100 years • At the proposed level: demonstration of viability regarding plasma stability in 5 to 10 years, maybe less • Ultimate FRC availability for space use: depends on NASA commitment and nature's cooperativeness -- Could be 20 to 30 years •Small size + simplicity: provides unique opportunity for rapid development.

Figure 28. Program schedule status/projections for space fusion research.

KEY POINTS

With reference to the developmental responsibilities of fusion for space, there are several significant points that must be considered, Figure 29. Program success largely depends upon the last point, i.e., NASA has a vested interest.

Significant Points to Consider

1. The Mission Architecture for planning NASA's future manned and current science missions would incorporate the use of fusion energy now, if developed.
2. National fusion program addresses the use of fusion energy for commercial electrical power generation on Earth. That application is a function of international energy costs and fusion energy's competitive costs.
3. Fusion's availability for the space program's immediate needs is being determined by the Earth's energy supply and demand situation.
4. A space fusion research program existed at NASA Lewis, and in it significant contributions were made.
5. If developed sufficiently rapid, it could expedite manned Mars exploration and eliminate some major steps in the current planning:

    -man is "0"- G space qualified for 3 months
    -direct transfer to Mars w/o lengthy Earth/lunar human research
    -enhanced safety

Figure 29. Considerations in undertaking a space fusion program.

Fusion energy can serve as a key element in the mission architecture in accomplishing the "U. S. National Space Policy." That is based upon an excellent matching of fusion's capabilities with the technical requirements that result from the policy -- as discussed in this report's content: "The overall goals of the United States space activities are: ... (2) to obtain scientific, technological and economic benefits for the general population and to improve the quality of life on Earth through space-related activities and to expand human presence and activity beyond Earth orbit into the solar system." ("US National Space Policy," November 2, 1989, p 1 (ANON89)) "The objectives of the United States civil space activities shall be (1) to expand knowledge of the Earth, its environment, the solar system, and the universe; (2) to create new opportunities for use of the space environment through the conduct of appropriate research and experimentation in advanced technology and systems; (3) to develop space technology for civil applications and, wherever appropriate, make such technology available to the commercial sector; (4) to preserve the United States preeminence in critical aspects of space science, applications, technology, and manned space flight; (5) to establish a permanently manned presence in space; and to engage in international cooperative efforts that further United States overall space goals." (ibid. pp 2-3) In order to further and to continue research in space and to conduct manned exploration much beyond Earth orbit will entail the availability of high energy sources to move large payload masses and to conduct timely missions at greater and greater distances as the lesser energy demanding missions and space goals become fulfilled. The space program will be compelled to incorporate into its space transportation infrastructure more efficient systems that offer quantum leaps in performance rather than minor refinements in the lesser energy intense systems. That will be required for logistical support beyond the Earth-moon space operational regime to achieve the economy necessary for reasonable support of those missions. Fusion energy has the potential for providing that energy source due to its high specific energy release and variable high performance propulsion capability, provided that the technology can be appropriately developed for meeting the space application needs. We recommend leveraging of research funds for high leverage technological payoffs to assure that a US space vision for the future will materialize. Otherwise the space program's energy conversion infrastructure will not be in a position of advancing with the needs of exploration and science research programs.

CONCLUSIONS

Figure 30a and b presents the conclusions of the authors:

Conclusions

1. Fusion energy offers very attractive inherent features for accomplishing space mission requirements and becoming perhaps the key element in the United States Space Mission Architecture for fulfillment of the U. S. National Space Policy.

2. Fusion's application in space is for programs currently being planned and, if available as an element in the space transportation infrastructure, could have been used and incorporated into a more ambitious space science and exploration program.

3. A successful DOE fusion research program will produce fusion reactors useful on Earth, but not for space applications. There is a lack of commitment to space fusion energy conversion.

4. Fusion would greatly enhance safety for manned missions.

5. The space program's launch operational costs for manned logistic flights to Mars - using fusion energy conversion - would be substantially reduced.

6. Fusion energy's high specific power performance advantages will pay for the development costs many times over.

Figure 30a. Conclusions.

Conclusions

7. Strategical goals of NASA are served by fusion energy:

   - The mission enabling capability will enhance manned space flight safety.
   - Power will be available to accomplish future high energy missions.
   - Space science will be enhanced by enabling missions that improve our understanding of the solar system and nearest stars and star systems. Fusion would enable a substantial space exploration beyond current planning and a new space science program beyond our current visions.

8. Development of fusion and fission for space power and propulsion are unrelated technologies. The development of fusion does not depend upon the development of fission first. Fusion energy conversion operates on the basis of a charged particle system; fission is thermal.

9. It will be a technically very challenging job. It may not be quick to develop. To provide the energy for future missions now under consideration and for future anticipated missions, we must commence a space fusion energy program now.

10. Fusion provides NASA with an energy option to fission ... and more.

Figure 30b. Conclusions.

RECOMMENDATIONS

Recommendations are provided in Figure 31:

Recommendations

The United States should take a world leadership role in the development of fusion energy for space applications. We propose the following specific measures:

1. **NASA initiate a space fusion research program to develop high specific power propulsion systems -- on the order of 1 to 10 kW/kg,**
2. **As the first step, design, build, and test a FRC capable of burning deuterium-helium-3 which produces net power.**

Figure 31. Recommendations.

CONCLUDING REMARKS

The specific fusion reactor concept preferred is the Field Reversed Configuration (FRC). That reactor design approach inherently offers a high beta design; and although it is classified as a compact toroid, its external topology naturally lends itself to the generation of thrust. Burning deuterium and ^3He will reduce the neutron flux level substantially and will produce a very large part of the reaction's energy in charged particles for the efficient conversion of plasma energy directly to thrust without the inefficiencies associated with thermal systems. The primary concern with the FRC is plasma stability while operating under net power regimes, and that is a subject which will have to be addressed by full scale experiments. Neutral beam injection into the plasma is proposed to aid in plasma stability and for raising the plasma energy level to ignition. Helium-3 has been determined to be available on the moon in a sufficient quantity to support the space program's fuel requirements for flight programs. Enough ^3He is available on Earth now to commence a FRC D-^3He reactor experimental test program. One ^3He fuel supply option to lunar mining is the proton-lithium-6 reaction at least until the lunar supply becomes available. Fusion energy development is considered to be high risk research, but that risk is considered insignificant in comparison to the enormous benefits that can be realized from energy conversion systems having such desirable properties that enable future space missions.

In summary, a space fusion energy capability is considered to be mandatory for performing space missions which implement the "U. S. National Space Policy." If available, excellent use could be made of fusion energy **now**. With only the present DOE fusion research program -- one intended to produce electrical power for electrical utility companies as a profit making venture, the development of fusion energy for space -- a different application -- will not occur in the foreseeable future unless a major redirection of charter and program focus is mandated. Space fusion energy is considered to be high risk, but extremely high gain, research that must be undertaken by NASA. Otherwise the future of the United States' space program can be expected to stagnate as advanced missions in space become energy constrained in the not too distant future. If the United States does not act, some other country can be anticipated to fill the void by undertaking the development of fusion energy for space.

SYMBOLS

^3He	helium-3, isotope of helium
^{11}B	boron-11, isotope of boron
AU	astronomical unit = 1.5×10^{11}m
c	velocity of light = 3×10^8m/s
D	deuterium, isotope of hydrogen
E	energy
GW	gigawatts (10^9 watts)
I_{sp}	specific impulse, seconds
J	energy, joules
keV	kiloelectron volts
kg	kilograms
m	mass
m	meters
MeV	million electron volts
M_o	initial vehicle mass, MT (= propellants + inert vehicle + payload)
M_p	propellant mass, MT (includes fuels and diluent)
MT	metric tons
MW	megawatts
n	ion density, number of ions per cubic centimeter
n	neutron
$n\tau$	Lawson parameter, $cm^{-3}s$ (fusion plasma = plasma losses)
N	thrust, newtons
p	proton
P_j	jet power, kW
s	seconds
s	gyroradius, cm, (characteristic radius of a charged particle's orbit gyrating around field lines in a magnetic field)
t	flight time

T	temperature.°K
T	tritium, isotope of hydrogen
T_i	plasma's ion temperature, °K or keV

Greek

α_p	propellant system specific power, kW/kg
α_{p1}	propellant system specific power where α_p=1kW/kg
α_{p10}	propellant system specific power where α_p=10kW/kg
β	ratio of plasma pressure to magnetic field pressure, %
Δv	incremental velocity change, km/s
γ	payload mass fraction, % (payload mass/initial vehicle mass)
σ	nuclear cross section, cm^2
$<\sigma v>$	reactivity parameter, cm^3/s
τ	fusion reaction time, seconds

ACRONYMS

FRC	Field Reversed Configuration, magnetic confinement experiment
HESM	High Energy Space Mission
JET	Joint European Torus, magnetic confinement experiment
LEO	Low Earth Orbit
NERVA	Nuclear Engine for Rocket Vehicle Application (fission thermal rocket)
PLT	Princeton Large Torus, magnetic confinement experiment
TFTR	Tokamak Fusion Test Reactor,

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PRESENTATION 1.4.4

ADVANCED PROPULSION CONCEPTS