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INERTIAL ELECTROSTATIC CONFINEMENT AS A POWER SOURCE FOR ELECTRIC PROPULSION

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ABSTRACT

The potential use of an **INERTIAL ELECTROSTATIC CONFINEMENT** (IEC) power source for space propulsion has previously been suggested by the authors and others. In the past, these discussions have generally followed the charged-particle electric-discharge engine (QED) concept proposed by Bussard, in which the IEC is used to generate an electron beam which vaporizes liquid hydrogen for use as a propellant. However, in the present study, we consider an alternate approach, using the IEC to drive a "conventional" electric thruster unit. This has the advantage of building on the rapidly developing technology for such thrusters, which operate at higher specific impulse. Key issues related to this approach include the continued successful development of the physics and engineering of the IEC unit, as well as the development of efficient step-down dc voltage transformers.

The IEC operates by radial injection of energetic ions into a spherical vessel. A very high ion density is created in a small core region at the center of the vessel, resulting in extremely high fusion power density in the core. Present experiments at the U. of Illinois in small IEC devices (<60-cm. dia.) have demonstrated much of the basic physics underlying this concept, e.g. producing ~10^6 D-D neutrons/sec steady-state with deuterium gas flow injection. The ultimate goal is to increase the power densities by several orders of magnitude and to convert to D-^{3}He injection. If successful, such an experiment would represent a milestone proof-of-principle device for eventual space power use.

Further discussion of IEC physics and status will be presented with a description of the overall propulsion system and estimated performance.

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INTRODUCTION

Fusion energy offers an extremely attractive power source for fusion propulsion.(1-3) However, conventional approaches to fusion reactors for terrestrial use employ heavy components, i.e. offer too low a power-to-weight ratio, to be considered for space applications. In addition, in order to reduce neutron and radioactive propellants in space, the use of advanced fuels such as D-^{3}He is desirable. Conventional approaches such as the Tokamak appear marginal for burning such fuels. Consequently, new confinement approaches for space propulsion or power are needed. While several possibilities have been suggested,(4-9) inertial electrostatic confinement (IEC) appears to be one of the most attractive approaches because of ultra-low inert mass and advanced fuel-burning efficiency, as a result of a highly non-Maxwellian energy distribution for reacting ions.(10-12)

A difficulty in projecting the use of the IEC for propulsion is that the experimental data base is inadequate. Thus the extrapolation of design principles to a reactor design contains many uncertainties. Still, it was thought to be worthwhile to carry out the conceptual design study presented here, in order to understand issues that need further study and to illustrate the potential advantages of this approach.

The design goal was to use the IEC as the primary power source propulsion system, capable of making a trip to Mars in less than 120 days. A Direct Electrical Converter (DEC) is used to convert the IEC energy to a megavolt dc current. A unique electrical system transforms this voltage and current to levels required by the thrusters, which use hydrogen propellant to achieve the necessary thrust and specific impulse.

The total weight of the Mars-bound spacecraft is apportioned as follows: 120 metric tons for the propellant and tanks; 120 metric tons for the propulsion system (60% DEC, 15% IEC, 15% electrical system, and 10% thrusters); and 60 metric tons for crew compartment, cargo, and shielding material. To complete the mission in the required time, a specific impulse, I_{sp}, of 3000 seconds is necessary. To achieve this, the five parallel thrusters deliver a mass flow rate of 11.5 g/s and a thrust of 340 N.

The craft is launched from a low Earth orbit. Succeeding sections contain a description of the various subsystems in more detail. An earlier concept for IEC-based propulsion was proposed by R.W. Bussard,(9) who envisioned an advanced electron beam-heated thruster. Here we explore the use of an alternate thruster based on magneto-plasma-dynamic (MPD) and arcjet concepts.

INERTIAL ELECTROSTATIC CONFINEMENT (IEC)

The proposed power source is a fusion system, based on the principles of the IEC, a method of electrostatically confining a fusion plasma first proposed by Salisbury(13) and Farnsworth.(14) Early experimental studies were carried out by Hirsch,(15) but little was done after that until recent experiments at the U. of Illinois.(12, 16-18) The IEC device is spherical and consists of two concentric spherical grids. (Fig. 1) The inner grid, the cathode, is placed at a large negative potential with respect to the outer grid, which is grounded. When small amounts of gas are puffed into the grids, the high electric field ionizes the gas and accelerates the ions towards the center of the device. As these ions converge upon the center, they form a dense core region where fusion can take place. Because of space charge build-up of the ions and electrons in the core region, virtual anodes and cathodes are formed in a spherical potential well structure.(12, 15) This serves to enhance the ion confinement and to produce a very dense center spot where fusion occurs. U. of Illinois experiments have been quite successful to date, achieving a measurement of the potential well during low current operation (20 mA) and also achieving strong (1.2×10^6/sec) 2.45-MeV neutron emission when deuterium fill gas is used. Still, these experiments are 3 to 4 orders of magnitude (in current) below breakeven. Consequently, several key scale-up experiments are needed to confirm the feasibility of this approach. In the discussion below, we examine fundamental IEC design concepts to produce a fusion propulsion system of 21.4 MW.

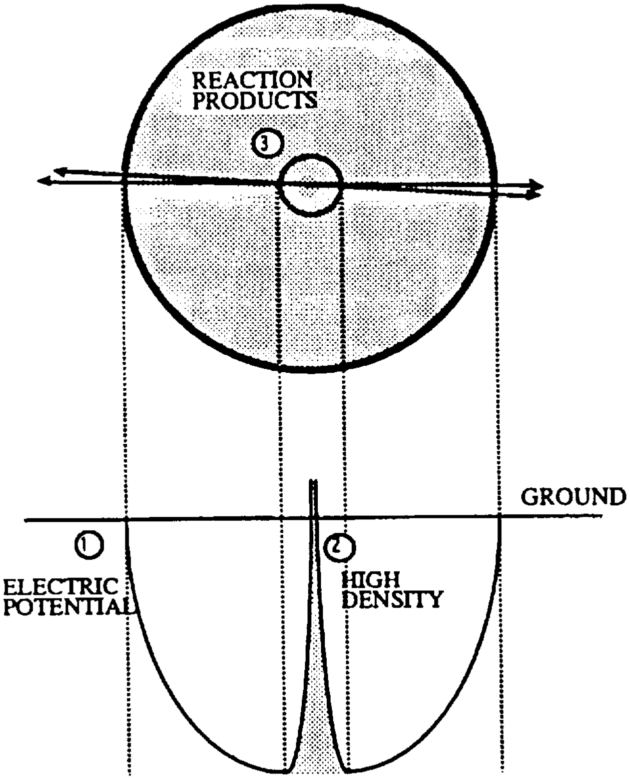


Figure 1. IEC concept

POWER FLOW

The power analysis of the IEC requires an assumption of how the fusion rate scales with current. A graph of the fusion rate scaling is shown in Fig. 2. Calculations are shown for I^5 and also a more pessimistic I^3 scaling to illustrate the range of possibilities. For the final rocket design, I^5 scaling has been chosen. This assumes that a fully-developed potential well structure is achieved.

Figure 2. Scaling laws for IEC with potential wells and (ICC) compression

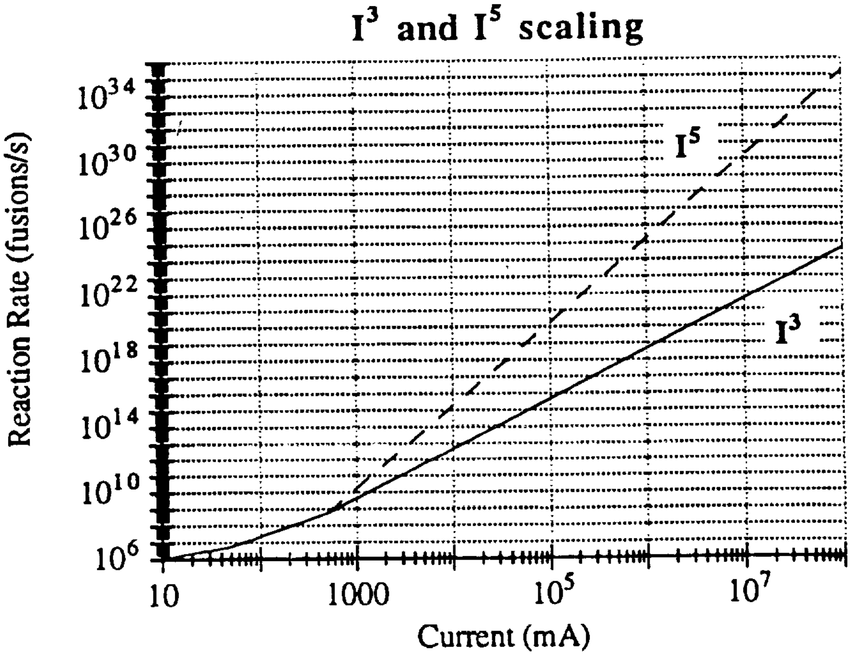


Fig. 3 shows a power flow chart for the overall system, while the specified subsystem parameters are given in Table I. The results of calculations based on these parameters are shown in Table II. An attractive fusion energy gain is predicted, giving 21.4 MW to the DEC with only 4.16 MW of injected power. This design gives a thruster power of 10 MW.

Figure 3. IEC fusion rocket power flow chart

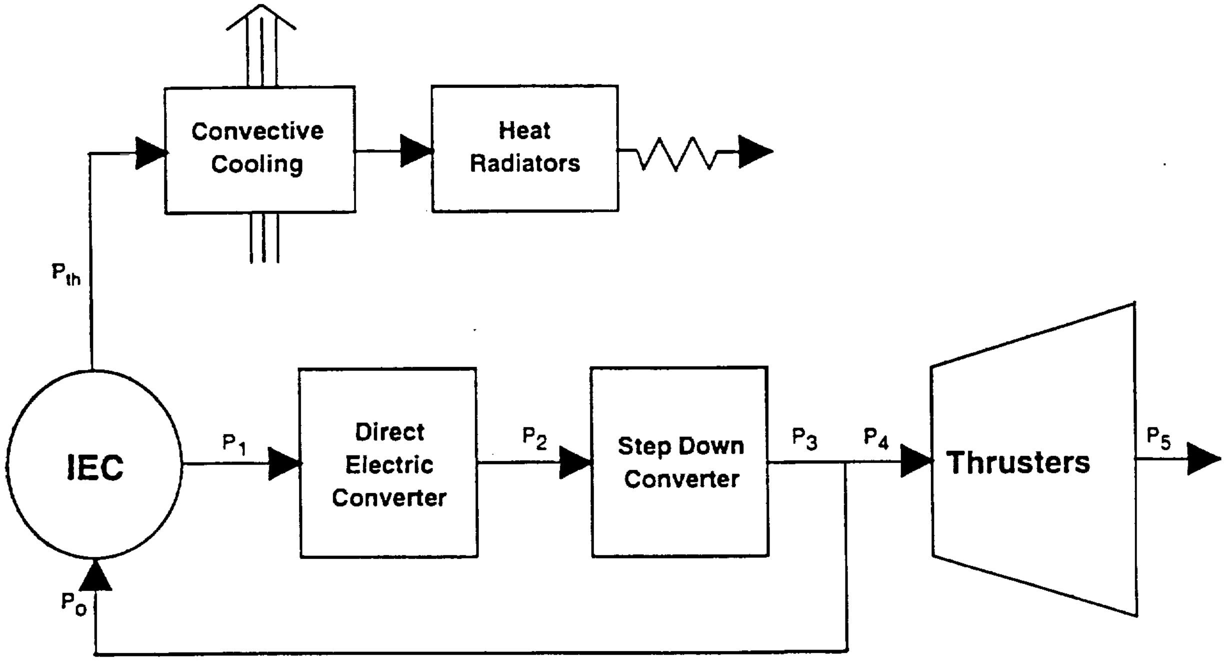


Table I. Estimated efficiencies of various components

COMPONENT	EFFICIENCY
Direct Electric Converter	$\eta_{DEC} = 0.80$
Step-Down Converter	$\eta_{STD} = 0.95$
Thruster	$\eta_{TH} = 0.50$

Table II. Power flows corresponding to Fig. 3

$P_0 = 4.16$ MW	$P_1 = 21.40$ MW
$P_2 = 17.12$ MW	$P_3 = 16.26$ MW
$P_4 = 12.00$ MW	$P_5 = 6.00$ MW
$P_{excess} = 0.104$ MW†	

†P_{excess} is excess power which is available for use for extraneous ship functions such as life support systems, communication devices and experimental research.

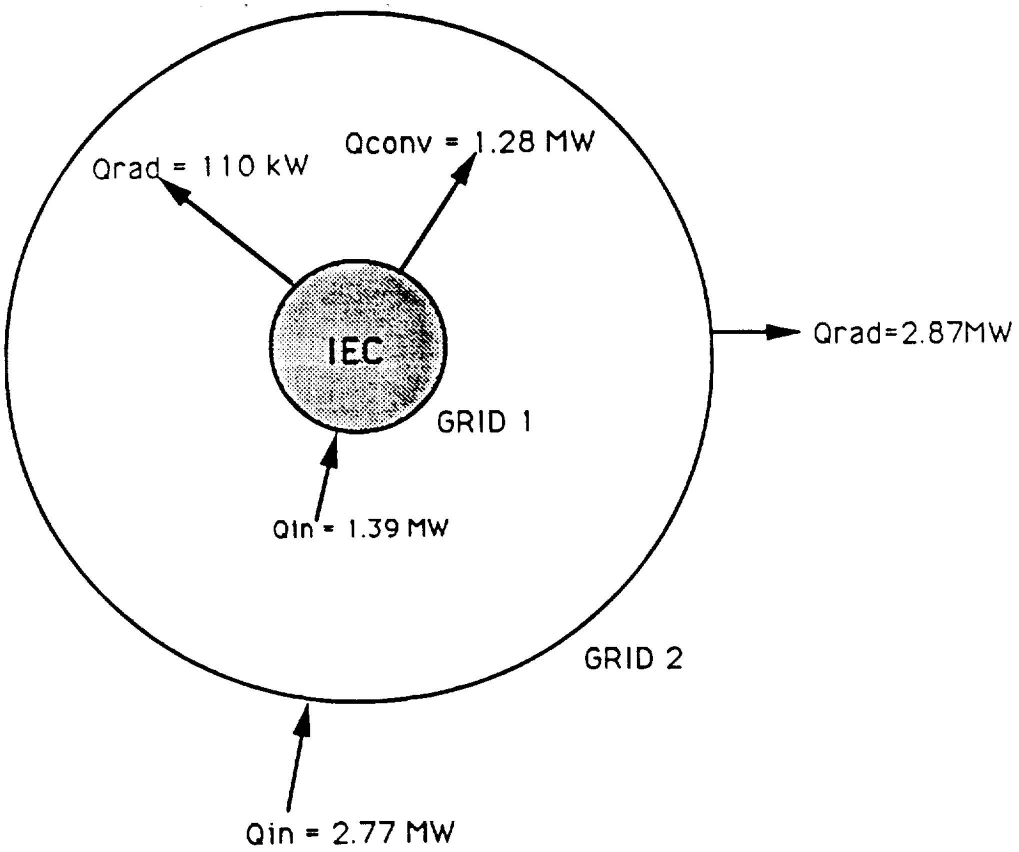
There are several major concerns to be addressed. One is a need to recirculate the fusion fuels, ^{3}He and deuterium. Only a small fraction of the fuel is actually burned, ~5%, and the rest must either be retained in the system or collected and returned to the IEC. This is especially important for the ^{3}He because of its high cost. Another concern to be addressed is the accumulation of reaction products, such as tritium, in the IEC core.

GRID HEAT REMOVAL

The IEC grid structure is comprised of a network of equilateral triangles forming a geodesic structure. This structure maintains the electrostatic field necessary for IEC operation. In order to maintain the desired transparency of 95%, the ratio $d/a < 0.0577$ is necessary, where the grid tubing diameter is given by "d" and the length of a triangle side is "a". The grid is constructed of tungsten which melts at 3683 K; the surface temperature of the inner grid will be 2121 K (0.58 T_m).

The radius of the inner grid is $r = 0.75$ m, roughly a minimum value, in view of the strong heating as a result of plasma particles and radiation hitting it. The diameter of the grid tubing is 0.5" (0.0127 m) which yields a triangle side length of a = 0.722' (0.22 m). The heat dissipated to the two IEC grids is determined to be $P_o = 4.16$ MW. (See Fig. 4) The inner grid will dissipate one-third of this energy while the remainder will be deposited on the outer grid. The outer grid can successfully dissipate its heat by radiative cooling, while the inner grid requires additional forced cooling. The following discussion will focus on the inner-grid heat removal. The total power incident on the inner grid is 1.39 MW. Q_{rad} is calculated to be 110 kW, so the remainder, $Q_{conv} =$ 1.28 MW must be removed by a coolant flowing inside the tubular grid. The cooling system will be closed loop with a separate H_2 tank at 0.01 MPa. The coolant will circulate through the inner grid and dissipate the heat evenly. The total mass flow rate required is 61.4 g/s, and the coolant will leave the grid at 1420 K. The convected coolant will be radiated into space by radiators with a surface area of 200 m^2. The coolant exits the radiators at 300 K.

Figure 4. Heat flow diagram for IEC grids



SHIELDING CONSIDERATIONS

Shielding must be provided for both solar and IEC radiation. Solar radiation consists primarily of protons and heavy ions (Galactic Cosmic Rays), while the IEC radiation consists of neutrons and x-rays.(19) One goal is to keep the crew's exposure to under 47 Rem for the 270 day mission, 3 Rem less than the annual dose limit set for astronauts. The other goal is to minimize the shielding mass, 45 metric tons being the maximum design goal. For solar particle shielding, polyethylene shields of 9-g/cm^2 and 8-g/cm^2 surround the entire crew quarters, a compartment of 10 x 5 x 3 meters. Part of the shielding will be movable in the event of an anomalously large (AL) solar flare. By doubling up some of the polyethylene, a smaller triangular compartment of 2.5 x 2.5 x 3 meters can be constructed. The "storm shield" will then be shielded by a double thickness of polyethylene. Table III shows the radiation doses received for a 270-day mission to Mars. These results are based on 9-g/cm^2 of polyethylene shielding during normal solar activity, and 18-g/cm^2 during the one AL flare expected for the mission. Results are given for both solar minimum and solar maximum conditions. This table also shows the mass of the needed shielding.

Table III. 270-Day Dose from Galactic Cosmic Rays

SOLAR CONDITION	NORMAL DOSE	AL DOSE	OR DOSE	TOTAL DOSE	SHIELD MASS
Maximum	19 Rem	8 Rem	4 Rem	31 Rem	17.1 Metric Tons
Minimum	47 Rem	0 Rem	0 Rem	47 Rem	17.1 Metric Tons

Even though there are no flares expected for periods of solar minimum, the shielding appears to be more than adequate to handle a mission during a period of solar maximum. These periods are fairly easily predicted, as the sun has about an 11-year cycle of sun spot events.

The other area of concern is the IEC radiation. Neutrons will be produced from both D-D and D-T reactions. Calculations indicate a D-D to D-^{3}He reaction rate ratio of 8.69%, giving a D-D reaction rate of 3.475×10^{17}-neutrons/sec. This reaction also produces tritium. We assume that all of the tritium then fuses via D-T reactions, giving a 14.1-MeV neutron. The result is a total neutron source rate of 6.95×10^{17}-n/sec.

The 50-m long hydrogen propellant tanks will provide significant shielding between the IEC and the crew compartment. The hydrogen in the tanks will thermalize the IEC neutrons and allow them to be absorbed before reaching the crew. The resulting flux at 50-m (the length of the propellant tanks) away from the IEC was found to be completely negligible, even at the minimum hydrogen residuals in the tanks at the end of the mission. Therefore, no additional shielding is used between the IEC and the crew.

There are still several issues to be addressed in this analysis. Most of the electronics will have to be protected from radiation. The neutrons going away from the crew, towards the DEC, can easily be moderated and absorbed; and solar radiation can also be shielded against. However, this added shielding has not yet been included in the weight estimates for the craft.

DIRECT ELECTRIC CONVERTER (DEC)

The objective of the DEC is to convert the kinetic energy of the fusion products to electrical current to be used by the thrusters to propel the ship. The direct fusion products of the D + ^{3}He reaction employed in the IEC are a 14.7-MeV proton and a 3.6-MeV alpha particle. Other charged products come from "side" D + D reactions in the form of an 0.8-MeV ^{3}He atom and a 3.1-MeV proton. In addition, a side D + T reaction produces a 3.5-MeV alpha. A "Venetian-blind"-type electrostatic energy converter is employed.(20, 21) Its collectors are charged to a potential slightly below the average energy of the particle to be collected. This design will utilize three separate sets of collector plates. (See Fig. 5.) One will be at a voltage of 0.8 MV to capture the tritium atoms produced through D + D reactions before they fall back into the IEC plasma. Another will be at 1.5 MV to collect the alpha products. The outer collector will be at 14 MV to collect the D + ^{3}He proton products.

Since the fusion products will be emitted isotropically from the core of the IEC, the DEC will utilize spherical geometry. The 0.8-MV and 1.5-MV collectors will be nearly perpendicular to the outer spherical surface of the IEC, while the 14-MV collector will be tangent to the outer surface. The orientation of the first two collectors allow the 14-MeV protons to pass these plates and collect on the outermost plate. Thus, the lower potential collectors are highly "transparent" to the 14-MeV proton.

Secondary electrons emitted when the charged particles hit the collector surfaces can result in unwanted leakage currents between the high voltage plates.(20) Electron suppressor grids are employed to prevent this. High voltage breakdown on the surface of the insulators separating the collectors will limit the distances between each successive plate. The suppressors are placed in the "shadow" of the collectors in order to prevent excessive interaction with the high energy ions.

This "Venetian-blind"-type DEC potentially offers a high conversion efficiency.(21) The distance between the 0.8-MV, 1.5-MV, and 14-MV collectors are limited by the high voltage breakdown field along the surface of the insulator being used. Teflon has been selected as the insulator. A fluted surface-type insulator design has been analyzed, giving the distances between successive plates as indicated in Table IV. Due to the limitations on the size of the rocket, a safety factor of 2 will be the design's goal.

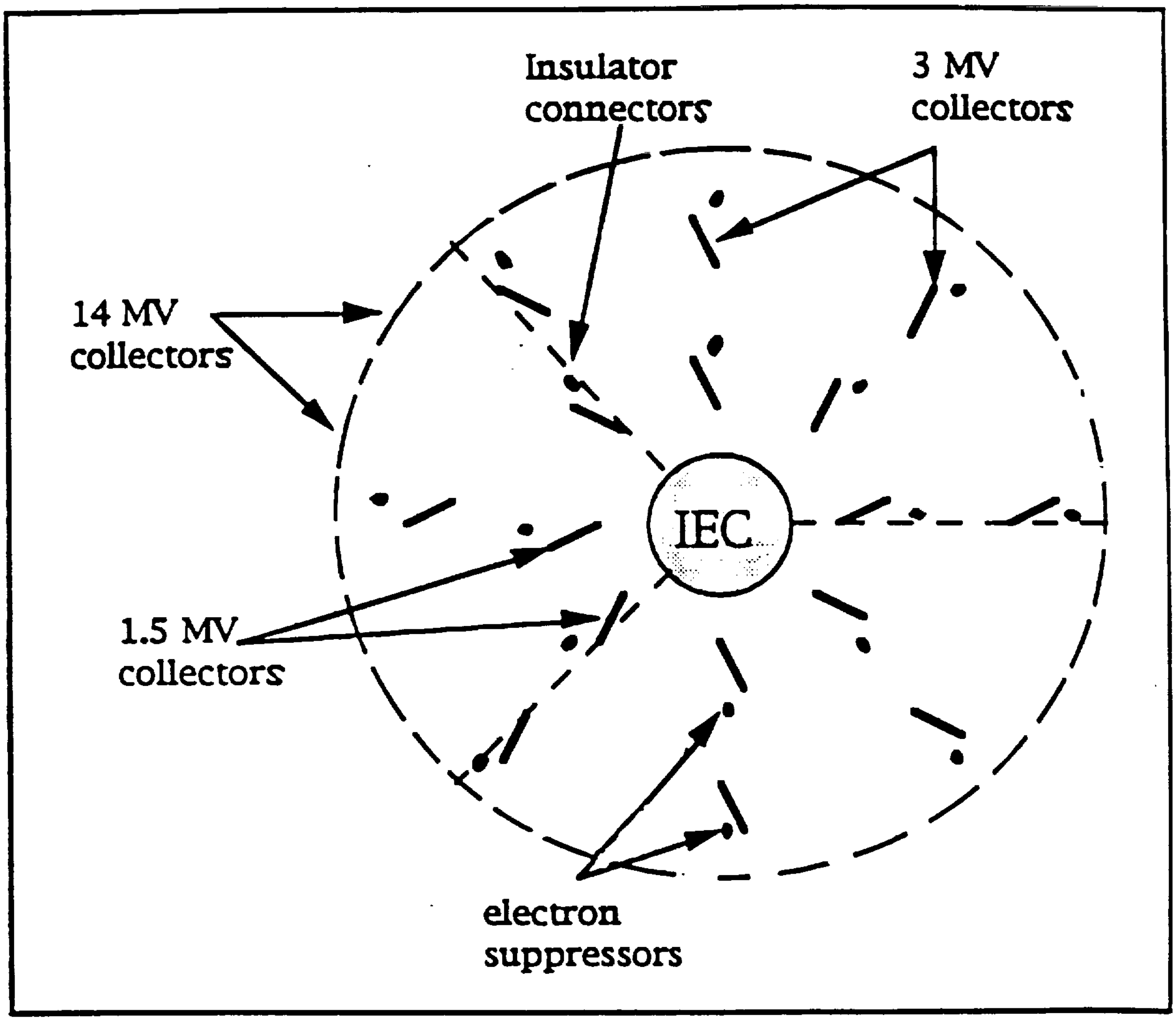
Table IV. Distances between collectors in the DEC‡

FROM COLLECTOR (MV)	TO COLLECTOR (MV)	DISTANCE (cm)
0.0	-0.1	3.3
-0.1	0.8	30.0
0.8	0.7	3.3
0.7	1.5	26.7
1.5	1.4	3.3
1.4	14.0	420.0

‡Positive potentials signify high energy particle collectors, while negative potentials signify electron suppressors.

The approximate length of each collector plate is 5 cm. Thus, the DEC system will have an outer radius of 517 cm beyond the outer grid of the IEC. This is rather small, considering the IEC has an outer radius of 6 m. Therefore, the IEC and DEC system have a combined radius of 11.2 m.

Figure 5. A cross-sectional view of the DEC outside the IEC. For simplicity, only representative collector plates are shown. A close packed configuration is envisioned for the actual design.



ELECTRICAL CONVERSION SYSTEM

The electricity produced by the DEC must be converted into a form that can be used by the thrusters and also be fed back to the IEC. For this purpose, the 14-MW potential output from the DEC must be converted to 1 kV and ~10^4 A. A capacitor storage system is used to provide the 10,000 pulses per second required to drive the thrusters.

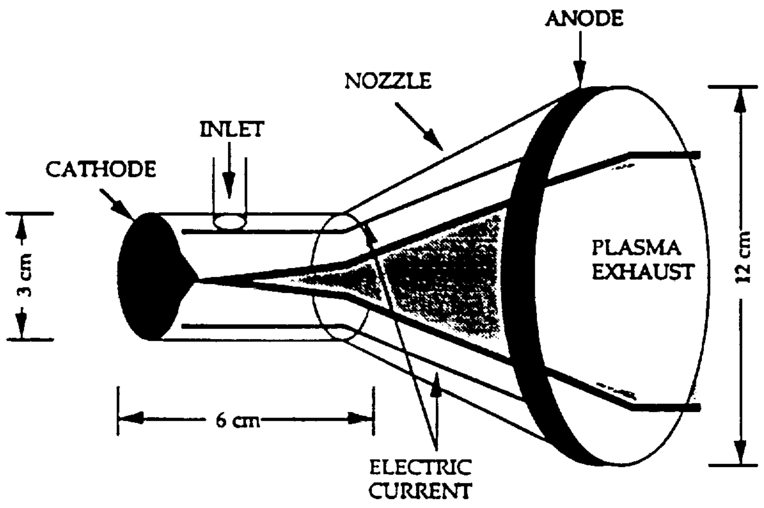
The converter works on the principle of an electrostatic (ES) generator. The charge on the DEC induces a charge on the probe which charges a capacitor. As the relay allows the probe to be grounded, the capacitor charges. As the relay connects to capacitor to the load, the capacitor is placed in parallel with the ion thruster. With an additional parallel RC circuit, the output from the charged capacitor to the ion thruster can be "smoothed out."

ELECTRIC THRUSTER

The thruster envisioned for this mission is a new hybrid design. It combines features of the traditional arcjet thruster and the magneto-plasma-dynamic thruster (MPD). The design (Fig. 6), uses the same electric current to provide both an electrothermal and a magnetic acceleration, yielding an I_{sp} of 3000 seconds and a thrust of 68 N per thruster.

Hydrogen gas is continuously fed into a 3-cm diameter by 6-cm long thruster chamber at a rate of 2.3 g/s. As the gas fills the chamber, a charge builds up on a small capacitor bank, coupled to the two electrodes. When the electrodes reach a potential of 1 kV, they discharge an electrical pulse with a current of 20 kA, dissociating and ionizing the hydrogen, sharply raising its pressure, and accelerating it toward the conical nozzle region. As the hydrogen reaches the nozzle section of the thruster, it is further accelerated by an azimuthal magnetic field generated by the current flowing between the anode and the cathode, accelerating it in an axial direction.

Figure 6. The hybrid thruster design



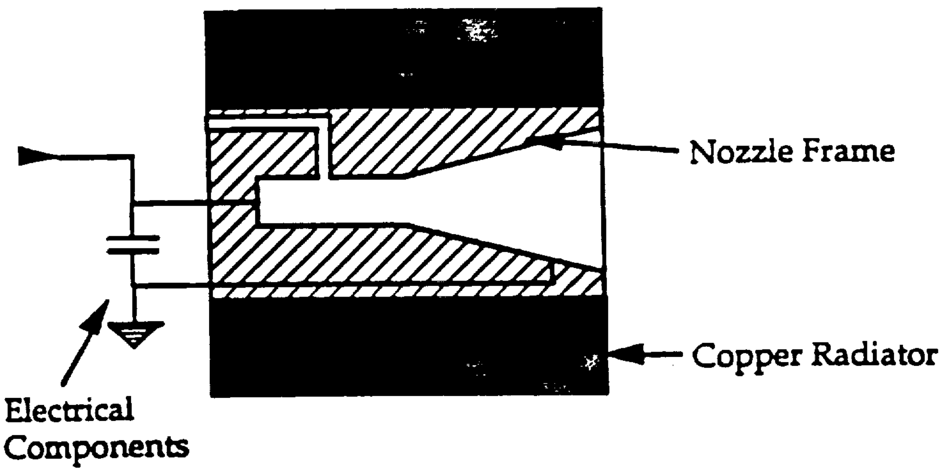
The thruster is operated with a pulsing frequency of 10,000 per second. This is necessary to prevent overheating and to increase chamber pressure. Between pulses, the hydrogen collects in the chamber, increasing the pressure. By the time the hydrogen escapes the nozzle, another electrical pulse expels the gas from the chamber. The increase of the pressure in the nozzle to a few atmospheres offers several benefits. Dissociation and ionization losses are reduced, energy is gained from hydrogen recombination within the nozzle, and the Reynolds number is increased. The energy gained by recombination further accelerates the flow and the increased Reynolds number reduces frictional forces on the wall of the thruster.

Each thruster has an average power input of 2 MW, with a peak power of 10 MW. Although it has an efficiency of only 50%, each thruster can deliver 2.3 g/s of propellant at a velocity of 29.4 km/s, producing 68 N of thrust with an I_{sp} of 3000 seconds. Since there will be five thrusters, the total thrust will be 340 N.

A large amount of propellant is required for this mission. Although the mass flow rate appears small (11.5 g/s), the total mass needed over the 120 days is 127.5 metric tons, including 5% added for reserve. Stored as liquid hydrogen,(22) this requires a volume of 1960 m^3, which will be divided among fourteen tanks.

Each thruster has three main components, as shown in Fig. 7. The nozzle and capillary tube are constructed using an insulator with a high melting point, such as Si_3N_4. The electrical components include the charging capacitors and the electrodes. Copper heat radiators are required, weighing about 700 kg per thruster. A 3-cm thick radiator of this type would occupy 13 m^2, which can easily be accommodated. The estimated total mass of each thruster is 1760 kg, or 8800 kg for all five thrusters.

Figure 7. Diagram of complete thruster

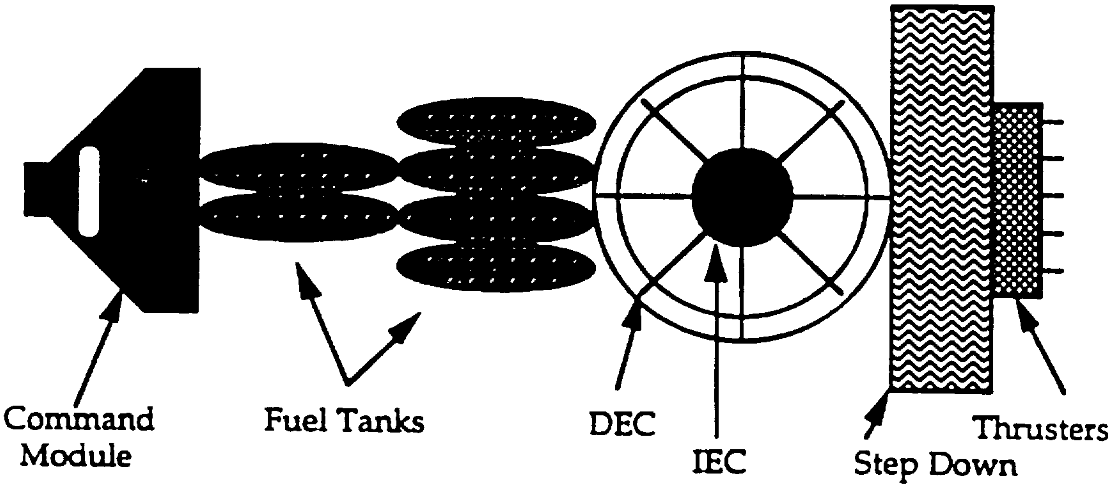


CONCLUSION

A schematic drawing of the approximate positioning of the various components is shown in Fig. 8. As discussed earlier, the propellant tanks are located between the IEC and command module to provide shielding from IEC neutrons. The step-down and pulse forming subsystem, located between the IEC and the thrusters, required added shielding for sensitive electronic components.

This design must be viewed as very preliminary, since many issues have been uncovered that require much more exploration before the feasibility of this concept can be fully verified. However, the results confirm the initial view that the IEC could provide an exceptionally attractive spacecraft for deep missions such as MARS, provided the physics of this approach works out as anticipated. Thus, in the present design, a 21-MW IEC provides the power needed for the hybrid thrusters giving 340 N and an I_{sp} = 3000 sec. in a spacecraft configuration of overall weight of 300 metric tons. This allows an attractive 120-day trip time to Mars for a manned exploration mission.

Figure 8. Possible configuration of the IEC fusion rocket components



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REFERENCES

1. N. Schulze, "Fusion Energy for Space Missions in the 21st Century", TM4298, NASA Headquarters, 1991.
2. G.H. Miley, et al., Advanced Fusion Power: A Preliminary Assessment, Committee on Advanced Fusion Power, Air Force Studies Board, Commission on Engineering and Technical Systems, National Research Council, Washington, DC: National Academy Press (1987).
3. G.H. Miley, ed., Proceedings, Minicourse on Fusion Applications in Space, ANS Topical Meeting on Fusion Technology, Salt Lake City, UT, 9 October 1988.
4. R. Chapman, G.H. Miley, and W. Kernbichler, "Fusion Space Propulsion with a Field Reversed Configuration" Fusion Technology, 15, 2, Part 2B, 1154 (1989).
5. G.H. Miley, J.H. Nadler, T. Hochberg, O. Barnouin, and Y.B. Gu, "An Approach to Space Power," Vision-21 Symposium, NASA Conf. Publ. 10059, 141, Cleveland, OH (1991).
6. R. Nachtrieb, O. Barnouin, B. Temple, G. Miley, C. Leakeas, C. Choi, and F. Mead, "Computer Model for Space Propulsion Using Dense Plasma Focus," 18th IEEE Intern. Conf. on Plasma Science, 155, Williamsburg, VA (1991).
7. N.R. Schulze, G.H. Miley, and J.F. Santarius, "Space Fusion Energy Conversion using a Field Reversed Configuration Reactor," Penn State Space Transportation Propulsion Technology Symposium, 453-499 (1990).
8. E. Teller, A.J. Glass, T.K. Fowler, A. Hasegawa, J.F. Santarius, "Space Propulsion by Fusion in a Magnetic Dipole," Fusion Technology, 22, 1, 82 (1992).
9. R.W. Bussard, "Fusion as Electric Propulsion," J. Propulsion, 6, 567 (1990).
10. R.W. Bussard, "Some Physics Considerations of Magnetic Inertial-Confinement: A New Concept for Spherical Converging-Flow Fusion," Fusion Technology, 19, 2, 271 (1991).
11. N.A. Krall, "The Polywell™: A Spherically Convergent Ion Focus Concept," Fusion Technology, 22, 1, 42 (1992).
12. J.H. Nadler, G.H. Miley, Y.B. Gu, and T. Hochberg, "Characterization of an Inertial-Electrostatic Confinement Glow Discharge (IECGD) Neutron Generator," Fusion Technology, 21, 1639 (1992).
13. W.W. Salisbury, "Method and Apparatus for Producing Neutrons," U.S. Patent No. 2,489,436, issued Nov. 29, 1949, filed Dec. 17, 1947.
14. P.T. Farnsworth, "Electric Discharge Device for Producing Interactions Between Nuclei," U.S. Patent No. 3,358,402, issued June 28, 1966, initially filed May 5, 1956, rev. Oct. 18, 1960, filed Jan. 11, 1962.
15. R.L. Hirsch, "Inertial-Electrostatic Confinement of Ionized Fusion Gases," J. Appl. Phys., 38, 11, 4522 (1967).
16. J. Javedani, Y. Yamamoto, and G.H. Miley, "Development of a Novel Neutron Source with Applications in Calibration and Monitoring," APS Division of Plasma Physics Meeting, 8S26, 1581, Seattle, WA (1992).
17. G.H. Miley, J. Javedani, R. Nebel, J. Nadler, Y. Gu, A. Satsangi, and P. Heck, "An Inertial-Electrostatic Confinement Neutron/Proton Source," Proceedings, Third Intern. Conf. on Dense Z-pinches, Imperial College, London, 19-23 April 1993.