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MARS MANNED FUSION SPACESHIP

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Fusion Propulsion has an enormous potential for space exploration in the near future. In the twenty-first century a usable and efficient fusion rocket will be developed and in use. Because of the great distance between other planets and Earth, efficient use of time, fuel, and payload is essential. A nuclear spaceship would provide greater fuel efficiency, less travel time, and a larger payload. Extended missions would give more time for research, experiments, and data acquisition. With the extended mission time, a need for artificial environment exists. We address the topics of magnetic fusion propulsion, living modules, artificial gravity, mass distribution, space connection, and orbital transfer to Mars.

The propulsion system is a magnetic fusion reactor based on a tandem mirror design. This allows a faster, shorter trip time and a large thrust-to-weight ratio. The fuel proposed is a mixture of deuterium and helium-3. Helium-3 can be obtained from lunar mining. There will be minimal external radiation from the reactor resulting in a safe, efficient propulsion system.

INTRODUCTION

The use of fusion power will be a major development in space travel. Last year, a design project was started on a manned Mars mission using fusion propulsion. This year's design team has continued the analysis on the spacecraft with a general emphasis on the living quarters design.

Due to the extended length of a Mars mission, there is a need for artificial gravity. A state of zero gravity tends to weaken the body by bone decalcification, diminishing bone marrow, reduced tone and atrophy of the heart and lungs. We have chosen to create a 0.8g environment in order to reduce design implications and yet have a healthy environment.

The initial design, Figure 1, incorporates a ring of modules about the magnetic fusion reactor supported by four radial shafts. To produce artificial gravity, the modules will be spun about the axis of the ship to produce constant gravity around the ring. Spinning the modules too fast will cause motion sickness of the astronauts. A study done by the Navy[1] reports that for spin rates less than 5 rpm, people will lose all effects from motion sickness within 24 hours. A radial velocity of 4.2 rpm will produce the 0.8g environment.

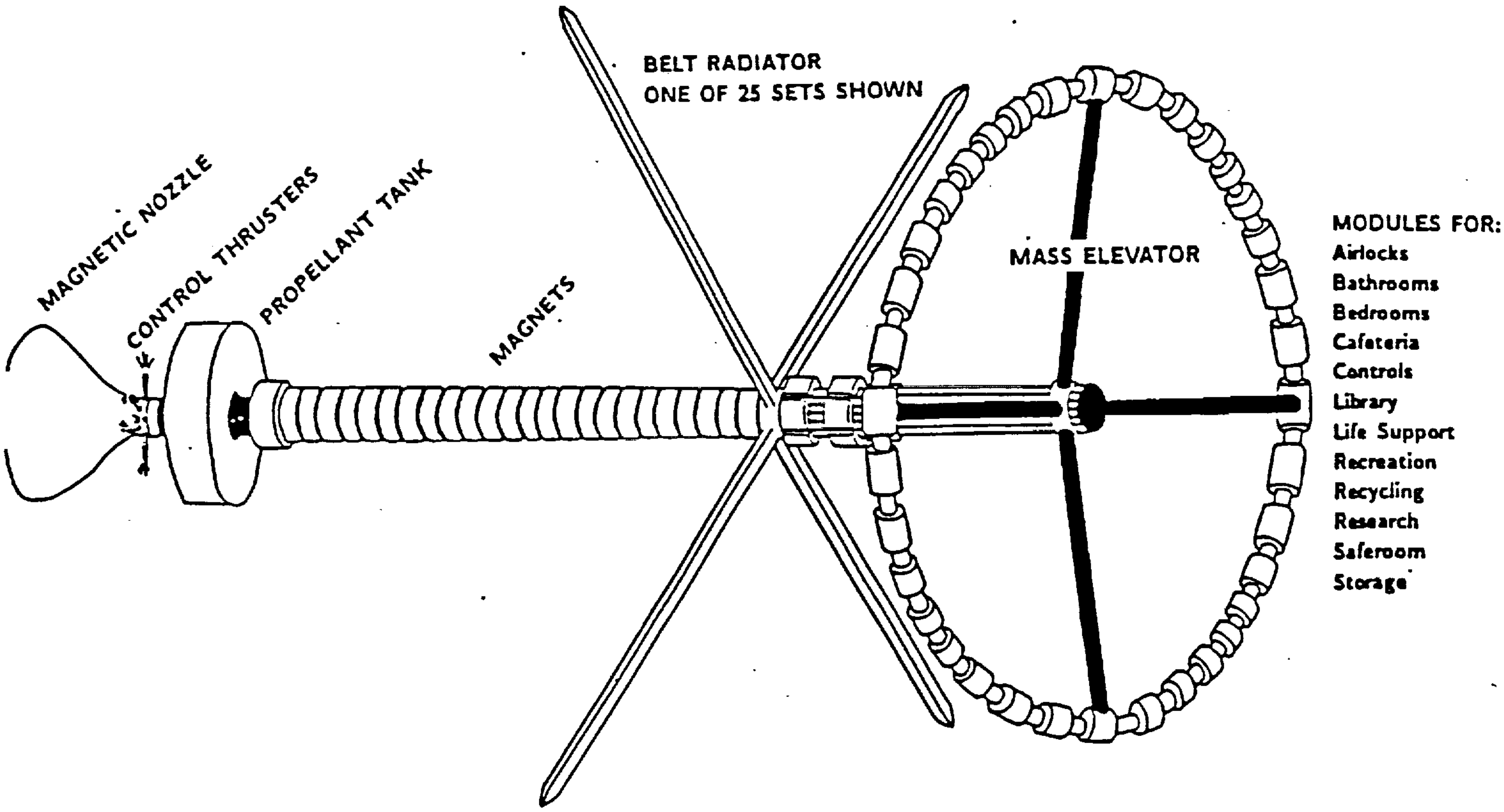


Fig. 1. D-^{3}He Fusion Propulsion Reactor Design with Living Quarters

Due to cosmic radiation, the living modules needed to be constructed out of a material to shield the crew while also having a high strength-to-weight ratio. For this purpose, the modules are made out of an aluminum-lithium alloy.

Each individual module was chosen to be an enclosed capsule consisting of 3 joined cylindrical pieces. They are 4 m in diameter and approximately 7.3 m in length. When coupled together, the 36 modules form a ring with a 80 m diameter. The modules were not chosen to be curved since disorientation occurs when one walks on what feels to be a flat surface, but appears curved.

In this paper, we present most of the design work our team did along with a brief description of the power system.

POWER SYSTEM

The power source chosen as the basis of the present design is a linear magnetic fusion reactor. The fuel cycle, deuterium and helium-3 (D-^{3}He), produces over 95% of its power as charged particles, which are confined by a magnetic field and guided to provide direct thrust. Most of the present fusion research effort focuses on a different fuel, deuterium-tritium (D-T), which gives 80% of its power as neutrons. The copious neutrons from D-T fuel lead to more massive radiation shielding requirements and to the use of a thermal cycle for energy conversion, with consequent low efficiency, large radiator mass, and a separate system for converting electricity to thrust. The choice of a linear design, the tandem mirror, provides the benefit of allowing direct thrust by guiding the fusion plasma along magnetic field lines and out the end of the magnetic 'bottle.' Linear configurations, however, are less developed than their toroidal counterparts, such as the tokamak, which more easily confine a plasma, but are more difficult to configure for direct thrust.

The specific configuration used is based on the D-^{3}He tandem mirror reactors designed for use either on Earth[2] or in space[3]. The basic principal of the designs is that plasma losses out the end of a linear magnetic field configuration are greatly reduced by a combination of increasing the magnetic field (creating a 'magnetic mirror') and by generating an electrostatic potential to enhance ion confinement. A key critical issue is verifying tandem mirror physics for reactor conditions. The main parameters for the design are given in Table1[3]. Note that 77% of the fusion power is converted to thrust, and that the specific power of the fusion propulsion system is 1.2 kW/kg, including radiators.

Table1. D-^{3}He Tandem Mirror Fusion Propulsion System Design Parameters.

Specific power	1.2 kW_{thrust}/kg
Fusion power	1960 MW
Thrust power	1500 MW
Thrust efficiency	77%
Input power	115 MW
Thermal power (Bremsstrahlung and synchrotron radiation, neutrons, plasma not usable for thrust)	574 MW
Total mass	1250 Mg
Total length	113 m
Midplane outer radius	1.0 m
Main magnetic field	6.4 T
^{3}He to D density ratio	1
Neutron wall loading	0.17 MW/m^2

LIVING MODULES

Stress Analysis

The thickness of the module walls was earlier determined to be 4 cm thick[9] to shield the living quarter from cosmic radiation present in the solar system. The stress calculations of the module shell have resulted in the fact that stress is not a design constriction for the module shell. This thickness is almost twice as that needed to safely contain the environment of the modules.

The modules were modeled as a beam rigidly fixed at both ends in cylindrical coordinates. A continuous load developed by the module and cargo masses per radian multiplied by 0.8g is applied to the beam. From standard calculations, the maximum shear and normal stresses can be found. By using a Mohr's circle analysis the maximum shear stress was found to be on the order of 22 MPa. This value is well below the maximum allowable shear stress for the aluminum-lithium alloy.

Spacedoor

A door is needed between modules to isolate the module in case of emergency such as wall rupture, toxic gases, or a fire. There will be a door present between each of the 36 modules. The door must operate in low temperatures, hold 14.6 psi pressure, and close automatically at high speed. A sandwich panel is used for the door because of its light weight and high strength. An aluminum honeycomb 13.5 cm thick is sandwiched between two titanium sheets, each 0.25 cm thick. The door is 187 cm high and 93.1 cm wide having a total mass of 10.7 kg. The bottom and top edges are rounded in shape to prevent the corners from curling and to press equal force around the edge on the seal.

The door slides on tracks and can be closed by a spring or electric motor. The door can also be opened and closed manually. Sliding in tracks allow the door to be close faster in response to emergency. A control system would be needed to release and close the door. A pressure difference between modules will push the door against an O-ring seal resulting in an effectively sealed doorway. The door can also be sealed manually if there is no pressure difference.

Pressure Loss

An important calculation for the module door design is the time for the pressure to fall from one atmosphere to a minimum value of 55 kPa for human habitation[4]. If this time is known, then we can design the door drive system to close the door in that time. As a 'worst case' assumption, we chose the puncture size to be greater than door size, so we can use the door size which gives a nozzle area of 1.67 m^2.

The calculation begins by determining the critical pressure ratio for sonic flow through the opening. The ratio of space pressure to internal pressure will always be less than critical since space is at 0 kPa. With sonic flow, the weight flowrate equation[5] gives a flowrate of 3000 N/sec.

To obtain a loss time, we used initial and final conditions to find the specific volume of the air and from there find the mass of air which left the spacecraft. For one module, the fastest time of pressure loss is 0.03 sec and for the entire living quarters, the time is 1.14 sec.

Thermal Radiation Loss

The question was raised as to whether the living quarters could be used to dissipate some of the heat generated by the reactor. To determine the emissive power of the living quarters, we took the maximum emissivity e of aluminum (0.84) and found what kinds of power values we can expect to emit at different locations. We chose three cases for exchange: the spacecraft at Earth orbiting at Lagrange Point 1, the ship orbiting at Mars, and the ship radiating to empty space.

From Incropera and DeWitt[6], we can use the radiation exchange equation:

$$q_m = (E_{bm} - J_m) \times (e \times A_m) / (1 - e)$$

where: E_{bm} = blackbody radiation from a module
A_m = surface area of a module

The radiosity of the module is:

$$J_m = (e \times E_{bm}) + (1 - e) \times G_m$$

The irradiation to the module is:

$$G_m = (A_p \times E_{bp} \times F_{pm} + A_s \times E_{bs} \times F_{sm}) / A_m$$

where: A_p = surface area of planet
E_{bp} = blackbody radiation from planet
F_{pm} = view factor of module by planet
A_s = surface area of the sun

E_{bs} = blackbody radiation from the sun
F_{sm} = view factor of module by the sun

The view factors are calculated after reading the view factors of the planet or sun by the ship off of a graph from Chapman[7].

We have determined the radiation from the living quarters at Earth to be 1.15 MW[8]. At Mars the radiation is 1.21 MW and in empty space the heat loss is 1.22 MW. This is not enough heat loss to be used as an effective radiator and insulation of the modules is not a major design consideration.

RADIATION SHIELDING

Shadow shielding

Since there will be some external radiation present from the reactor, the living modules must be shielded to protect the astronauts. A dose of 2.5 millirem/hr[10] is an amount of exposure that can be exposed to humans. Shadow shielding was the first idea since it seemed logical that a shadow shield close to the module would provide the required protection and minimize the mass of the shield. This method of shielding takes advantage of the $1/r^2$ fall off over the distance from the reactor to the modules. Boric acid (H_3BO_3) was chosen as the shielding material because of its shielding effectiveness and low density. The boric acid shield includes a steel tank in calculations (5% of the weight, about 4-5 cm thick). A shield thickness of 1.75 meters and a total mass of 3.89×10^6 kg is needed to shield the modules in this way.

Reactor Cover Shielding

The shielding mass for the shadow shielding seems to be a quite large number. Because of the large mass of the shield, a second shield calculation was done for a shield around the reactor. The shield thickness is 1.37 meters and mass of this type of shielding is 1.97×10^6 kg about half of the shadow shield requirement. Diagrams of these two shielding methods are shown in figure 2.

Although it would seem that the reactor cover shield would seem a better alternative, it was initially neglected because of the heat produced by the reactor. A complex method of cooling the magnets would be needed, if even possible, to cool the magnets so they do not melt. The shield may need to be a few centimeters thicker because to a cooling system. However, if possible, this would still be the lightest shield.

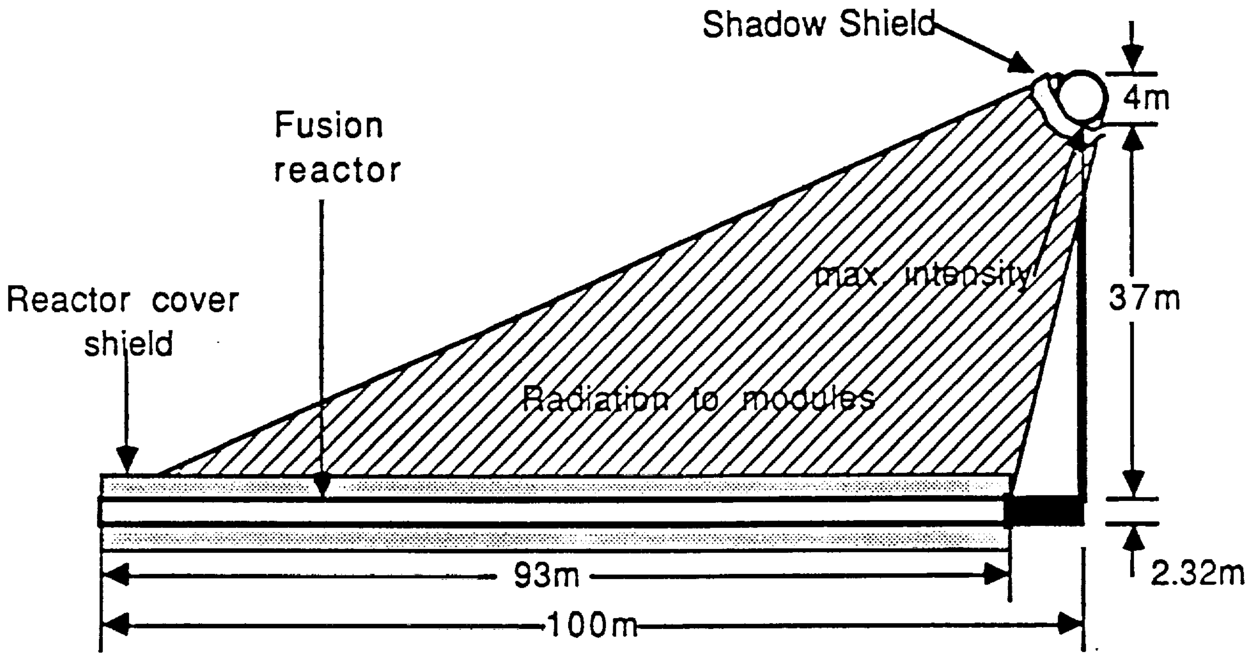


Figure 2. Diagram of reactor radiation

MASS ELEVATORS

One problem with rotating the living quarters is that the stability of the spacecraft is offset with changes in the distribution of mass around them. To account for these small changes, we incorporated masses in the four radial support shafts which move with crew movement so that the mass center remains at the rotational center of the ship.

In order to determine how large the moving masses have to be, we must find the worst mass distribution problem. As an estimate, we assumed that 52.5% of the mass is evenly distributed on one side of the living modules while the remaining 47.5% is distributed on the other[8]. The corresponding mass elevator is moved out to its furthest position to keep the mass center at the longitudinal axis of the spacecraft. For a total living quarter mass of 13000 Mg, each mass elevator is calculated to be 481 Mg. We decided that the elevators must be as dense as possible for them to fit into such a small volume, so we decided to make them out of cast iron. The mass would be cylindrical with a radius of 1.8 m and length of 6.15 m.

Since the moving mass introduces a Coriolis acceleration, we must be careful not to move them too fast so that the force exerted on the support shafts is tolerable. A maximum velocity of 0.1 m/s was chosen, however, no stress analysis was done on the shafts.

ELEVATOR SHAFTS

The living quarters is held in place by four radial spokes or shafts. These shafts are also used for housing the 'mass elevators' or movable masses which correct for uneven mass distribution.

These shafts were designed to be 38 m in length and and outside diameter of 4 m with a 13.2 cm thickness[8]. The design needs to be analyzed with the Coriolis force mentioned earlier and does not represent a final decision.

We did choose to make the shafts out of Al 2014 for its ability to remain tough in cold temperatures and for its high strength-to-weight ratio.

MASS ESTIMATE

As in any space mission, mass reduction is a critical part of design. We have started with an allowable mass of 13.000 x 10^6 kg for the life support system. The life support masses were determined by adding the masses of several significant components: Mass elevators, module shell, and radiation shielding. This was subtracted from the total allowable mass. The remaining amount is considered to be the payload. The radiation shielding is by far the heaviest component of the five. The masses of each of the components are given in table 2. Note that the pay load is more than half of the mass of the life support system. The reactor and radiator masses will be on the order of about 2 x 10^6 kg. Payload will then be about 45% of the total mass, which is very good for a trip of this length.

Radiation shielding	3.890 x 10^6 (kg)
Elevator masses	1.920 x 10^6
Module 'shell'	3.202 x 10^5
Elevator shaft	1.780 x 10^5
Payload	6.692 x 10^6
Total mass	13.000 x 10^6 (kg)

Table 2. Component masses

SPACE COUPLING

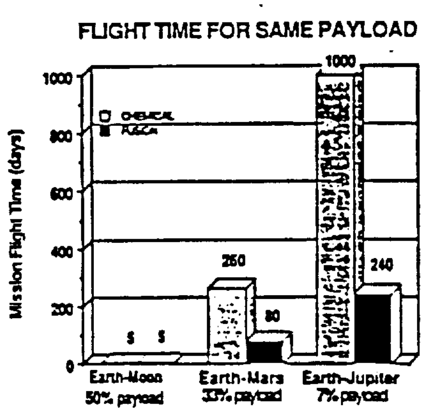
The modules and spaceship will be assembled is space before operation. Initially the modules will be brought together and held magnetically. Magnets are ideal for space, since they require no mechanical force to implement. Magnets can also be used to orient the modules correctly before permanent coupling is made.

The modules will be more permanently secured with some type of mechanical device which can be operated from within the modules themselves. This will save time and money from having to secure the living quarters with spacewalking operations.

LOW THRUST TRANSFER

Much emphasis has been placed on the use of low thrust propulsion systems, such as fusion power, to propel spacecraft to other planets. Missions beyond the moon need faster trip times and with larger payload fractions than chemical rockets[3]. The key to satisfying these needs is high exhaust velocity, since payload fractions depend exponentially on $-(v_f - v_i)/v_{ex}$. A low thrust fusion propulsion system also has many other advantages over a chemical system:

- High specific power values
- Direct conversion of energy to thrust
- Thrust-mode flexibility over a wide range of thrust-to-weight ratios and specific impulses



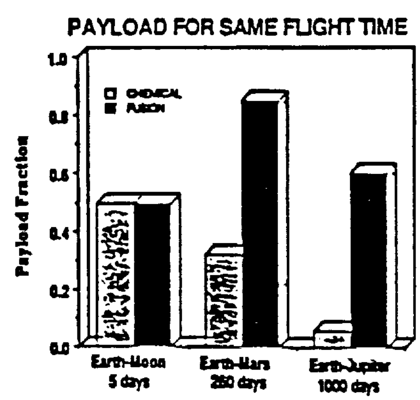


Fig. 3. Flight Time and Payload Comparisons

As with any transfer, we would like to optimize payload and transfer time. For a trip to Mars, our low-thrust rocket will use about 70% less fuel than a high thrust chemical rocket with comparable transfer times.

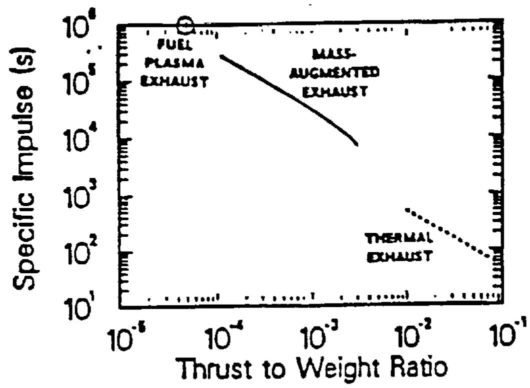


Fig. 4. Thrust to Weight Ratio vs. Specific Impulse

The analysis of transfer is broken up into three stages: the escape, the transfer, and the capture. In the transfer, one can obtain two differential equations from the equations of motion. To solve, one needs to use computational techniques using 6 boundary conditions and selecting acceleration components which produce these restraints[11]. Another analysis technique which we could use is to manipulate energy equations and differentiate to maximize payload or minimize transfer time[12].

Several calculations for the trip have been done by Stuhlinger[12] for motion in a central gravity field. For one particular trip, he showed that, using variable thrust, and Earth to Mars trip would take 178 days at an acceleration of 1.6×10^{-4} Earth gravities with a resulting payload fraction of 0.40.

CONCLUSIONS

We have covered a wide range of topics in our work. This is one indication of the enormous size of such a project and how much work is left to do. We have laid the basic foundations for future design and have not run across any major design problems.

Our work has covered the areas of module dimensions and stresses, module door analysis, initial coupling processes, mass distribution correction procedures, radiation shielding requirements, and the low thrust analysis used for travel to other planets.

Future work may include design of the drive system for the doors, the drive system for the mass elevators, finding coupling power requirements, and look at possible windows for launch to Mars or Jupiter.

ACKNOWLEDGEMENTS

Special thanks to Dr. J.F. Santarius and Ron Thomson for their help and support throughout this semester. Funding provided by NASA through NASA Lewis Research Center.

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