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FUSION ROCKET CONCEPTS

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ABSTRACT

This paper presents a study of steady-state thermonuclear rocket systems. Such systems, if they become feasible, are characterized by high specific impulse and relatively low specific mass. These features make them potentially attractive for manned exploration of the solar system and other high-energy space missions. The objectives of this paper are: (1) to estimate achievable specific masses; (2) to identify the differences between ground power and space propulsion applications; (3) to identify critical problem areas; and (4) to suggest priorities for future research needs. Specific masses were estimated to range from 1 to 0.5 kg/kW for rockets in the 200 to 1000 MW jet-power range respectively. Fusion rockets should provide variable specific impulse from 2500 to 200 000 sec for optimum propellant utilization. Two of the major challenges in the application of fusion to space propulsion are: (1) efficient extraction of energy from a toroidal reactor in the form of charged particles; and (2) efficient conversion of the charged particle energy into jet power.

INTRODUCTION

As part of its research program on advanced propulsion concepts, NASA Lewis Research Center is studying the feasibility of thermonuclear power for propulsion. Although controlled thermonuclear reactors have not yet been achieved, the present state of the world-wide fusion effort and its present rate of progress make it likely that the feasibility of controlled fusion will be demonstrated in this decade (Ref. 1). Even after such a laboratory demonstration, however, there are many severe problems to overcome before fusion power plants on earth or in space can be constructed. Some problems are common to both applications, while others are peculiar to either the ground power plants or to the fusion rocket.

Many excellent review articles exist on the status of world-wide fusion research presenting discussions of both the fundamental plasma problem and the technological problems of fusion reactors (see for example, Refs. 1 to 3). The purpose of this paper is not to add another review article, but rather to point out how the unique requirements of space propulsion will influence the selection of the fuel cycle, the confinement scheme, the plasma heating methods, and the structural design.

Previous sytems studies of the fusion rocket (Refs. 4 to 6) gave estimates of specific masses and identified the major system components. Both the previous and present studies

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concur that a specific mass of about 1 kg/kW jet should be achievable. It is fairly conclusive that a closed geometry is needed to attain these specific mass estimates (Refs. 6 and 7). The extraction of charged particle energy from closed systems and guiding these particles into a unidirectional beam is one of the challenging problems. Power balance calculations for the D-He-3 fuel cycle (Ref. 8) indicate that if a large fraction of fusion energy is to be extracted in charged particle form, cyclotron radiation losses must be minimized. This imposes important constraints on plasma confinement requirements and on wall reflectivity for cyclotron radiation. These matters are touched upon in this paper.

For this paper only the mass of the basic rocket engine is considered. Other components such as crew shielding and energy storage systems for restart are briefly discussed in Ref. 6.

Concepts presented in this paper are for steady-state or continuous-operation of the fusion reactor. Pulsed fusion reactions are also being considered for ground and space applications. Pulsed rockets for space are considered elsewhere in this Symposium.

FUSION ROCKET CONCEPT

To explain how we could apply fusion energy to a propulsion system, refer to Fig. 1. This is a simple schematic of a fusion rocket. A fusion fuel, here taken to be a mixture of deuterium and helium-3, is injected into the reaction chamber. Only a few percent of the injected fuel undergoes fusion reactions. The fusion energy heats the unreacted fuel to extremely high temperatures. At these high temperatures the fuel is a fully ionized gas or plasma. Magnetic fields are used to hold the plasma fuel away from the reaction chamber walls and to guide it into a nozzle mixing chamber. Hydrogen propellant is injected into the mixing chamber and is ionized and heated by the hot plasma ions that come from the reactor. The thermal energy of the propellant is converted into directed motion in the magnetic nozzle to produce thrust. Mixing with a propellant is required because the escaping fusion-reaction products by themselves would have a specific impulse in the range of 200 000 sec - far beyond the optimum value for planetary propulsion times and estimated specific masses.

Some of the potential advantages of the fusion rocket are apparent from this simple schematic. First, we note that the fuel directly heats the propellant. This advantage is also common to the solid-core and gaseous-core fission-rockets. Direct propellant heating eliminates the need for a major onboard power generating system, such as used in the nuclear-electric rocket. Waste heat can therefore be rejected at a maximum temperature, thus minimizing the radiator mass. This results in one of the major reductions in specific mass over the fission nuclear electric rocket.

For optimum propellant utilization, the specific impulse should be variable during a given mission. By throttling the hydrogen propellant flow, the specific impulse of the fusion rocket could be varied from 2000 up to 200 000 sec (Ref. 9). This is particularly important for the difficult manned missions where specific impulses greater than 3000 sec are required (Ref. 6).

Another attractive feature of fusion rockets is that it may be possible to achieve negligible radioactive waste in the exhaust. For example the fuel cycle may be adjusted to minimize the tritium formed in the D-D side reaction. This feature should simplify development and testing phases on the ground. Furthermore, it reduces contamination of the space environment and it can result in substantially lower shielding mass for the crew.

Finally, a fusion rocket is inherently fail safe since there is no critical mass as in a fission reactor. The lower hazard in a fusion system relative to a fission system could result in considerable cost savings.

The deuterium-helium-3 fusion reaction is shown on Fig. 2. A deuterium ion, consisting of one proton and one neutron, collides with a helium-3 ion, consisting of two protons and one neutron. Upon fusion, one heavier particle, and one lighter particle is formed, a helium-4 ion and a proton respectively. The fusion energy shows up in the form of kinetic energy of the reaction products, with the proton carrying away about 80 percent of the energy. These high energy reaction products collide with the other fuel particles and heat them to very high temperatures.

The D-He-3 fuel cycle permits most of the fusion energy, carried by the charged reaction products, to be transferred to the unburned fuel (Ref. 8). Because the reaction products are charged, they readily exchange energy with the main body of plasma, and they can also be confined by the magnetic field. Furthermore, only a small amount of fusion energy is released to energetic neutrons by a side D-D reaction. Neutrons are the main source of heat load on the superconducting magnets. This is an important factor since large amounts of refrigation equipment are very heavy. In contrast, if the helium-3 is replaced by tritium, about 80 percent of the fusion energy would be released in the form of energetic neutrons. The neutrons pass through the plasma and deposit their energy in the shields surrounding the reaction chamber. The D-T fuel cycle is suitable for ground power where thermal energy output can be used, but it is unsuitable for the fusion rocket where charged particle energy is required. Also, the large flux of energetic neutrons from the D-T reaction would necessitate massive neutron shields to prevent excessive magnet heat loads.

The plasma ions must have a very high temperature. Both fuel ions, deuterium and helium-3, carry a positive electric charge. As they approach each other, they experience a mutual electrostatic repulsion. If the fuel ions are to overcome the electrostatic barrier and come close enough so that the nuclear forces can interact, they must approach with extremely high kinetic energies. According to energy balance calculations an optimum temperature is about a billion degrees (100 keV) for the dueterium-helium-3 reaction if energy loss by cyclotron radiation is negligible (Ref. 8).

Other important reactor operating parameters can also be determined from the energy balance calculations. The fusion power production is proportional to the square of the fuel number density. For the power levels under consideration, the particle density is about 10^{21} particles per cubic meter. This is about 1/10,000 of the particle number density in our atmosphere. However, because of the high temperatures, the pressure in the reaction chamber is about 150 atm.

In a steady-state reactor, the energy released by fusion must equal the energy lost from the system by radiation and by escaping particles. Although the plasma does not radiate like a black body at 10^9 K, it emits electromagnetic radiation. Even in a well-designed system (negligible cyclotron radiation losses) at least 15 percent of the fusion will be lost by radiation (bremsstrahlung). But most of the energy will be carried away in the hot plasma escaping from the reactor. Energy balance calculations indicate that the mean residence time of a particle in the reaction chamber must be on the order of one second. If this residence or confinement time is less than about one second, then more energy will be removed from the plasma than is produced by fusion and the reaction will fizzle out.

As mentioned above, magnetic fields are used to confine these particles inside the reaction chamber for this relatively long time. The fields will range from about 5 to 20 T (50 to 200 kG).

Fig. 3 illustrates how magnetic fields help to increase the confinement time. In the absence of magnetic fields the plasma would rapidly diffuse to the walls in about a microsecond, which is far less than the required one second confinement time. Since all the plasma particles bear an electric charge, they interact strongly with a magnetic field. This is illustrated in the upper right-hand corner. The dashed lines represent the magnetic field lines. The trajectory of a single charged particle is a spiral about the magnetic field line. Hence, the particle is effectively prevented from moving across the field lines, but is able to move freely along the field lines. In a plasma, collisions between particles knock them across the field lines. The real effect of the magnetic field is to drastically reduce the diffusion perpendicular to the field lines. Next we must reduce the particle losses parallel to the field lines. One possible way to reduce the parallel losses is by increasing the magnetic field strength at the ends of the system as shown in the lower left-hand figure.

The trajectory of a charged particle moving into a stronger field region is illustrated in the lower right-hand corner of the figure. The particle experiences a force pushing it toward the weaker field region. Therefore the parallel speed of the particle is reduced and the spiral becomes tighter and more of the particle energy is contained in the velocity components perpendicular to the magnetic field. If the initial parallel speed is low enough the particle will be stopped and forced back toward the weaker field region. We say that the particle has been "reflected" by the stronger magnetic field and therefore refer to these strong field regions as "mirrors."

Incidentally, the magnetic nozzle operates on the same principle, namely that a plasma always experiences a force pushing it toward the weaker field regions. Since the hydrogen propellant is ionized, it can be accelerated in the magnetic nozzle fields where the thermal energy in components perpendicular to the magnetic field is converted into directed energy along the nozzle axis.

To make fusion attractive for space propulsion, superconducting windings must be used to produce intense magnetic fields over the large reactor volumes. In the superconducting state a material offers no resistance to the flow of electric current. To attain the superconducting state the windings must be cooled nearly to absolute zero - commonly with liquid helium to about 4 K. Although superconducting magnets require no electrical power to maintain the electric current in the windings, they do require a refrigeration system to maintain the magnets at these very low temperatures. Since the refrigeration system is fairly massive, and electric power is required to operate the refrigeration plant, magnet heating must be minimized.

The main source of magnet heating is neutrons. With the D-He-3 cycle side reactions of deuterium with deuterium produce a significant number of neutrons. The plasma also radiates bremsstrahlung energy in the x-ray and γ-ray spectrum. To achieve minimum propulsion mass, magnet heating is minimized by placing a bremsstrahlung radiation shield and neutron shields between the plasma and the superconducting magnets.

A schematic of the fusion rocket with the major components included is shown in Fig. 4. The helium cryoplant rejects its heat to the liquid hydrogen propellant at 20 K. The hydrogen leaves the cryoplant in the vapor state and then passes through the shields where it is further heated and dissociated prior to injection into the nozzle mixing chamber. Plasma escaping from the reactor impinges on the hydrogen, ionizes it and heats it. The thermal energy in the propellant is converted into directed kinetic energy in the magnetic nozzle.

Waste heat is removed from the reactor walls and primary shield by means of the liquid metal coolant loop. The liquid metal coolant flows through a space radiator where the heat is rejected at the maximum possible temperature (say 2000 K) to minimize the radiator mass.

REPRESENTATIVE DESIGN REQUIREMENTS

Representative design requirements for a fusion propulsion system are listed in

Table I. A major objective in this concept is to guide the escaping plasma into the rocket nozzle. At least 80 percent of the particles leaving the reactor should be delivered to the nozzle where they can heat the propellant.

The next line, entitled "conversion to propulsive power" means that 25 percent of the energy delivered from the reactor to the nozzle should be converted into propulsive power. A theoretical analysis (Ref. 9) indicates that the 25 percent figure is possible. The major loss is in the energy expended to ionize the propellant.

It is desirable that the energy loss from the plasma by radiation to the walls should be held to less than 20 percent of the fusion energy. This will probably require the use of reflectors to reflect the long wave-length (cyclotron) radiation back into the plasma.

Minimum magnet heat absorption requires a high electrical current density in the magnet windings. A high current density means that the solenoidal windings will be thin enough so that a large percentage of the neutrons will pass through the windings. A current density of 10^9 amp/m^2, about a factor of 10 higher than used in today's superconducting magnets, is desirable (Ref. 10). However, 10^9 amp/m^2 have been achieved in short sample, laboratory tests (Ref. 11).

Earthbound helium cryoplants have not been designed for minimum mass, so we have assumed a value of 10 lb/W, which is about a factor of five below existing systems. However, experts in the business say that this should be achievable (Ref. 5).

Finally, if the space radiator can be operated at 2000 K, then the radiator will not be a major portion of the specific mass. In a later section, estimates will be given of the specific mass of a fusion propulsion system based on the assumptions listed in Table I.

PARTICLE EXTRACTION SYSTEM

As already mentioned, one of the major jobs of the fusion propulsion engineer is to remove the charged particles from the reactor and deliver them to the nozzle. The earlier schematic (Fig. 4), which showed an open-ended magnetic mirror configuration, made the job look simple. Unhappily, it won't work that way. The particle confinement time in open-ended systems is orders of magnitude lower than the required 1 sec, in spite of the mirrors at the ends. In earthbound applications, fuel ions may be injected with very high kinetic energy to compensate for the end losses. However, the injection system requires large amounts of electric power to accelerate the incoming fuel ions. This would require a very large thermal power conversion system which would make the system too heavy for space.

To increase the confinement time, a toroidal magnetic field configuration is used as illustrated in Fig. 5. In this arrangement there are no end losses because there are no ends! The particles circulate around the torus, following the field lines, and slowly diffuse toward the walls. Note that this torus has a special section called a divertor which prevents particles from diffusing to the torus walls. As the circulating particles diffuse toward the wall, they eventually reach a field line that flows into the divertor section. And on their next pass around the torus they follow the field line into the divertor. This divertor is a simple concept, and according to R. G. Mills of Princeton Plasma Physics Lab (Ref. 12), only 3×10^{-5} of the escaping particles strike the wall. The remainder, 99.997 percent of the escaping particles, are caught by the divertor. Obviously, this is the kind of scheme we need for getting particles out of the reaction chamber. Next, they must be guided into a nozzle. The solution to this problem is not so obvious. An improved version of a scheme suggested earlier (Ref. 7) is a "partial" divertor as shown on Fig. 6. Since particles actually move in a very slow spiral about the minor axis of the torus, a large percentage of the particles may move into the removal area before reaching the walls. However, this is a complicated problem requiring extensive research to determine the exact shape of the field lines, and the charged particle trajectories. The use of electric fields has also been suggested for aiding the extraction process (Ref. 13). An artist's concept of a fusion rocket utilizing a partial divertor on a toroidal machine is shown in Fig. 7.

Just as an aside, if a partial divertor were effective, it could have important consequences for ground power applications. It might be used to convert the escaping charged particle energy directly into electrical power by means of an electrostatic conversion scheme suggested by R. F. Post (Ref. 14). Efficient, direct converstion could significantly reduce the thermal pollution of our environment.

Back to fusion propulsion. Experimental toroidal reactors do have much better plasma confinement, but it is still not good enough to produce a steady-state reaction. Inadequate confinement has been the major road block in the world-wide fusion program. Excessive loss rates are generally attributed to plasma instabilities or plasma turbulence. High frequency electric fields are thought to cause rapid diffusion of particles across the magnetic field. However, over the last five years there has been a steady improvement in confinement times. At present, the most practical experimental toroidal reactors that have yielded best combination of density, temperature, and confinement time are the Tokamak machines. The success of the Tokamaks has lead many in the fusion research community to predict a feasibility demonstration within this decade (Ref. 1).

SPECIFIC MASS ESTIMATES

We have made specific mass estimates for fusion rockets assuming the required confinement times will be achieved. The assumed reactor geometry for these calculations is shown on Fig. 8. The reactor is a compact torus, with plasma radius, R, and with a major radius of 2R. This compact geometry requires minimum crew shielding against γ-rays and neutrons. The reactor components include primary and secondary shields, the superconducting windings, and structure to support the magnets. The structure is placed outside of the superconducting windings so that the entire structure does not have to be maintained at liquid helium temperatures.

Tungsten was assumed for the primary shield because of its good bremsstrahlung and neutron absorption characteristics and because it can be operated at the high temperatures required for efficient rejection of waste heat. Lithium hydride was assumed for the secondary shield because it is a good neutron absorber and is light weight. Since it must be operated below 680° C, it would be cooled by the hydrogen propellant.

Component masses were estimated in a manner similar to that presented by Englert (Ref. 5). However, for this report, the magnet heat load due to bremsstrahlung radiation was found to be negligible for primary tungsten shield thicknesses of 3.5 cm or greater. The primary shield thickness was set at 3.5 cm and the secondary lithium-hydride shield was varied in thickness to achieve a low rocket specific mass. Specific masses were estimated for two different superconductor current densities. The results of these calculations are summarized in Figs. 9 to 11. Fig. 9 is a plot of rocket specific mass in kilograms per kilowatt of jet-power as function of confining magnetic field in tesla (1 T is equal to 10 000 G). The upper curve is for 200 MW jet-power and the lower curve is for 1000 MW. The assumed refrigeration plant specific mass was 10 lb/W and the current density in the superconductors was assumed to be 10^9 amp/m^2. The minor radius of the plasma torus was respectively 1.0 and 1.35 m for the 200 and 1000 MW jet-power rockets. The specific mass is on the order of 1 to 0.5 kg/kW jet for a range of jet powers from 200 to 1000 MW. These results show a substantial improvement over the fission electric systems which have estimated specific masses of about 5 to 15 kg/kW jet (Ref. 6). Consequently, the fusion rocket offers about a factor of four faster round-trip times for manned exploration of the planets (Ref. 6). The fusion rocket could also provide quick round-trips to the moon for very large payloads.

The magnetic field was chosen as abscissa in Figs. 9 to 11. Confinement should improve as magnetic field increases, but the actual value which might be achievable is not yet known. The magnetic field must be great enough that its pressure equals or exceeds the pressure of the plasma it confines. (The magnetic pressure is proportional to the square of the magnetic field.) The ratio of the plasma pressure to the external magnetic pressure, denoted by β, must be less than unity. The upper limit of magnetic field will be set by materials considerations - either the characteristics of the superconductors or of the structural members. The current density which a superconductor will carry decreases with increasing magnetic field and at some "critical field", the material loses it superconducting properties and reverts to a normal conductor. For present superconductors, this critical field is less than 20 T. The stresses imposed on the structural members by such a field are at the same time approaching materials limits. Consequently, a value of about 20 T was taken as an upper limit for this parametric study.

The constant power curves slope upward with increasing magnetic field because the winding thickness, and the structure increase with field strength. Thicker windings absorb a higher percentage of the incident neutron energy.

Fig. 10 presents the distribution of specific masses among the various components for the 200 MW rocket. These specific mass calculations brought out one very important fact. Most of the system mass is due to the requirement that the superconducting windings be cooled to 4 K. The two shields and the refrigeration plant account for 70 percent of the 200 MW system at low fields and 45 percent at high fields. It is therefore essential to continue research on high field, high current density superconductors and low mass refrigeration plants.

Cryogenic refrigeration systems designed specifically for minimum weight do not exist because this has never been a requirement for ground-based operation. However, as mentioned above, cryogenic refrigeration experts say that with the existing technology, the cryoplants could be reduced in weight by as much as a factor of five. At working temperatures near absolute zero the Carnot refrigeration efficiency and the mechanical efficiency of gas working fluid refrigerators are both quite low. By employing the hydrogen propellant, at 20 K, as a heat sink for the refrigeration cycle, a reasonable Carnot efficiency (25 percent) can be achieved. However, the mechanical efficiency for gas working fluid refrigerators drops to about 10 percent or less for operation around 4 K.

However, an alternative to the gas working fluid refrigerator is the magnetic refrigerator (Ref. 15). Today's high-field large-volume superconducting magnets remove constraints that previously confined magnetic cooling applications to heat rejection temperatures around 4 K and source temperatures below 1 K. Magnetic fields of up to 15 T can significantly order the spins of a paramagnetic system at temperatures as high as about 50 K. Mechanical efficiencies as high as 72 percent have been estimated for the magnetic refrugeration cycle (Ref. 16). Such efficiencies would significantly reduce refrigeration masses - perhaps as low as 0.5 to 2 lb/W. For such lightweight refrigeration systems, the thickness of the primary tungsten shield could be reduced to meet only the minimum structural requirements for the vacuum wall, say about 2 cm. The seceondary shield thickness could also be reduced. Fusion rocket specific masses might be reduced by a factor of two below the values shown in Fig. 9. There still remains one constraining factor, however. If the magnet heat load exceeds the heat sink capacity of the hydrogen propellant, heat rejection via a radiator at relatively high temperatures could reduce the Carnot efficiency sufficiently to nullify the gains in mechanical efficiency.

Thus, a careful heat balance study is required to determine the optimum permissible refrigeration load.

The sensitivity of rocket specific mass to the assumed superconductor current density is illustrated in Fig. 11, which shows results for the 1000 MW system with two different values of magnet current density, 10^8 and 10^9 amp/m^2. Because the secondary shield is a very effective neutron absorber an order of magnitude decrease in current density results in only a factor of two or three increase in rocket specific mass. Much research has been sponsored on high intensity, large volume superconducting magnets (Ref. 17). As mentioned above present superconducting magnets have maximum current densities of a few times 10^8 amp/m^2. Short sample tests have indicated that 10^9 amp/m^2 is possible, but much research is still required to develop stable working magnets with these current densities.

Although a large world-wide research and development effort is underway on controlled fusion power, it is presently directed toward earthbound applications. The most promising toroidal reactor designs for ground power are not directly applicable to space propulsion. For ground application, practical toroidal reactor geometries require that at least one phase of the plasma heating process be accomplished by means of heavy iron-core transformers. This is illustrated in Fig. 12. The torus forms a single turn secondary of an iron-core transformer. A pulse of current in the primary induces a large electric current, tens of thousands of amperes, to flow in the plasma. This electric current then heats the plasma by resistive or I^2R heating. These iron cores and associated capacitor banks or other forms of energy storage are probably too heavy for space propulsion, and therefore some other means of heating the plasma must be found for space propulsion. In addition to heating the plasma, the Tokamak also depends on the induced current to produce a magnetic field component in the plasma which is essential to the confinement process. Therefore, the Tokamak, in its present form seems too heavy for space. However, a scheme has been suggested by T. Ohkawa (Ref. 18), in which injected ion beams would produce the Tokamak current with relatively low injection power requirements. Fortunately, other toroidal machines are not absolutely dependent on the circulating current, thus the torus is not ruled out for space.

Another problem with the present class of toroidal machines is that they are limited to very low beta values (less than a few percent) for stable operation (Ref. 19). For low specific mass systems, the value of beta should be as large as possible (see Fig. 9). Also, large beta values will help keep the cyclotron radiation losses to a minimum as discussed below. Therefore, it seems that the toroidal machines for fusion rockets will not be developed from direct extension of present experiments. However, in the literature (Ref. 19) there are discussed extensions of both the Tokamak and Stellarator concepts for operation at high beta. Included are techniques such as feedback stabilization.

The effects of cyclotron radiation on the potential performance of the fusion rocket are illustrated with the aid of Figs. 13 to 15. Fig. 13 is a plot of the fraction of reactor output power carried by the charged particles for the D-He-3 cycle as a function of reactor ion temperature. The parameter is the cyclotron radiation loss coefficient, C, which is a measure of the energy lost from the plasma by cyclotron radiation (Ref. 2 and 8). It accounts for the fact that the cyclotron radiation is partly reflected at the electrically conducting vacuum wall and partly absorbed in the plasma. It will take on more significance when Fig. 14 is discussed. The main point of Fig. 13 is that as C increases the fraction of reactor output power in charged particles decreases, and for C greater than 2.5, less than about 10 percent of the power output is in charged particles. The remainder of reactor output energy is in cyclotron and bremsstrahlung radiation which serve only as a burden on the fusion rocket. Increased radiation results in both a larger reactor for a given charged particle energy output, and a larger heat rejection system. Therefore the reactor should operate with C as close to zero as possible for the fusion rocket.

Fig. 14 shows the relation between C and the physical quantities of reactor, beta and vacuum wall reflectivity. To achieve a low value of C it can be seen from Fig. 14 that either a high value of beta or a very high value of reflectivity, or more likely, both are required. Values of reflectivity for radiation in the cyclotron frequency spectrum and for a tungsten wall at 2000 K have been estimated to be 0.99 or higher. Fig. 14 is not suitable to determine the required values of beta for reflectivities above 0.99. For that purpose Fig. 15 is presented, which shows a plot of required C against beta with reflectivity as a parameter. Fig. 15 shows that for values of C less than 0.01, values of beta greater than 0.6 will be required, even for reflectivities as high as 0.998. Although the curves presented in Figs. 13 to 15 are obtained from a simplified theoretical approach, they still serve to indicate the potential importance of cyclotron radiation in the future development of the D-He-3 fuel cycle for space propulsion applications.

MAJOR RESEARCH AND DEVELOPMENT REQUIREMENTS

Table II is a list of the major research and development requirements for three different fusion applications: (1) laboratory feasibility demonstration; (2) ground power; and (3) fusion rocket. The number of X's reflects both the relative difficulty as well as the importance of the requirement. The confinement goal has not yet been achieved, and it is obviously a difficult task. If a D-He-3 fuel cycle is used for the fusion rocket, the required confinement parameter $n\tau$ (product of density and confinement time) is about a factor of five higher than for ground power requirements. As confinement is improved, start-up and heating requirements will be less severe. However, ignition of a self-sustaining fusion reaction is still the focal point of the present world-wide research effort. Efficient heating methods will be exceedingly important in the economics of ground power. For space, the heating and restart problems are crucial. The space system ignition requirements must be minimized. Also, efficient, lightweight energy storage and transformation systems must be developed. Either chemical or electromagnetic storage systems may be used.

While divertors are not presently used on the Tokamak machines, they are an essential component of the fusion rocket. Divertors might someday be used in conjunction with direct conversion schemes for ground power. The jet mixing chamber and nozzle are essential to the fusion rocket. A nozzle and jet mixing chamber might also find application in the fusion torch concept (Ref. 15).

Although high beta operation does not appear crucial to the economics of ground power, the fusion rocket requires it for low specific mass and possibly for adequate reduction of cyclotron radiation. Cyclotron radiation should be minimized to assure that the maximum amount of fusion energy is carried by the charged particles.

While superconducting magnets are not essential to the feasibility demonstration, economic considerations will require the use of superconductors for efficient production of ground power. In space, high current density magnets or high critical temperature superconductors will be needed to reduce specific mass to minimum. Lightweight, efficient cryogenic refrigeration plants are essential to the fusion rocket.

Although a tritium breeder blanket is not required for space, the question of availability of helium-3 is not yet answered. Finally thermal engineering and reliability are equally important for ground and space applications. The heat transfer problems in going from about a billion degrees to 4 K over relatively short distances are indeed not trivial. Great ingenuity will be demanded possibly involving the use of heat pipes and special radiation shields.

There are many refinements that can be made to the mass estimates reported herein. For example, more exact shield calculations should be made such as a Monte-Carlo calculation which include the effects of gamma decay radiation and multienergy groups of neutrons. Laminated shield designs should be considered. Proper consideration should be given to the heat balances in the coolant circuits. Realistic heat removal systems can be studied. The feasibility of placing all support structure outside the superconducting windings should be determined through engineering analysis. Specific mass should be determined for several torus aspect ratios.

CONCLUDING REMARKS

In conclusion, for fusion propulsion systems in the jet-power range of 200 to 1000 MW, specific masses on the order of 1 to 0.5 kg/kW jet may be possible. This represents considerable improvement over the estimated values of 5 to 15 kg/kW jet for a high-power fission electric propulsion system. The improvement over fission-electric propulsion results from elimination of the thermal power conversion equipment and heavy, lower-temperature radiator.

An important research area is the removal of particles from the reactor and delivery to the nozzle. At present there is no research aimed at solving this problem. Propellant heating and production of thrust is another key area for which some theoretical work has been done at Lewis Research Center (Ref. 9). This theory was based on simple coulomb collisions as the energy transfer mechanism. Hopefully, some form of turbulent heating might be triggered to get more of the reactor plasma energy into the propellant. Jet-mixing and magnetic nozzle experiments could be devised to test the theory.

In all of the above discussion we have been assuming a steady-state fusion reactor. Pulsed fusion reactors are also being considered. We do not rule these out for space propulsion.

Obviously, the status of controlled-fusion research means that the sizes and masses estimated here are only first approximations. The best that can be said is that, so far, nothing has turned up that rules out the eventual achievement of specific masses considerably lower than those achievable with nuclear-electric propulsion systems.

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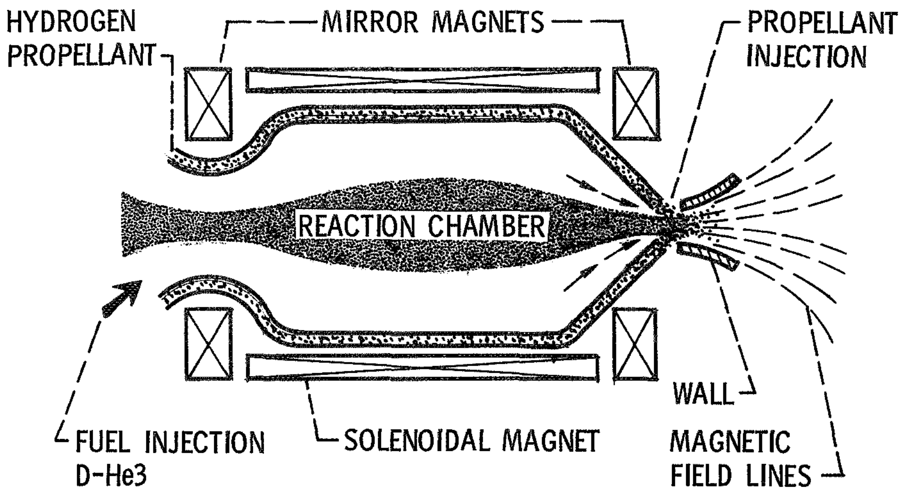
TABLE I. - REPRESENTATIVE DESIGN REQUIREMENTS

Particle delivery to nozzle	>80%
Conversion to propulsive power	~25%
Radiation to walls	<20%
Minimum magnet cooling load	$J = 10^9$ amp/m^2
Refrigeration mass	<10 lb/W
Space radiation temperature	~2000 K

TALBE II. - MAJOR RESEARCH AND DEVELOPMENT REQUIREMENTS

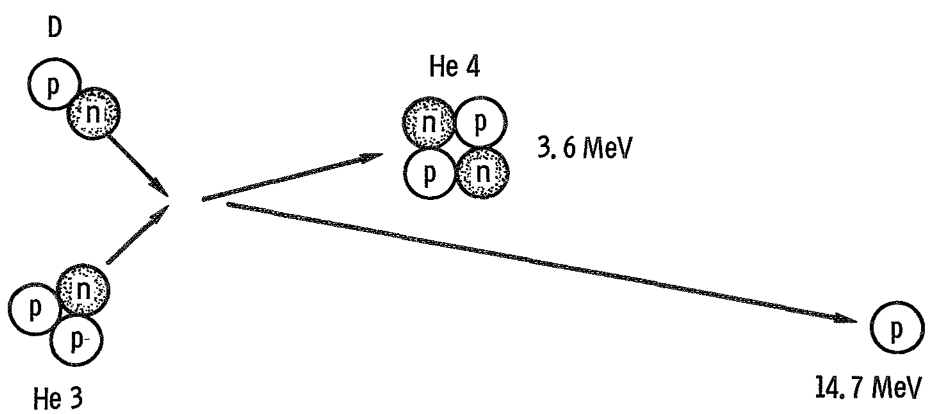
Area	Lab	Ground	Space
Confinement	XX	XX	XXX
Start-up, heating	X	XX	XXX
Divertor	?	?	XXX
Jet mixing chamber and nozzle	-	?	XXX
High-beta operation	-	-	XX
Synchrotron radiation	-	X	XX
Superconductors	-	X	XX
Refrigeration	-	X	XX
Breeder blanket	-	XXX	-
Thermal engineering	-	XX	XX
Reliability	-	XX	XX

E-6298



CS-55898

Figure 1. - Fusion rocket schematic.



CS-55904

Figure 2. - D-He 3 Fusion reaction.

E-6298

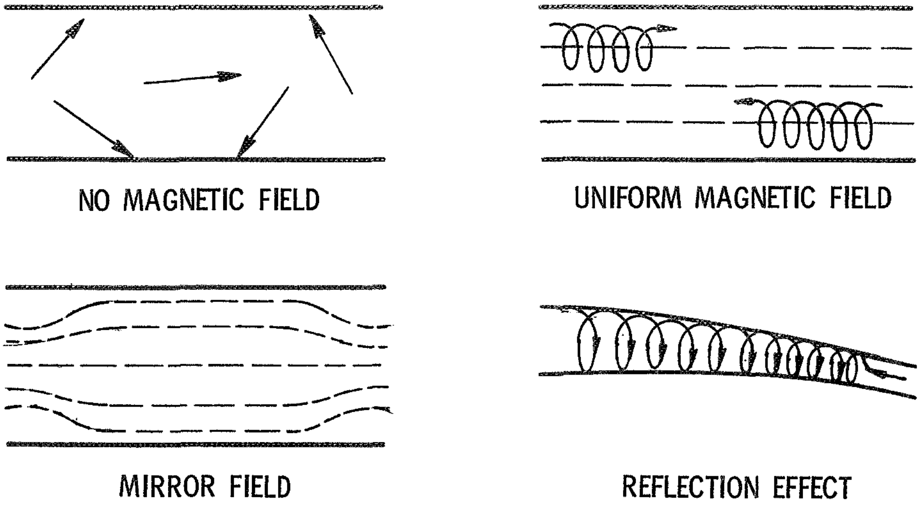


Figure 3. - Charged particle motion in magnetic fields.

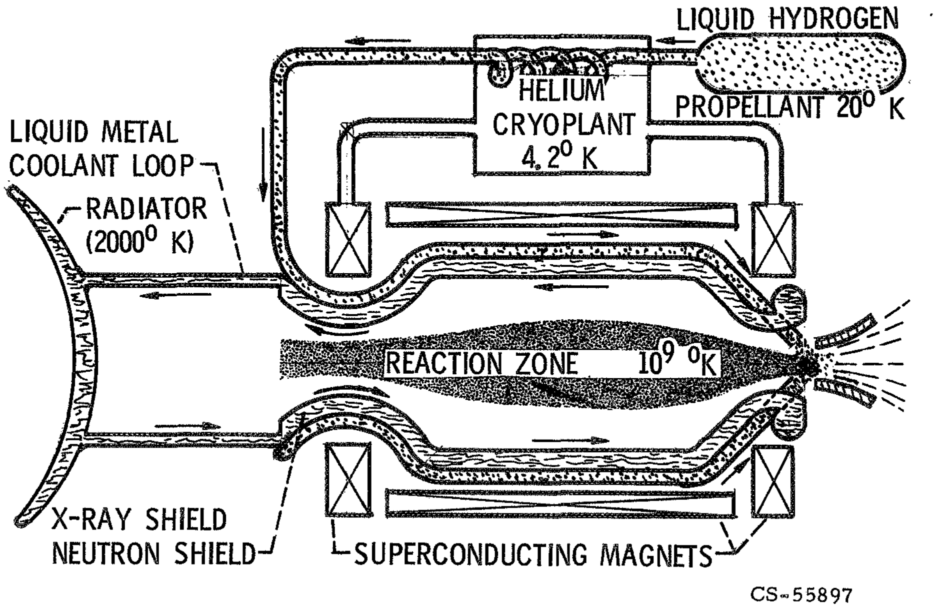


Figure 4. - Fusion rocket schematic.

E-6298

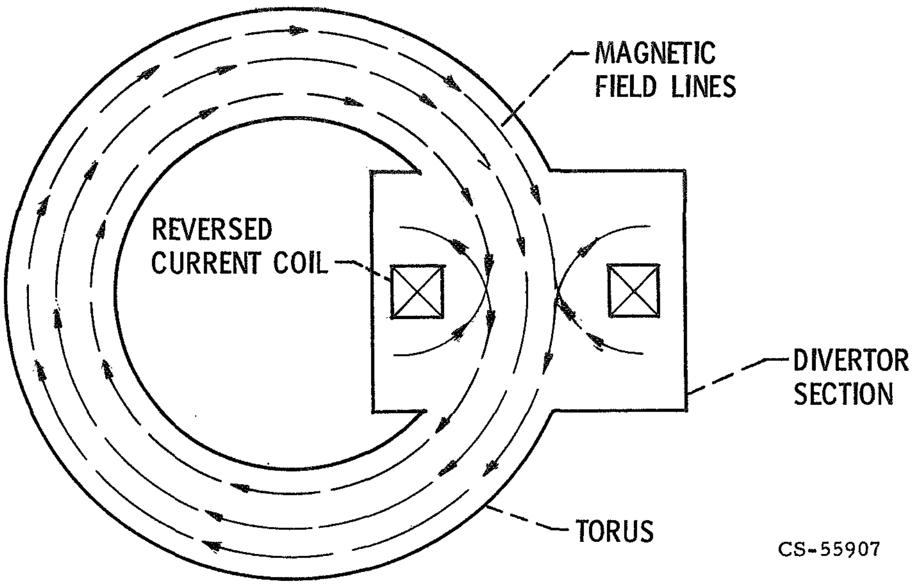


Figure 5. - Torus with divertor.

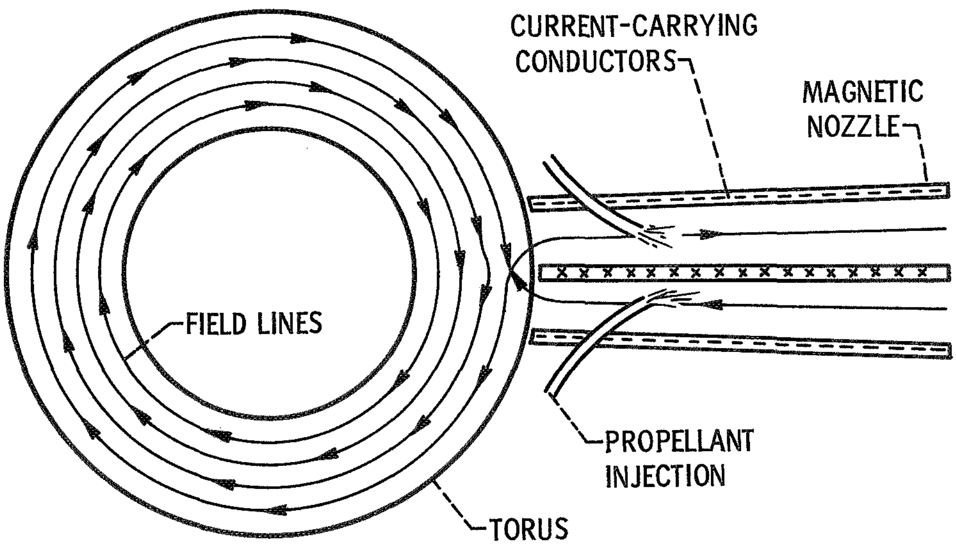


Figure 6. - "Partial" divertor for propulsion.

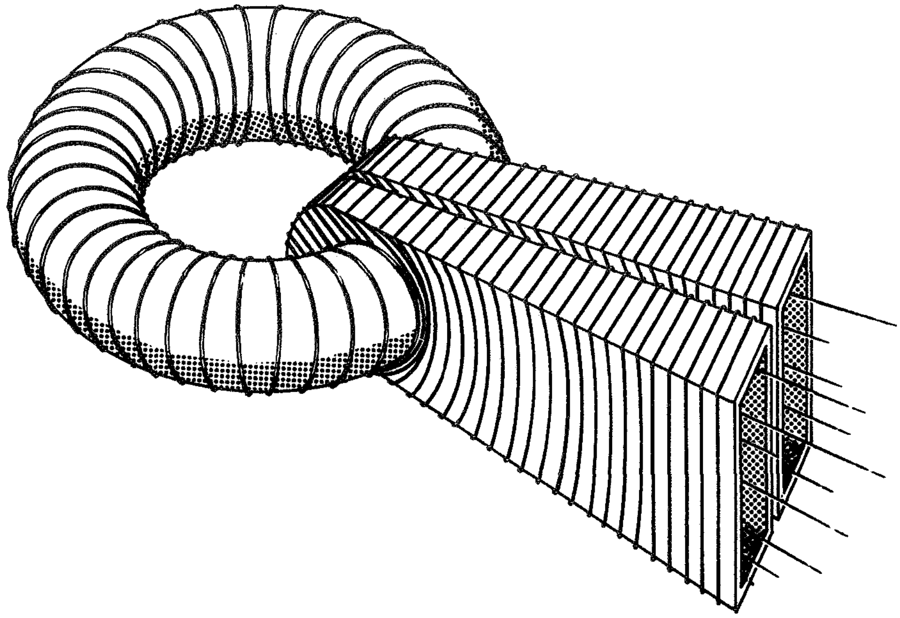


Figure 7. - Divertor concept for propulsion.

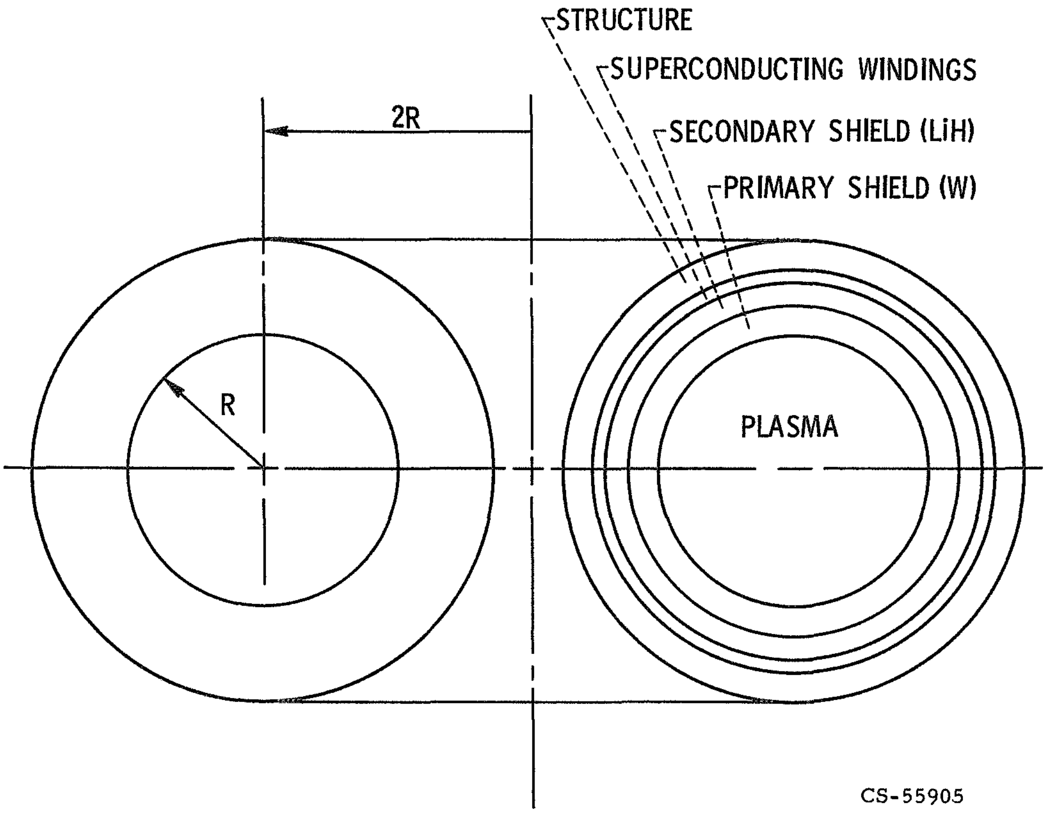


Figure 8. - Toroidal reactor cross-section.

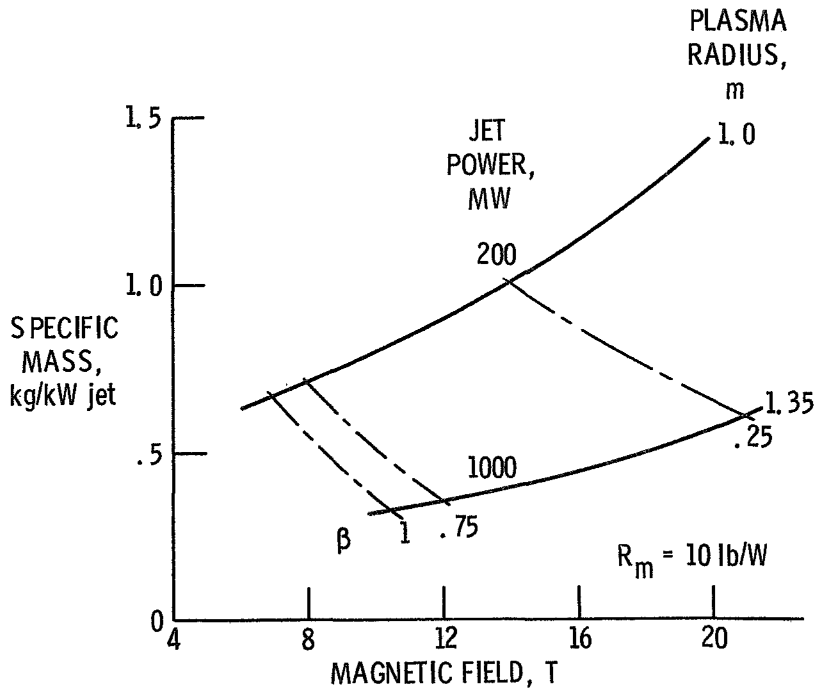


Figure 9. - Fusion rocket specific mass.

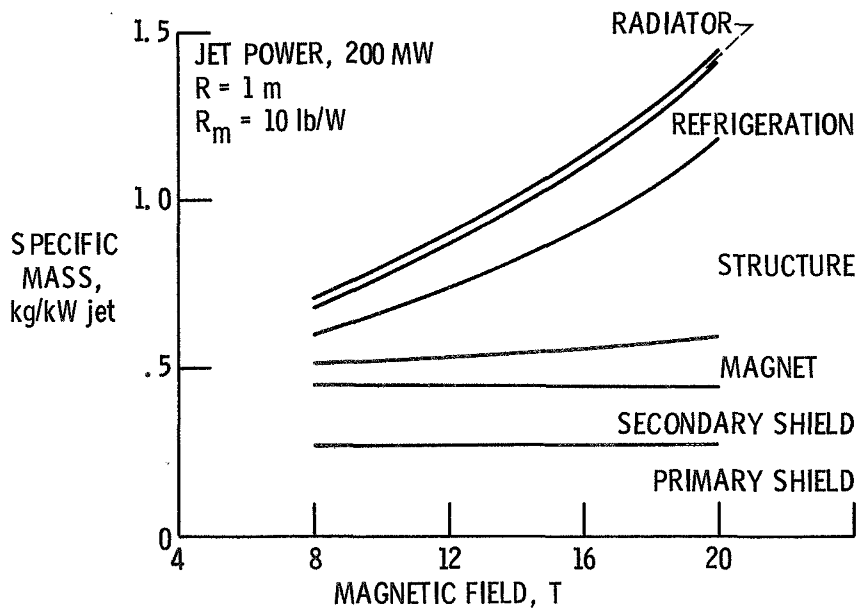


Figure 10. - Distribution of specific mass.

E-6298

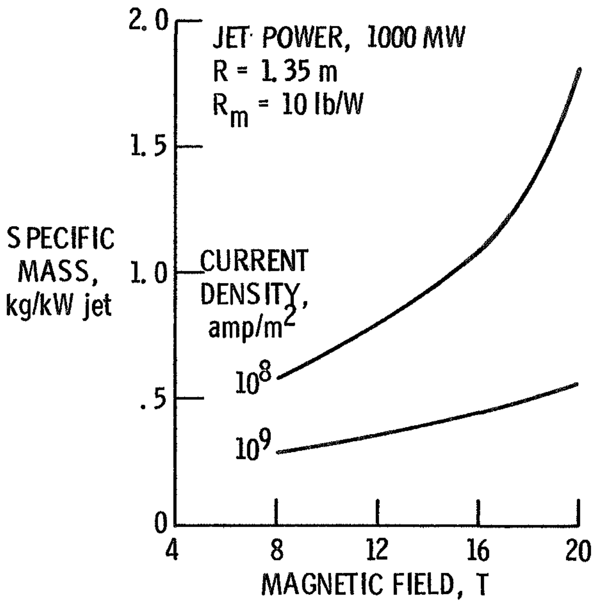
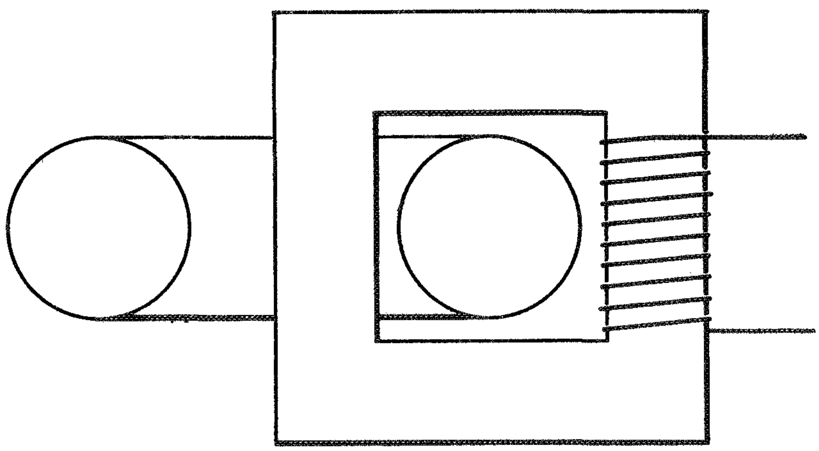


Figure 11. - Fusion rocket specific mass for two magnet current densities.



CS-55901

Figure 12. - Toroidal reactor with iron core transformer.

E-6298

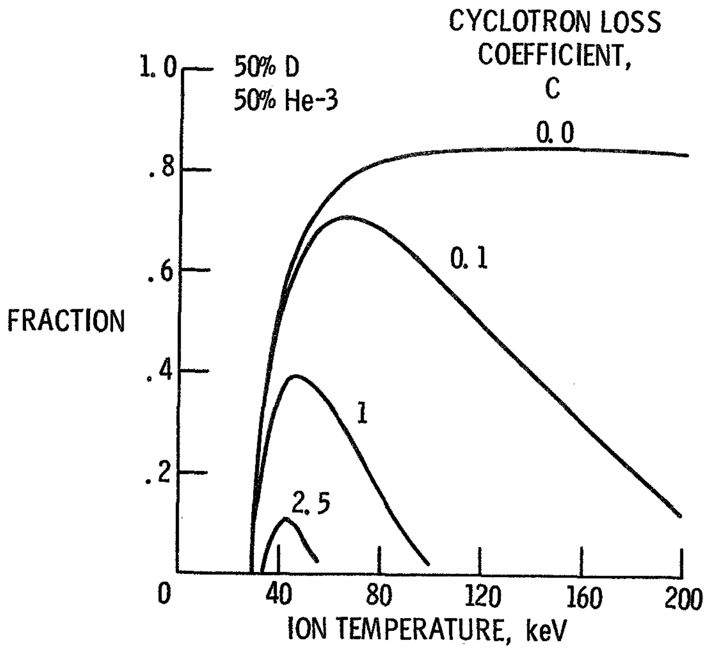


Figure 13. - Fraction of output power in charged particles.

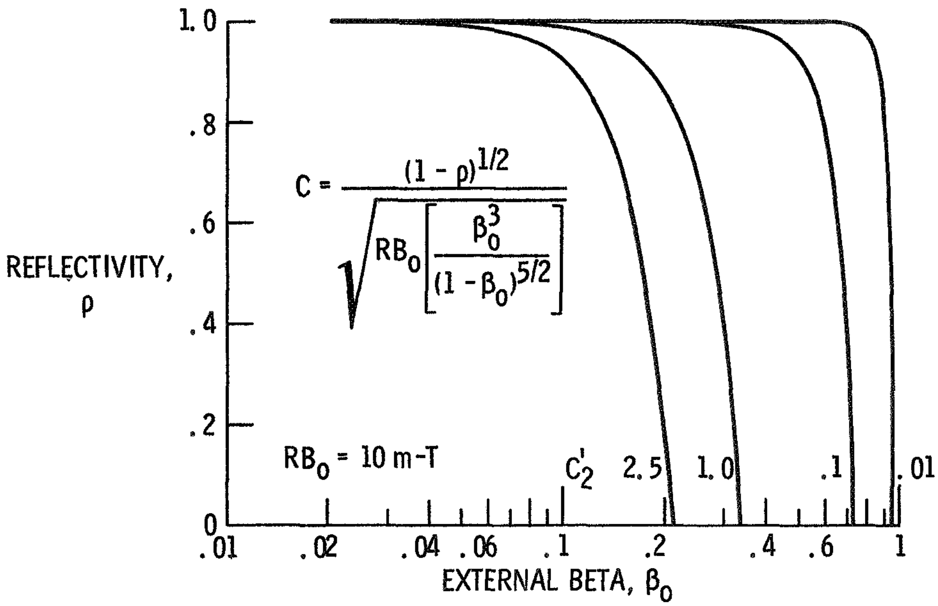


Figure 14. - Required vacuum wall reflectivity for cyclotron radiation.

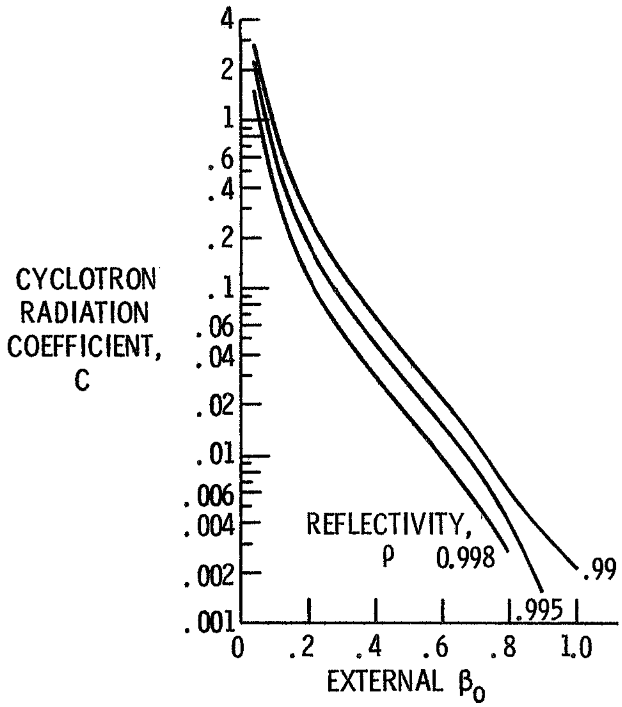


Figure 15. - Relationships among cyclotron radiation coefficient, reflectivity, and beta.