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SAFETY AND ENVIRONMENTAL CONSTRAINTS ON SPACE APPLICATIONS OF FUSION ENERGY

by

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Abstract

This paper examines some of the constraints on fusion reactions, plasma confinement systems, and fusion reactors that are intended for such space-related missions as manned or unmanned operations in near earth orbit, interplanetary missions, or requirements of the SDI program. Of the many constraints on space power and propulsion systems, those arising from safety and environmental considerations are emphasized in this paper since these considerations place severe constraints on some fusion systems and have not been adequately treated in previous studies.

Introduction

It is very probable that only nuclear fission or nuclear fusion energy will be capable of satisfying space-related requirements for more than a few hundred kilowatts of steady state electrical power. Early work at the NASA Lewis Research Center on fusion propulsion systems between 1958 and 1978 [refs. 1 and 2] examined the application of steady state fusion reactors, generating several hundred megawatts of thermal power, to direct fusion rockets for manned interplanetary missions. More recent design studies of fission and fusion space electrical power systems [refs. 3 to 6] have addressed the long-term needs of the strategic defense initiative (SDI) program, for which a requirement of 1 to 10 megawatts of steady state electrical power is anticipated, with a further possible requirement of up to several hundred megawatts of "burst" electrical power for periods of hours. A preliminary report on advanced fusion power for space applications of interest to the Department of Defense has recently been published by the National Academy of Sciences, under the sponsorship of the Air Force Studies Board [ref. 7]. The data in this report indicate that fusion power and propulsion systems may have a lower specific mass (kilograms per kilowatt of electrical power) than that anticipated for fission-electric systems.

Of the many constraints on fusion space power and propulsion systems, those arising from safety and environmental considerations will be emphasized in this paper, since these considerations place servere constraints on some fusion systems, and they have not been adequately treated in previous studies. This paper first discusses the safety and environmental factors which affect the selection of fusionable fuels, followed by a consideration of factors which affect the choice of confinement concept. Finally, some conclusions are drawn, on the basis of safety and environmental considerations, about the choice of magnetic vs inertial fusion; the best apparent choice of fusion reaction; and the constraints which magnetic containment concepts must satisfy for space applications.

Safety and Environmental Factors

Affecting Fusion Fuel Selection

Tritium in Space

Whatever the merits of the DT reaction for electric utility powerplant reactors [ref. 8], the constraints of the space environment, to be discussed below, make it desirable to consider other fusion reactions. Utilization of the DT, DD, or catalyzed DD reactions would necessitate the use of radiologically significant amounts of tritium in space, and one must ask whether the risks of doing so can be reduced to acceptable levels.

A benchmark for large-scale radiological accidents was established by the Chernobyl nuclear accident of April, 1986 [refs. 9, 10]. The approximate radioactive source terms and inventories associated with this accident are listed in the first column of Table I. As a consequence of this accident, approximately 50 megacuries of biologically inert noble gases, mostly krypton and xenon, were released into the atmosphere. An additional 50 megacuries of biologically active fission products were released and spread over a large portion of the Eurasian continent. It is instructive to compare these inventories with the radioactive inventories associated with the Starfire DT tokamak reactor [ref. 11], a gigawatt level powerplant fusion reactor. The Starfire reactor had a total tritium inventory of 11.6 kilograms, which is approximately 110 megacuries of volatile radioactive material. This is more than twice as great as the biologically significant (non noble gas) radioactivity released during the Chernobyl accident.

TABLE I

Fission and DT Fusion Radiological Hazard Comparison

1 GWE Operation for One Year

Reactor Characteristics	Chernobyl Accident	Typical LWR	Starfire DT Tokamak
Biologically Inert (noble) Gas Release, (MC_i)	~50	----	----
Biologically Active Radiation Release, (MC_i)	~50	----	----
Tritium Inventory (MC_i)	----	----	111
Nonvolatile Core/Blanket Inventory (MC_i)	1500	----	6140
Annual Radioactive Waste Production, Tonnes/Year	----	30-60	69

By comparing inventories and source terms in Curies, it is intended to provide an indication of relative public acceptability, public perception of relative risk, and relative immediate consequences of an accident. Such immediate consequences include exposure of operating staff and emergency crews, the necessity of evacuating large areas, and other emergency measures taken for public safety. Long-term consequences such as genetic or somatic damage to individuals or populations would require, in addition, consideration of the relative biological effectiveness (RBE) of each species released, along with its environmental pathway and source term. While the relative biological effectiveness may be useful for assessing the long-term consequences of a particular accident, it probably has little impact on the social acceptance of a nuclear technology prior to its introduction.

If a DT reactor were used in space, the penalties associated with a lithium breeding blanket for the tritium would probably be so great that tritium fuel would be supplied from ground-based sources. In a direct fusion rocket, or in a fusion-electric system based on a direct converter, it will be very difficult to recover the unburned tritium, and it is therefore prudent to assume that all unburned tritium is lost to space and unavailable for reinjection into the reactor. Since the burnup fraction [ref. 12] of tritium will likely be in the range from 5 to 30% for DT reactors, much more tritium will be required to fuel a reactor than is actually burned to produce electrical power or propulsion. Depending on power level, from 10 MWT to 1GWT, a space power or propulsion system might use from approximately 0.03 kilogram to 3 kilograms of tritium per day. Safety considerations make it necessary to be concerned both about lifting this tritium fuel into orbit in the first place, and then assuring that it does not re-enter the atmosphere.

The particles trapped in the earth's magnetosphere are supplied by the solar wind, and consist mostly of hydrogen with a small admixture of helium and other elements. If all of the hydrogen trapped in the magnetosphere were liquified, the liquid hydrogen would approximately fill an olympic-sized swimming pool. Thus, the total amount of matter in the magnetosphere is not very great, and one must be seriously concerned about the effects of adding charged particles or significant amounts of additional matter to that already present in the magnetosphere. The amount of matter in the magnetosphere is comparable to the propellant exhausted by many propulsion systems as they move through it. Since most particles trapped in the magnetosphere eventually find their way into the earth's atmosphere, one must be concerned about the possible effects of injecting tritium ions in the magnetosphere, which are later precipitated into the atmosphere by MHD instabilities.

If tritium or any other radioactive nuclear fuel is used in space, one must address the following accident scenarios: a) a Challenger-type accident in which the space shuttle ferrying the tritium into orbit blows up in the atmosphere and releases the tritium inventory; b) re-entry of the fuel inventory into the atmosphere as a result of atmospheric drag or an unintended change in the orbital elements of a spacecraft with a fusion reactor on board; or c) leakage of unburned fusionable fuel into the atmosphere by such routes as trapping of its ions in the magnetosphere, followed by auroral precipitation in the earth's atmosphere.

Neutron Fluxes in Space

Probably the single most important factor in optimizing a space power or propulsion system is to minimize the initial mass that must be placed in earth orbit, since transportation into orbit is very expensive. In consequence, there is a strong temptation to omit shielding to the maximum extent possible, in order to conserve mass. The 14 MeV neutrons produced by the DT reaction require at least a meter of shielding to be slowed down. A spectrum of blanket designs is possible, ranging from full shielding to a bare reactor. In very unusual circumstances, a partially or fully shielded neutronic reactor might be lighter than a bare aneutronic reactor, but this appears unlikely in view of the mass penalty of radiators and energy handling equipment required to deal with thermal energy deposited in the shield. Here, we assess the environmental consequences of the limiting case, a bare reactor.

It has not always been realized that unshielded fluxes of neutrons, charged particles, and x-rays can pose a serious environmental hazard over surprisingly large distances from an unshielded source. Let us consider a bare, unshielded fusion reactor, and focus on the consequences of an unshielded flux of neutrons from such a reactor. The flux of neutrons, ϕ_L, from a point source of S neutrons per second at a distance R_L is given by

$$\phi_L = \frac{S}{4\pi R_L^2} \text{ neutrons/m}^2 - \text{sec.} \tag{1}$$

The relationship between the power lost in the form of neutrons, P_N, the total fusion power, p_F, and the fraction of the power in neutrons, f_N, is given by

$$P_N = f_N P_F, \tag{2}$$

while the power in charged particles, P_C, is given in terms of the total fusion power produced by

$$P_C = (1 - f_N) P_F. \tag{3}$$

Combining Equations 2 and 3, the relation between the neutron power, the power in charged particles, and the fraction of the power in the form of neutrons is given by

$$P_N = \frac{f_N P_c}{1 - f_N} \qquad (4)$$

The source term from an unshielded fusion reactor generating neutrons is given in terms of the total neutron power, P_N, in megawatts, the electronic charge, $e = 1.60 \times 10^{-19}$ Coulomb, and the energy E_N of the individual neutron in MeV as follows,

$$S = \frac{P_N(\mathrm{MW})}{e\,E_N(\mathrm{MeV})} = \frac{f_N P_c(\mathrm{MW})}{(1 - f_N)eE_N(\mathrm{MeV})} \text{ neutrons/sec,} \qquad (5)$$

where Equation 4 has been substituted for the neutron power in Equation 5. Substituting Equation 5 into Equation 1, and solving for the standoff distance R_L, one obtains

$$R_L = \left[\frac{f_N P_c(\mathrm{MW})}{4\pi e\,\phi_L(1 - f_N)E_N(\mathrm{MeV})}\right]^{1/2} \text{meters} \qquad (6)$$

It is of interest to calculate the standoff distance based on radiological safety considerations for a typical fusion propulsion system. The design studies of references 1 and 2 indicate that a propulsion system utilizing a direct fusion rocket might require about 200 megawatts of charged particle power in the exhaust jet. For pure DT fusion, the fraction of the energy released in the form of neutrons is $f_N = 0.80$, and the neutron energy E_N is 14.1 MeV. The occupationally acceptable safe dose for 40 hour per week exposure to MeV neutrons is approximately 10 neutrons per square centimeter per second, or 10^5 neutrons per square meter per second. Since such a fusion propulsion system would start out orbiting the earth, the natural unit of length used to measure the standoff distance is the earth radius, R = 6378 kilometers.

The neutron fraction, neutron energy, and safe standoff distance under the above assumptions is shown for an unshielded fusion reactor with isotropic neutron production in Table II for 5 fusion reactions. The safe distance, beyond which the neutron fluxes are below the occupational standard, are also given in earth radii. Clearly, an unshielded fusion reactor will generate such a large neutron flux that no unshielded person or thing can approach safely within a very large distance of it. If one were to use a more demanding standard, like 10% of the background radiation level, for example, these standoff distances would be still larger. It should be noted that the same consideration applies to both unshielded magnetic and inertial fusion reactors, since the average of 200 megawatts for an unshielded propulsion system is based on the average power required for interplanetary missions.

TABLE II

SAFE DISTANCE FROM UNSHIELDED FUSION REACTOR WITH ISOTROPIC NEUTRON PRODUCTION

REACTION	NEUTRON FRACTION, f_n	NEUTRON ENERGY, E_n MeV	SAFE DISTANCE, R,KM	R/R_0
DT	0.80	14.07	16,800	2.6
DD	0.336	2.45	14,300	2.2
CAT DD	0.38	8.26	8,600	1.4
D^3He	0.02	2.45	2,900	0.45
p^6Li	0.05	1.75	5,500	0.86

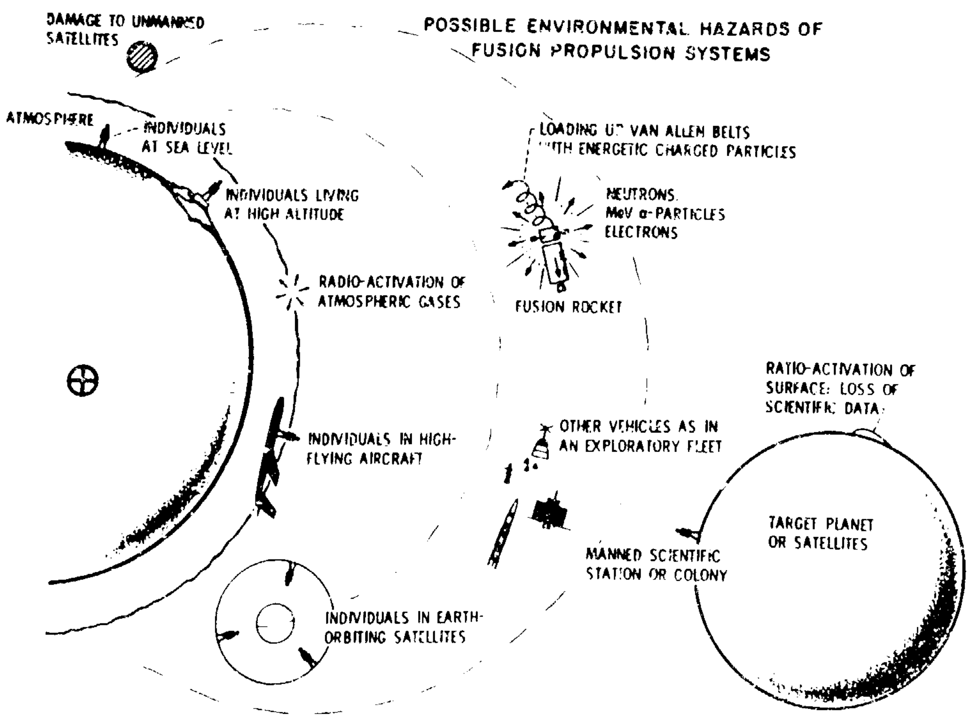
Assumptions:

a) 200 MW of charged particle power
b) Radiologically safe dose for continuous exposure to MeV neutrons: 10 neutrons/cm^2-sec
c) Earth radius R_0 = 6378 km

Some of the environmental hazards posed by an unshielded fusion reactor in space are summarized in Figure 1. These hazards could include the effects of neutrons, energetic reaction products, unburned fuel ions, electrons, and X-ray radiation. At least some of these hazards would result from the use of a bare reactor, regardless of the fusion reaction used. These forms of radiation could load up the magnetosphere with energetic charged particles; cause damage to unmanned satellites in earth orbit; damage other spacecraft, as in an exploratory fleet or a space shuttle; it could affect individuals in earth-orbiting satellites or in high flying aircraft; the radiation could activate atmospheric gases by direct interaction; and at optical frequencies, radiation could affect the work of individuals such as astronomers at high altitudes or even at sea level.

The detrimental environmental effects of an unshielded fusion reactor are not limited to low earth orbit. If such an unshielded fusion reactor or propulsion system were to approach another planet or satellite, the unshielded radiation could lead to activation of the surface and loss of scientific data. It could affect a manned scientific station or colony. Unshielded radiation on a target planet or satellite surface could alter or erase the cumulative effect of eons of integrated information from the solar wind, cosmic rays, or other long-term surface interaction processes.

The above considerations make it clear that neutrons should be shielded and not allowed to escape directly into space. If this is so, then their thermal energy must be disposed of. In space, the only way in which an isolated spacecraft can dispose of waste heat is by radiation, and the necessary radiators then represent a significant mass penalty which must be paid to accommodate the presence of neutrons. These considerations suggest strongly that the best way of avoiding what must be either a safety hazard or a mass penalty is to use fusion reactions which generate the minimum possible amount of neutron, radiant, or thermal energy.



Neutronic Activation of Structure

Both fission and fusion reactors will activate their shielding and structure to some extent. In fission reactors, activation arises from fission products and the interaction of low energy (below 1 MeV) neutrons with the core and shielding materials; in fusion reactors, the activation arises from 14.1 or 2.45 MeV neutrons which activate the material of the first wall and blanket. The magnitude of this activation is evident in the last line of Table I, where the nonvolatile core or blanket inventory is listed for the Chernobyl reactor at the time of the accident on April 26, 1986 [ref. 9, 10] and for the Starfire DT Tokamak after one year of operation [ref. 11]. These inventories were the result of about a year of full power operation at 1 gigawatt of electrical power output in each case. These inventories are, respectively, about 30 times and about 120 times the radioactive release of the Chernobyl accident, and are clearly much too large to dump into the atmosphere. Thus, any fission or DT fusion reactor, once operated in space, may become a serious radiological safety hazard upon re-entry into the atmosphere.

In low earth orbit, there is a narrow band of orbital altitudes within which manned operations are possible. Below approximately 300 kilometers, atmospheric drag is so large that the orbit of a space station would decay in a relatively short period of time; above about 500 kilometers, radiation fluxes from particles trapped in the magnetosphere are sufficiently high that sustained manned operations are not possible. Parenthetically, it is not generally realized that the Apollo astronauts acquired a whole body radiation dose of 50 rads during one round trip through the earth's magnetosphere. This is approximately 1/10 of the L-50 fatal dose.

Because of the hazard of the radioactive inventory of fission or fusion reactors, these reactors should be parked, after use, in a "nuclear safe orbit", that is, an orbit that is sufficiently high above the earth's surface that atmospheric drag will not cause the reactor to re-enter the atmosphere until the longest-lived radionuclide of any significance decays. For fission reactors, the lowest nuclear safe orbit is about 700 kilometers, thus placing the parking orbit for nuclear fission reactors beyond the 500 mile limit where manned operations are possible. The radionuclides in activated DT tokamak fusion reactors are, in most blanket designs, not as long-lived as those of fission reactors, and their nuclear safe orbit may be somewhat lower than the 700 kilometers appropriate for fission reactors.

The fact that the nuclear safe orbit is likely to be above the altitude band where manned operations are possible leaves open the possibility that a fission or fusion reactor associated with a manned space station might reenter the atmosphere. If it did so, the last line of Table I implies that an amount, in Curies, of radioactive material could be released into the atmosphere by the reentry process which would be about 30 times the Chernobyl release for a gigawatt fission reactor, and about 120 times the Chernobyl release for a DT fusion reactor comparable to the Starfire tokamak.

Availability of Fusionable Fuels

Most fusionable fuels are available for space applications in unlimited quantities. The only two fusionable fuels which may be in short supply are tritium and ^{3}He. Tritium has a half-life for decay into ^{3}He of 12.3 years,

$$T \xrightarrow{12.3\ \mathrm{YR}} {}^3\mathrm{He} + e \qquad (7)$$

and is not found to any significant extent in nature. ^{3}He is a stable isotope of helium, but is found with an isotopic abundance of only about one part in 10^6 on the surface of the earth.

Only a very limited number of fusion reactors will ever be required for space applications, and their fueling requirements will be far smaller than, for example, a ground-based fusion economy for the electric utilities. Thus, for space applications, it becomes possible to consider sources of tritium and ^{3}He which would not be feasible for ground-based electric utility applications.

In space, severe mass penalties will probably be associated with the recovery of unburned tritium fuel for reinjection into the plasma, or with any attempt to breed tritium on a space vehicle by the neutron-lithium breeding reactions [ref. 12, page 202] which have been proposed for ground-based electric utility DT powerplant reactors. The relatively small amount of tritium required for space missions, compared to the much larger amounts which might be needed in ground-based electric utility powerplants, should make it possible to increase the tritium breeding ratio of ground-based powerplants to an extent which will produce enough additional tritium for space missions.

Because of its extremely low isotopic abundance, very little ^{3}He will be available from natural sources on the earth's surface. Another source of ^{3}He is the decay of tritium, according to Equation 7 above, which is used for weapons and other purposes. It is likely that the total amount of ^{3}He which will be available early in the 21st century will be no more than a few hundred kilograms, an amount barely adequate for one or two space missions.

Other potential sources of ^{3}He include the decay of tritium specially produced by fission reactors for space missions; and semi-catalyzed DD reactors, following the suggestion of Miley, et al. [ref. 13], which are part of a ground-based fusion economy using DD reactions. The most promising source of large amounts of ^{3}He appears to be heating regolith on the lunar surface which has been implanted with ^{3}He over geological ages by the solar wind [refs. 7, 14]. It appears that essentially unlimited amounts of ^{3}He would be available for space missions from sources on the lunar surface, or the atmospheres of the outer planets or their satellites which have retained light elements in their atmospheres.

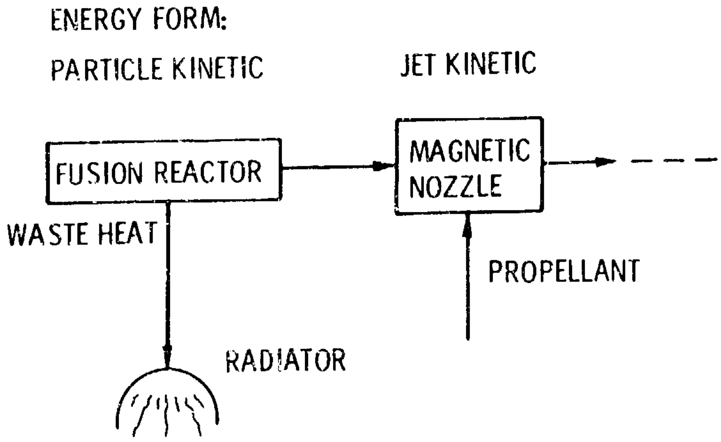
Safety and Environmental Factors

Affecting Confinement Concept

In this section some of the factors which affect the choice of confinement concept will be examined. This includes both the choice between inertial and magnetic fusion energy, and also the choice among magnetic containment concepts.

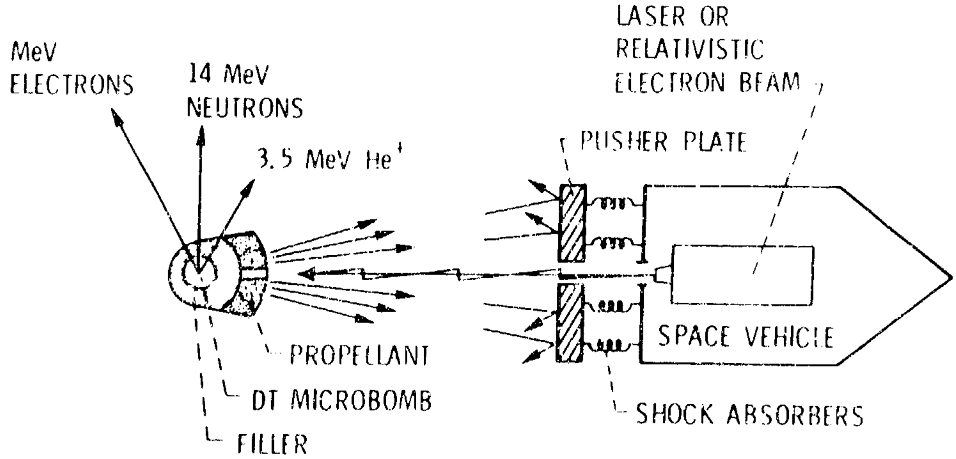
The most effective fusion propulsion system, which minimizes the size of the radiator required and the total mass, is the direct fusion rocket shown on Figure 2 [refs. 1,2]. In this propulsion system, the escaping unreacted fuel and reaction products are expanded in a magnetic nozzle, where they are mixed with cold propellant to achieve a unidirectional plasma jet with a spread of velocities, but an optimum mean exhaust velocity [Ref. 15]. If an aneutronic fusion reaction (one which produces few neutrons from all sources, including side reactions) is used, and if all the unburned reaction products appear in the exhaust jet, relatively little heat energy remains on board the spacecraft to be disposed of by massive radiators. This direct propulsion system may either require a very high burn-up fraction, or waste what might be a scarce or expensive fuel.

DIRECT FUSION ROCKET



On Figure 3 is shown one of many schemes put forward for space propulsion using inertial fusion. In this concept, a laser or charged particle beam is fired at a DT pellet which explodes, after which the propellent and some of the filler material bounces off a pusher plate, located at a sufficient distance that significant ablation does not occur. This pusher plate is connected to the vehicle by springs and dashpots, which absorb and transmit momentum to the spacecraft. Sometimes a magnetic field, which "catches" the charged reaction products, replaces the pusher plate in this concept. The repetitive explosion of these fusion microbombs can yield high accelerations, and short interplanetary round trip times. In most inertial fusion schemes, 14 MeV neutrons, 3.5 MeV helium-4 ions, radiation, and other materials are emitted isotropically (except those that intercept the pusher plate) into space.

NUCLEAR PULSE PROPULSION USING FUSION MICROBOMBS



Inertial Fusion in Space

Over the past 20 years there have been numerous design studies of space propulsion systems using inertial fusion. Most of these studies are of direct fusion rockets of the type indicated schematically on Figure 3, in which the initiating energy pulse is provided by lasers or particle beams. There have been few if any studies of inertial fusion systems for the primary purpose of generating electrical power in space. The large recirculating power flows usually required for inertial fusion, and the resulting mass penalties, may have discouraged detailed studies of inertial fusion for such applications.

Another characteristic of most engineering design studies of inertial fusion propulsion systems is that, as indicated in Figure 3, the neutrons and much of the radiant energy are unshielded and escape freely into the space environment. There appear to be few, if any, engineering design studies of inertial fusion space propulsion systems which fully shield the neutron, charged particle, and radiant energy fluxes produced by the explosion of the pellets.

Another problem with inertial fusion space propulsion systems is that investigations of burn dynamics with classified computer codes indicate that the energy gains of advanced fuels are insuffiicent to marginal for a pellet burn [Ref. 7]. Two unclassified papers [Refs. 16, 17] on advanced fuel inertial confinement show that a special pellet design (AFLINT) may be capable of burning the DD reaction, although with very high recirculating power flows [Ref. 17]. For such reasons as these, published design studies assume the DT reaction, the very high reactivity of which assures an adequate pellet burn. If inertial fusion systems in space are limited to the DT reaction, the implications of this are rather serious for the overall propulsion system. One must be concerned about the risk inherent in the tritium fuel, as described previously, and one must avoid contaminating either the atmosphere or the magnetosphere with radioactive tritium in the event of an accident, or escape of the tritium as unburned propellent from the reactor.

Conclusions

Magnetic vs Inertial Fusion in Space

For environmental and safety reasons touched upon in the above discussion, it appears that inertial fusion is at a disadvantage with respect magnetic fusion for application to space power and propulsion systems. Inertial fusion systems may be restricted to the DT reaction, raising the possibility of contamination of the atmosphere and/or the magnetosphere with radioactive tritium; and it appears difficult to shield the neutron, the charged particle, and the radiant energy fluxes that result from the explosion of the pellets without paying a large mass penalty for DT inertial fusion systems. It appears difficult to burn advanced fuels with reduced neutron production in inertial fusion systems because of the relatively low reactivity of advanced fuels relative to the DT reaction. Unclassified studies of advanced fuel inertial confinement [Refs. 16, 17] have demonstrated the feasibility of a fusion burn, although with high recirculating powers [Ref. 17]. Further research is needed to demonstrate really attractive ICF performance with advanced fuels. On present evidence, it appears that safety and environmental considerations make inertial fusion systems relatively a more difficult prospect for space applications than magnetic fusion reactors which, if they have low recirculating power flows, can burn advanced fuels.

Choice of Fusion Reaction for Space Applications

Considerations discussed in Ref. 12, Chapters 8 and 9, indicate that at kinetic temperatures below 100 keV, only the DT, catalyzed DD, and D^3He reactions are capable of producing power densities in the range of 1 to 10 megawatts per cubic meter at number densities, confinement times, and kinetic temperatures which are modest extensions of current DT tokamak research. If it is desired to minimize the transportation, handling, and leakage of tritium into the environment, that leaves only the catalyzed DD and D^3He reactions. If it is further desired to minimize the radioactivation and shielding mass associated with high levels of neutron production, that leaves only the D^3He reaction. On present evidence, it appears that the D^3He reaction is the all-around best choice for space applications of magnetic fusion energy.

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