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FOREWORD

This report was prepared by the Propulsion Physics Section, Electric and Advanced Propulsion Branch, Propulsion Laboratory, Directorate of Aeromechanics, Deputy for Technology, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. The work presented in this report was documented under AFSC Project 5350, "Advanced Concepts for Propulsion," with R. F. Cooper as project engineer for the Laboratory. The studies began in April 1961 and were concluded in June 1962.

The application of controlled thermonuclear reactions for the propulsion of a space vehicle has been subjected to an intensive in-house investigation under AFSC Project 5350. Three technical reports are to be published, which will summarize the results of these efforts. This is the first of the series and deals with the conceptual feasibility of the application. The second, in providing preliminary development of design philosophy, will give a detailed analysis of the physics and engineering problems that will be encountered in designing a controlled fusion thrustor for space application. That report, to be titled "An Analysis of Controlled Fusion for Space Propulsion Systems," has not yet been assigned a number. The third report discusses the mission capabilities of a typical controlled fusion propulsion device. It is being published as ASD Technical Document Report 62-696, "Mission Analysis for a Controlled Fusion Propulsion System."

ABSTRACT

Since controlled fusion will probably be achieved in the near future, the feasibility of applying it to the propulsion of space vehicles was studied. Some qualitative arguments are given to support the technical feasibility of this application. Problem areas that require solution prior to the establishment of design philosophy are also discussed. Because of the potential of a fusion-propelled space vehicle for the accomplishment of very high energy missions, a preliminary research program for investigating the feasibility of fusion energy for propulsion is deemed justified.

PUBLICATION REVIEW

This technical documentary report has been reviewed and approved.

FOR THE COMMANDER:

ROBERT E. SUPP
Chief, Electric and Advanced Propulsion
Branch
Propulsion Laboratory

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INTRODUCTION

A sustained controlled thermonuclear reaction (CTR) has never been achieved on earth. Under Project Sherwood of the Atomic Energy Commission, great effort has been spent on the design and construction of various devices in an attempt to accomplish this task. Project Sherwood's approach to the problem of achieving controlled fusion has been to develop a number of magnetic field geometries that could contain a reacting plasma and suppress instabilities. Three of the most common are the various pinch devices, the Stellarator, and the magnetic mirror. These three approaches are illustrated in Figure 1.

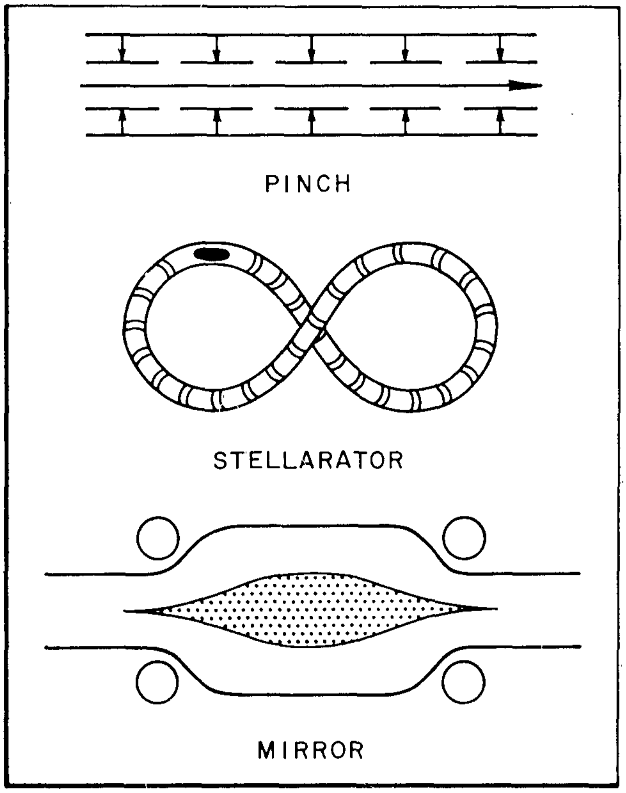

Figure 1. The Sherwood Approaches

In the pinch device, a plasma, which passes through a conducting tube, interacts with its own magnetic field to give a compression of the plasma toward the center of the tube. In the Stellarator, an external magnetic field provides the containment. In the magnetic bottle, or mirror, a non-uniform solenoid provides constant central fields with strong end fields, which cause the plasma particles to be reflected into, and contained within, the central region. The results of some 10 years of concerted efforts under Project Sherwood have been wholly unsuccessful in achieving a net power balance with a fusion reaction. However, previously unknown and even unexpected vistas of knowledge in the area of high-temperature

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plasma physics have been uncovered. It is extremely significant that no valid theoretical argument exists against achieving controlled fusion. The concensus of opinion of the majority of the workers in the field is that the steady advancement of knowledge in the area of plasma physics will, within the near future, allow the demonstration of a net power balance.

Since controlled fusion cannot as yet be used in a practical power-producing device, the question arises as to the advisability of investigating at this time the application of the process to propulsion schemes. Controlled fusion offers the most efficient energy production scheme presently achievable. Annihilation processes, or the total conversion of mass into energy, offer significantly greater energy production, but the use of such schemes in a practical device is at present far beyond the capabilities of modern technology. Perhaps eventually the possibility of tapping these essentially unlimited energy resources will exist. In the meantime, fusion, which appears much more easily attainable, is pursued as the logical intermediate step that follows the harnessing and efficient use of controlled fission (see Table 1). Because of this, and because of the optimism shown by Project Sherwood workers, investigations of the application of controlled fusion to propulsion are indeed warranted.

TABLE 1

Comparison of Mass-Energy Conversion for Various Propulsion Systems

Type of System	Mass-Energy Conversion	Cycle
Chemical	5×10^{-11}	Direct-turbine, nozzle
Fission	10^{-3}	Thermal
Fusion	4×10^{-3}	Direct
Photon	1	Direct

The conversion of mass to energy is shown with photon processes, the total annihilation of matter, normalized to unity. In chemical processes, mass is not converted to energy; the energy arises from molecular combinations and rearrangements. This energy is expressed per unit weight to provide comparison with the other systems.

In this study, the problem areas associated with a particular conceptual device are discussed; a majority of the problems, however, are characteristic of the fusion application, rather than of a particular method of effecting this application.

This report presents a qualitative discussion of some factors that will be involved in the application of controlled fusion to a space propulsion system. The primary purpose is to demonstrate that such a device is conceptually feasible within the next decade and to stimulate increased efforts in an area of technology that offers unmatched capability for future space propulsion applications.

APPLICATIONS OF CONTROLLED THERMONUCLEAR REACTION TO SPACE PROPULSION

The pursuit of applied research on a new or advanced propulsion concept must logically be based upon two criteria. First, the basic research and supporting analytical studies must demonstrate that the propulsion concept is both feasible and potentially competitive with contemporary schemes. Secondly, the advantages of this concept over those presently available or in development must be shown. Comparisons on the bases of thrust-to-weight ratio, payload fraction, specific impulse (I_{sp}), operating lifetime, fuel consumption, and secondary power and auxiliary system requirements show CFP to be highly competitive with, and in most cases definitely superior to, other contemporary propulsion devices.

The various propulsion systems presently existing or planned embrace a wide spectrum of thrust and specific impulse values (see Table 2). Since each propulsion system is best suited for operation in a particular regime, providing any reasonable common denominator for comparison of the potential of several propulsion devices in the performance of various missions is extremely difficult. The chemical rocket, with its extremely high thrust, finds its primary application in the earth-to-orbit, or launch, phase of space travel. For space exploration or other high ΔV missions, however, the low specific impulse of a chemical rocket would necessitate monstrous vehicles (with the majority of the weight consisting of fuel) and almost negligible payload fractions. For missions of this type, then, a high specific-impulse device is required. The nuclear heat-transfer rocket offers a factor of two or more increase in specific impulse over the maximum obtainable with a chemical engine. While of interest for Moon and other intermediate specific impulse missions, this specific impulse is still too low for the high ΔV missions. The nuclear-electric system provides the first true space propulsion system. While the thrust levels, and consequently

TABLE 2

Operating Parameters of Various Propulsion Systems

Type of System	Thrust (pounds)	Specific Impulse (seconds)
Chemical	$> 10^6$	< 400
Nuclear	$> 10^5$	< 1000
Electric		
Thermal arc jet	< 100	< 2000
Ion	< 10	$4000 \rightarrow 10^4$
MHD (magnetohydrodynamic)	< 100	$2000 \rightarrow 10^4$
Controlled Fusion	< 1000	Variable $\rightarrow 10^5$

the thrust-to-weight ratios, of these systems are order of magnitudes below those suitable for earth launch, they are ideally adapted for high ΔV space missions. The electric propulsion devices trade thrust for mission time; these low thrust engines require long periods to complete a given mission. This "persuasive push," as it is so aptly called, provides the most effective space propulsion device presently available. However, even these systems have limitations, with the limits on reactor fuel inventory as the most important for long-time missions. When the very high ΔV requirements (transfer of heavy payloads for long distances in minimum time, for example, or maneuvering large vehicles in the performance of rendezvous, docking, and inspection) are considered, even higher specific impulses and power levels are required. In this regime, the fusion propulsion scheme, as the logical follow-on to the nuclear-electric system, is most effective. Controlled fusion propulsion (CFP) couples a specific impulse, which is variable over all values that might conceivably be used for any mission in this solar system, with thrust levels many times higher than the maximum envisioned for nuclear-electric systems. With increased power densities, thrust-to-weight ratios approaching unity are not unrealistic.

For purposes of illustration, a comparison of all these propulsion systems might be effected on the general basis of "mission energy," the total energy increment necessary for mission accomplishment. This rather arbitrary quantity is a function of the total weight of the vehicle and the total velocity increment required.

The power-to-weight ratio is given by:

$$\frac{P}{W}\left(\frac{\text{power}}{\text{weight}}\right) = \frac{1}{2} g \; I_{sp} \; \frac{T}{W}\left(\frac{\text{thrust}}{\text{weight}}\right). \tag{1}$$

The power-to-weight ratio is plotted in Figure 2 as a function of mission energy for various propulsion systems. The curves show that a low-thrust propulsion system of large minimum weight is severely penalized for low energy missions. For missions that require higher energies, this disadvantage soon vanishes and the relative efficiencies of the system become apparent.

The power-to-weight ratio curves are plotted without coordinates. The points of intersection of the various curves will shift with variations in the parameters of the individual systems; the curves merely indicate general trends.

The ultimate usefulness of any propulsion system is measured in terms of its suitability for performing various missions. Obviously, the variable thrust and specific impulse available from a fusion engine will render a vehicle that is powered by this device highly versatile in its applications. Controlled fusion propulsion would be particularly well suited for interplanetary missions and for deep space penetration and/or loiter of large payloads; these might conceivably be any vehicles from inhabited space laboratories to large weapon systems. See Figure 3.

Logistics support is also an area for which thermonuclear propulsion appears particularly well adapted. The specific impulse and thrust of this system are ideally suited for orbit-to-orbit transfer of extremely large supply vehicles.

In-space fusion propulsion will provide an extremely flexible space maneuvering capability. The thermonuclear propulsion system has the potential of fulfilling the propulsion demands of all those missions requiring high ΔV's, high payload fractions, large payloads, and moderate reaction and mission times. Studies and calculations of applications of the reaction for space propulsion indicate its attractiveness; until the concept is developed such studies can only indicate the potential payoff.

The general characteristics and capabilities of a fusion propulsion system have been described above. The following discussion details the major requirements and applied research areas.

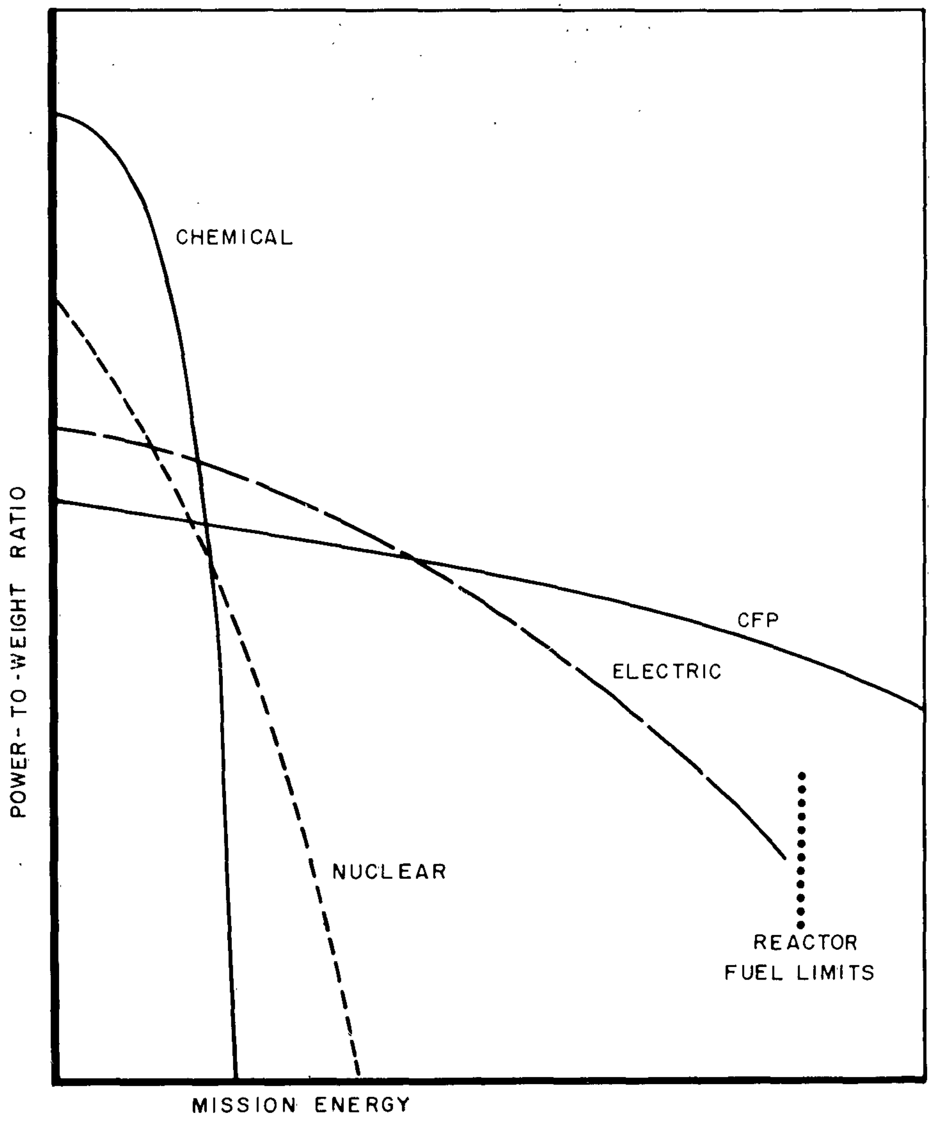

Figure 2. Comparison of Mission Capabilities for Various Propulsion Systems

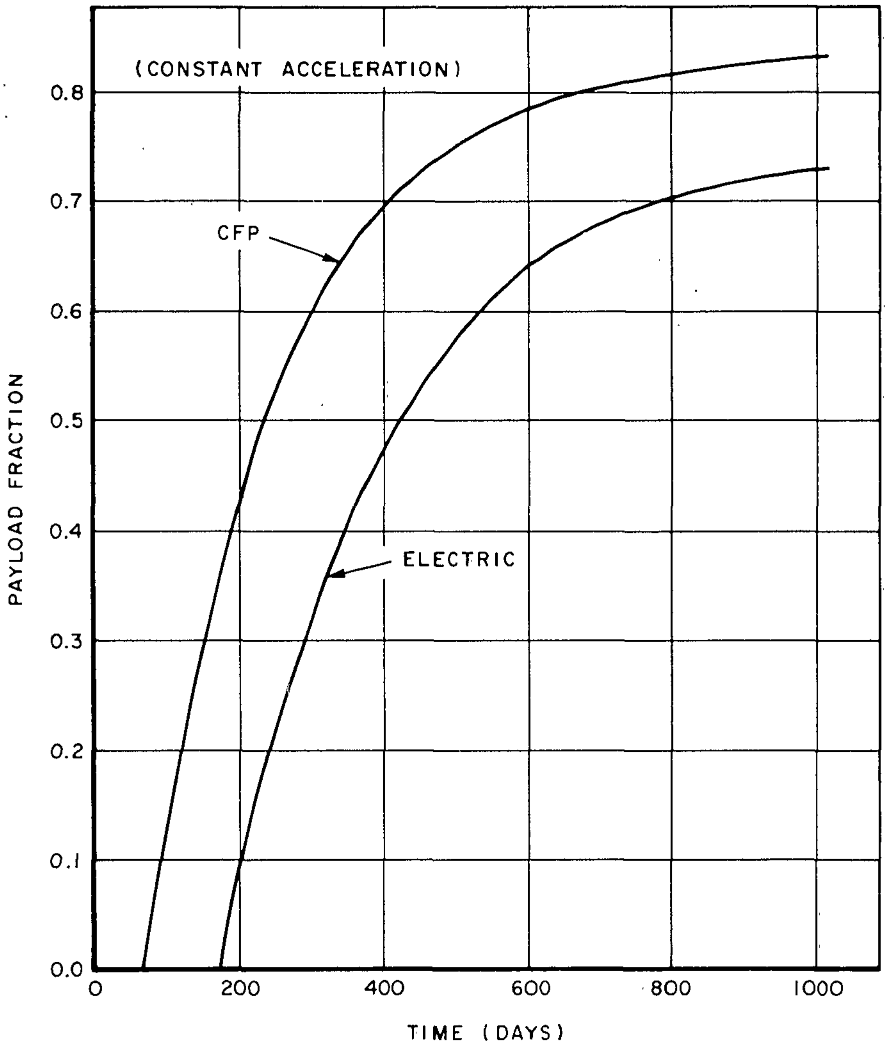

Figure 3. Comparison of Electric and CFP Systems for a Typical Mission (Round Trip to Mars)

SUPERCONDUCTIVITY AND ITS APPLICATION TO FUSION

The potential for production of extremely large amounts of energy is inherent in the fusion process; this potential, in the past, has been considered inapplicable to any extraterrestrial device. A plasma must be contained by magnetic fields and must operate at extremely high temperatures in order for fusion reactions to occur. Conventional electromagnets require enormous amounts of electrical power and coolant. Magnetic fields of the order of 10^5 gauss, generated by conventional means, require many megawatts of electrical power and megawatt cooling systems. The weight of the associated electrical equipment and cooling system is so large that even if fusion were easily achievable, usable devices for space application would have been completely impractical.

The high power requirements and resistance (joule) heating might be completely eliminated if the phenomenon of superconductivity were used in the generation of magnetic fields. A superconductor has, for all practical purposes, zero resistance below its transition temperature (the critical temperature). Although superconductivity has been known since 1911, its applications have been limited. Researchers discovered early that the phenomenon is destroyed when the superconductor is placed in a large magnetic field. The critical magnetic field (Bc) is that field strength which first destroys superconductivity; Bc is a characteristic of each material. Prior to February 1961, the highest critical fields obtainable were less than a few thousand gauss.

In early 1961, development of superconducting alloys and intermetallic compounds (e.g., Nb_3Sn, V_3Ga, NbZr, and MoTc) made possible the use of superconductors in magnetic fields of up to several hundred kilogauss. The relationship between critical field and critical temperature is shown in Figure 4. Although a superconductor can produce a magnetic field of this magnitude without quenching itself, the attainment of such field strengths in a usable geometry is quite difficult. Nb_3Sn, for example, is extremely brittle; however,

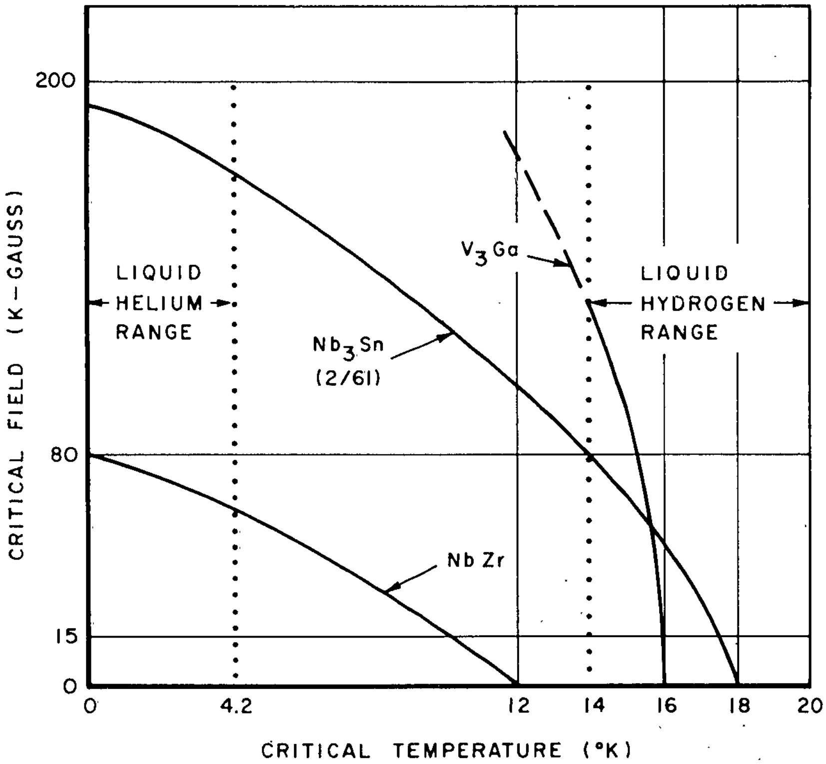

Figure 4. Relationship of Critical Field and Critical Temperature for Various Superconductors (R → 0), where R = electrical resistance

the winding of a small coil of this material has recently been accomplished. NbZr is ductile and easily wound into a coil; unfortunately, its critical field is less than 100,000 gauss, and commercially prepared coils generally yield less than 60,000 gauss. MoTc also has a critical field below 100,000 gauss. A later development, V_3Ga, appears to offer a Bc approaching 500,000 gauss. This material is also extremely brittle. The possibility for eventual development of large high-field superconducting coils, however, is most promising.

In operation, a perpetual current would be initiated in the coils while the propulsion device is still earthbound. No further power would be required to maintain the current and induced magnetic field of the coil. However, a cryogenic cooling system that requires large amounts of electrical power for operation would be needed for space operation. In spite of this power requirement, significant overall savings in power would be realized.

CHARACTERISTICS OF A CONTROLLED FUSION THRUSTOR

Engineering analyses have been performed in attempts to define the operational characteristics of a typical controlled fusion thrustor. Physics studies must be undertaken in five diversified areas, which are discussed in the succeeding paragraphs.

FUSION

A controlled thermonuclear reaction, exhibiting a net gain of energy, is possible in principle and could serve as a source of useful power. If thermonuclear reactions are to produce enough power to be self-sustaining, they will occur in a plasma having a temperature and density that is above some minimum value. Once the ions of the plasma have been confined in a suitable manner, the coulomb barrier between particles (like-charged particle repulsion) must be surmounted before thermonuclear reactions take place. The two particles must be given enormous amounts of energy, equivalent to temperatures as high as billions of degrees, so that they may approach closely enough to coalesce and undergo a fusion reaction. The coulomb barrier is proportional to the product of the participating ion charges. In view of this and because the radiation losses afflicting a fusion reaction are effectively proportional to the cube of the atomic number of the isotopes, only the isotopes of hydrogen and helium may undergo thermonuclear reactions at ion temperatures that may hopefully be obtained.

The thermonuclear reactions that are generally considered to be of interest are given in the following equations:

$$ {}_1D^2 + {}_1D^2 \longrightarrow {}_2He^3 + {}_0n^1 + 3.27\text{ Mev}^* \tag{2} $$

$$ {}_1D^2 + {}_1D^2 \longrightarrow {}_1T^3 + {}_1H^1 + 4.03\text{ Mev} \tag{3} $$

$$ {}_1D^2 + {}_1T^3 \longrightarrow {}_2He^4 + {}_1n^1 + 17.6\text{ Mev} \tag{4} $$

$$ {}_1D^2 + {}_2He^3 \longrightarrow {}_2He^4 + {}_1H^1 + 18.3\text{ Mev} \tag{5} $$

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*Mev = million electron volts

The energy term in these reaction equations is the release of nuclear energy that is manifested in the kinetic energy of the reaction products. This nuclear energy is the difference between the binding energies of the two original nuclei and the binding energy of the resultant nucleus.

A propulsion system of reasonable size that uses ordinary hydrogen as fuel cannot maintain a favorable power balance. Any isotopes that have a mass larger than that of helium-3 or atomic number (Z) greater than two cannot be used because of the catastrophic bremsstrahlung losses that occur. The minimum operating temperature (corresponding to the average particle energy) is $\sim$ 36 kev* for the D-D reaction, $\sim$ 4 kev for D-T, and $\sim$ 80 kev for the D-He^3 reaction, where 1 kev is equivalent to 1.16×10^7 degrees Kelvin. In Equations (2) and (4), most of the fusion energy is released in the form of neutrons. Neutrons and other uncharged particles are not retained by a magnetic field; their energies are immediately lost from the plasma. If a reaction in which the energy is released as charged particles is used, this power loss could be minimized. This neutron production assumes major importance in the design of a controlled fusion thrustor for use in space. Neutron heating of the superconducting coils and of the cryogenic refrigerants will result in a sizable heat load.

The deuterium-helium-3 reaction can be used to produce only charged particles. The reaction temperature that is required to make this system attractive (the temperature required to give Maxwellian distribution cross sections high enough for a feasible device) approaches 100 kev. At this energy, however, the D-T and the D-D reactions also have significant cross sections (see Figure 5). Consequently D-D and D-T reactions cannot be avoided in a fully fueled D-He^3 system. At a temperature of 100 kev, approximately 5 percent of the fusion energy in a D-He^3 system is discharged as neutrons from D-D and D-T reactions. Even this low percentage, however, corresponds to an extremely high neutron flux.

The optimum operating temperature of a thermonuclear device is determined primarily on the basis of cross sections (Figure 5), particle density, power density, and structural limitations. However, other considerations may necessitate operation at temperatures that are off-optimum (e.g., a temperature desirable on a cross section basis may lead to an increased occurrence of undesired reactions, as in the preceding illustration). In addition, the optimum operating temperature might be so high as to be unrealizable in a practical system.

The D-He^3 reaction would seem to be the most promising for a space propulsion system, since it produces such a large fraction of its energy in charged particles. Indeed, this reaction may be the only one suitable for space applications.

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*kev = thousand electron volts

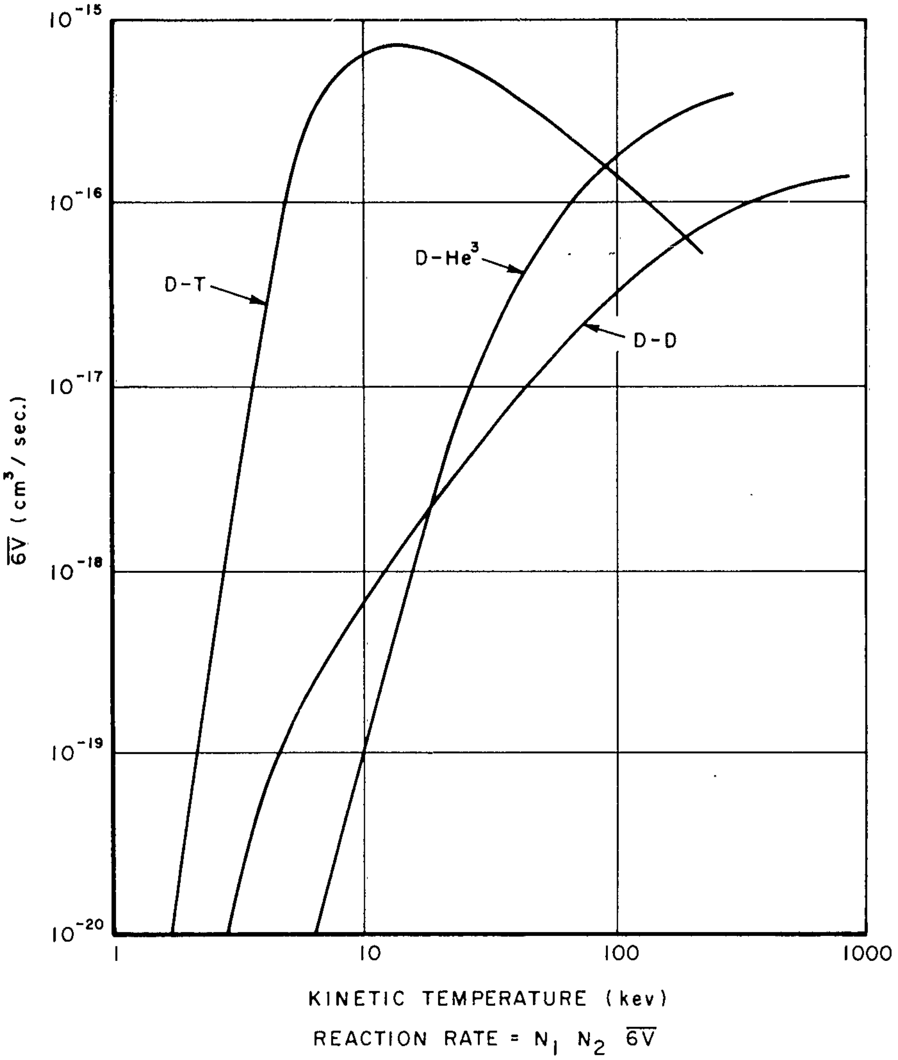

Figure 5. Reaction Rate for Maxwellian Distribution

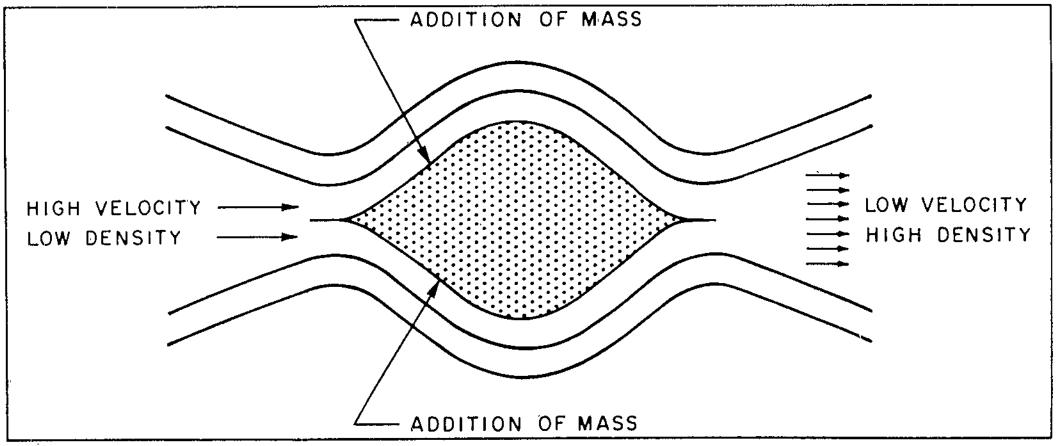

Figure 6. Proposed Scheme for Exhaust Beam Thermalization

CONTAINMENT GEOMETRY

The confinement of a plasma, which satisfies certain minimum conditions (e.g., suitable energy, density, and volume) for a sufficient time, presents the major problem in the attainment of controlled fusion. Given this confinement researchers generally feel that the other problems that are associated with the reaction system (production and heating of the plasma, etc.) will be solvable. Because of the extremely high energies involved, a physical containing chamber cannot be used. Some method of electric or magnetic containment is the logical alternative. Earnshaw's theorem, together with other qualitative arguments, rules out confinement by electric fields. Consequently, the approach of the Sherwood Program has been to develop a number of suitable magnetic containers. The most familiar are the pinch, Stellarator, mirror, cusp, and variations thereof (see Figure 1). For propulsion applications of thermonuclear processes, the magnetic mirror geometry appears the most attractive. In this system, the confining longitudinal magnetic field is applied by means of a solenoid. The field strength is not uniform but is greater at the ends; a "potential well" is thus formed in the central region, with the mirrors reflecting charged particles back into the region of weaker field. Since the mirrors inhibit the escape of the particles in this way, a small difference in the magnitude of the mirror fields will allow nearly total leakage through one of the mirrors. This method suggests a simplified approach to the problem of achieving directed thrust.

The major drawbacks of the magnetic bottle are: large (cyclotron) radiation losses, injection problems, high operating temperatures, and the presence of certain instabilities. These instabilities may be partially alleviated by recourse to various "hybrid" configurations. A combination of the basic mirror with the cusp geometry, as proposed by Ioffe of the USSR, appears promising (see Reference 3 of the Bibliography).

INJECTION

The "feeding" of fuel into a magnetic mirror geometry is an especially difficult problem, since a magnetic field configuration which demonstrates good containment properties for charged particles is automatically a good reflector of such particles. Thus some special means of injecting the fuel into the mirror must be found. Once inside, the particles must be trapped long enough for fusion reactions to occur. Liouville's theorem requires that ions of fixed charge to mass ratio injected into a conservative field must eventually escape from that field unless acted upon by an external force. The obvious methods of circumventing this restriction are through injection of neutrals with subsequent ionization within the mirror or through dissociation of molecular ions within the chamber. Two approaches to the trapping problem are immediately apparent: (1) an extremely "hot" (energetic) plasma may be injected into the fusion chamber and then trapped inside or (2) low energy particles may be injected and the plasma "heated" by some means (e.g., magnetic compression) within the chamber. For various reasons, the former appears much more attractive for a space propulsion system. Certain schemes based on this approach have been used in the various Sherwood fusion machines.

The ignition temperature is the minimum operating temperature at which a thermonuclear reaction will become self-sustaining; i.e., the thermonuclear energy deposited in the system just exceeds the energy dissipated through various loss mechanisms. One of the major sources of energy loss is bremsstrahlung ("braking" radiation). Bremsstrahlung, which is radiated in a continuous energy spectrum, is caused by the coulomb accelerations of charged particles within the thermonuclear plasma. The rate of bremsstrahlung radiation is proportional to the square of the atomic number of the plasma ions. Since any impurity ions in the system will have an atomic number higher than that of the fuel, bremsstrahlung will increase markedly as the impurity concentration increases.

The impurity level must, therefore, be kept extremely low. The temperature at which the thermonuclear energy deposition just exceeds the bremsstrahlung losses is called the "ideal" ignition temperature.

In addition to the loss of energy as bremsstrahlung, cyclotron radiation becomes a significant source of loss when the plasma temperature approaches the ideal ignition temperature. Cyclotron radiation is emitted by charged particles undergoing acceleration in spiraling around the flux lines of the externally applied magnetic field. The particles spiral at definite "gyromagnetic" frequencies. The radial acceleration of these gyrating particles is accompanied by the emission of cyclotron radiation.

Bremsstrahlung is emitted in the X-ray and ultraviolet regions of the electromagnetic spectrum, while cyclotron radiation is mainly in the infrared and microwave regions. There is no way to retain the bremsstrahlung energy in the fusion chamber by reflection or absorption; however, a highly reflective material on the walls of the reaction chamber will reflect cyclotron radiation. The general feeling is that the energy will be partially reabsorbed if the radiation can be passed through the plasma many times by reflection. In addition to the electromagnetic radiation, thermonuclear reactions released high energy neutrons. These neutrons are not confined by the magnetic field and their kinetic energy is, therefore, lost to the system. The actual ignition of a self-sustained thermonuclear reaction, therefore, occurs when the thermonuclear energy retained in the system just exceeds the energy dissipated by all of the previously mentioned processes. A self-contained device, such as a fusion-propelled space vehicle, will require additional energy for purposes of injection of fuel and refrigeration of superconducting coils. The removal of this energy from the thermonuclear plasma by a magnetohydrodynamic (MHD) type device will have the effect of increasing the minimum ignition temperature.

EXHAUST THERMALIZATION

The charged particles that leak through the end of a magnetic mirror possess extremely high velocities. If a reasonable reaction temperature is assumed, the average particle velocity within the chamber is of the order of 10^6 meters per second. If a Maxwellian distribution of velocities (or energies) is assumed, the highest energy particles will have velocities far in excess of this figure. From scattering considerations, the lower energy ions would be expected to provide the majority of the leakage from the system. However, the electrical potentials established because of preferential electron leakage will increase the energy of the escaping particles. On the average, then, the energy of the escaping particles will be greater than the average particle energy within the chamber. The exhaust velocities will correspond to specific impulses of greater than 10^5 seconds. These specific impulses are unnecessarily high for any missions within this solar system. Reducing the average velocity and I_{sp} to some value that is an "optimum" for the particular mission would be desirable. This reduction may be accomplished in several ways. For example, the generation of auxiliary electrical power by some MHD method decreases the average particle velocity as desired, but unfortunately also decreases thrust. The most promising concept thus far proposed is a "thermalizer" as shown in Figure 6. This is a chamber in which the energetic exhaust particles would mix with low energy fuel and become thermalized to any desired velocity, depending upon chamber density, temperature, etc. This procedure offers the obvious advantage of variable thrust and I_{sp}; however, it requires increasing the mass flow rate by a factor which is the square of that by which the thrust is increased.

The low energy plasma presents a containment problem during the thermalization process. As in the fusion chamber itself, containment requires the design of a suitable magnetic field. The major goal is the attainment of suitable mixing of the two gases to achieve efficient transfer of energy and subsequent exhaust-beam thermalization. Electron-ion interactions will play the major role in this mixing. The design of a suitable nozzle must also be considered. This design is required if directed thrust is to be obtained from the reaction products that leave the thermalization chamber. The particles escaping from the thermalizer will possess some velocity distribution. This spread in exhaust velocities can be related directly to an efficiency factor. A good velocity profile (limited spread in velocity distribution) will be required. Since exhaust temperatures are extremely high, a material nozzle will be impossible. The magnetic field at the rear of the thermalizer chamber must be shaped so that it serves as a nozzle.

ANALYSIS OF LOADS AND SELECTION OF MATERIALS

The major portion of the total weight of a controlled thermonuclear propulsion system appears to consist of structural materials that are necessary to support the cryogenic coils and auxiliary equipment. The initial step in determining the magnitude of these weights lies in a complete and detailed analysis of the loads that are placed on the structural members while they are in the operating environment. The primary loads are those of stress, heat, and nuclear radiation.

The currents that provide the high containment magnetic fields in a mirror geometry will produce between the superconducting coils attractive forces that tend to collapse the entire system. The coils must consequently be separated by support structures that can withstand compressive loads of the order of 10^5 pounds per square inch or greater. In addition, the individual coils will experience radial stresses and must be supported by some hoop structure. Several materials appear feasible for these applications. Maintaining the coil supports as well as the coils at cryogenic temperatures may be necessary. This should not significantly increase the structural problems since a number of materials possess tensile strengths that increase with decreasing temperature. The heat shielding problems will, however, be increased.

The primary thermodynamic problems to be considered are: (1) heating of the superconducting magnetic coils by thermal heat leakage and nuclear radiation, (2) cryogenic refrigeration for removing this heat, (3) recovery of useful power from the waste heat resulting from the attenuation of bremsstrahlung, neutron, and unreflected cyclotron radiation, and (4) rejection of waste heat to space through thermal radiators. These considerations are further complicated by the necessity of minimizing weight while maximizing reliability and operational lifetime. The inner surface of the fusion chamber would be covered with some material that is a reflector of cyclotron radiation. The chamber would then be surrounded by a bremsstrahlung shield and a neutron shield.

Circulating a coolant through the shields, removing some of the heat, and using this heat in a thermal cycle for auxiliary power generation might be possible. Optimization of the heat removal and radiation temperatures would depend primarily upon the electrical system requirements. However, eliminating the thermal cycle entirely will undoubtedly prove more advantageous. If the D-He^3 reaction in which only a small percent of the energy is given off as neutrons is used, this energy might be allowed to escape from the system entirely. Minimum neutron shielding would then be provided, and the bremsstrahlung shield surrounding the fusion chamber would be allowed to radiate directly to space.

The necessity of maintaining the magnetic coils at superconducting temperatures ($\sim 5^\circ$ - 10°K) requires that the coils be well insulated from high-temperature heat sources.

The entire vehicle will be subjected to a high neutron flux. If a neutron shield surrounds the reaction chamber, the flux levels will be lowered sufficiently so that structural materials will not be seriously affected. The neutron and secondary gamma loads may still be sufficiently high to deposit large amounts of heat in the cryogenics and to affect the superconducting properties of the coils. Neutron heating of the coils and support structures will undoubtedly result in a sizable penalty in the form of increased refrigerator weight and power requirements.

CONCLUSIONS

On the basis of energy-production efficiencies alone, a controlled fusion propulsion system will obviously possess definite advantages in the performance of high ΔV missions. As mentioned previously, no valid theoretical argument exists against achieving controlled fusion. In addition, the analyses that have been performed to date by the USAF, NASA, and various industrial organizations indicate that no insoluble engineering problems would be associated with adaptation of controlled fusion to the propulsion of a space vehicle. If such an application is to be realized, however, a number of areas of technology require intensive effort at this time. Primarily, we must determine whether the preliminary choice of the D-He^3 reaction is indeed the correct one. The most suitable approaches to the solutions of the problems of controlled fusion, especially such problems as containment, injection, trapping, burnout, etc., must be examined and analyzed for their applicability to a space propulsion device. Eventually, some detailed engineering analyses of the system-oriented problems of electrical power and refrigeration requirements, materials selection or development, etc., will have to be performed. An imaginative sketch of a possible design of a vehicle is shown in Figure 7.

If some effort in controlled fusion propulsion were initiated now, proof of concept feasibility and design of test-bed hardware could conceivably be accomplished within this decade. Productive years, so vital in this time of national need, may be irrecoverably lost in the transition from concept to usable device unless the groundwork for this development is laid immediately.

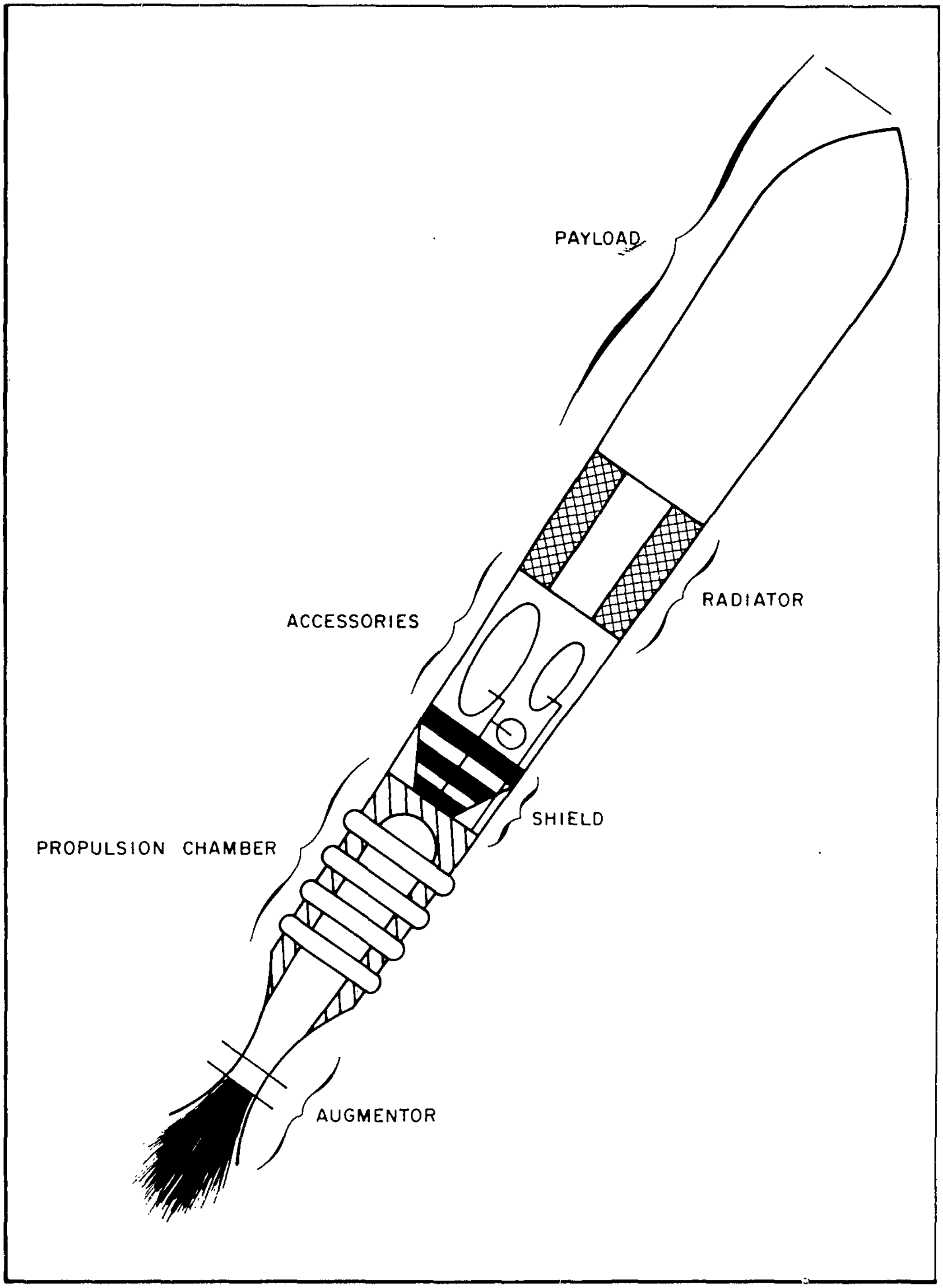

Figure 7. A Possible Configuration of a Controlled Fusion Space Thrustor

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Rpt Nr ASD-TDR-62-698, CONTROLLED FUSION FOR SPACE PROPULSION. Apr 63, 16p. incl illus., tables, 6 refs.
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Since controlled fusion will probably be achieved in the near future, the feasibility of applying it to the propulsion of space vehicles was studied. Some qualitative arguments are given to support the technical feasibility of this application. Problem areas that require solution prior to the establishment of design philosophy are also

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