Characterization of Advanced Electric Propulsion Systems

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Characteristic parameters of several advanced electric propulsion systems are evaluated and compared. The propulsion systems studied are mass driver, rail gun, argon MPD thruster, hydrogen free radical thruster, and mercury electron bombardment ion engine. Overall, ion engines have somewhat better characteristics than the other electric propulsion systems.

Introduction

THE specific impulse of chemical rockets is limited, even for the most energetic propellant combinations, to below 500 s. Beyond this lies a variety of propulsion modes which promise a specific impulse measured in thousands of seconds. Many of them use electrical energy as input energy and, by employing various methods, convert part of the input energy into kinetic energy of the masses exhausted from the thrusters. These electric propulsion systems are distinguished by high exhaust velocities, low propellant consumption, low thrust, and long operating times. Reported herein are the results of a study made to establish and compare the performance parameters of a selected number of electric propulsion systems. The propulsion systems studied are: 1) linear electromagnetic accelerator or mass driver;[1] 2) DC electric rail gun thruster[2]; 3) magnetoplasmadynamic (MPD) thruster[3]; 4) free radical thruster[4]; and 5) mercury ion engine.[5]

System Description

Each system is briefly described in this section. A large volume of information on designs, performances, and mission characteristics of these systems already exists in the literature.

Mass Driver

The mass driver is a linear electromagnetic accelerator capable of launching reaction masses when designed as a rocket engine. A cylindrical bucket with superconducting coils carrying payloads is accelerated inside a coaxial assembly of drive coils several kilometers long. The payload is released after the desired velocity is achieved, and the bucket is decelerated and returned to the starting position along a return track to be used again.

This device behaves essentially as a linear synchronous ac motor. The accelerating force is generated by a traveling magnetic field interacting with a magnetic dipole. The bucket is supported and guided without physical contact with the drive coils by dynamic magnetic levitation.

A small number of drive windings contained in one sector are excited at any given time to minimize power dissipation. A capacitor bank in each sector discharges current through feeders and through silicon-controlled rectifiers to the drive windings.

Rail Gun Thruster

The rail gun consists of a pair of separate parallel conductors connected by a movable conductor. A large current (kiloamperes) flows in a short burst from one rail to the interconnecting conductor to the other rail. The interconnecting conductor is normally a thin metallic fuse which becomes a plasma when the large current is discharged through it.

The rail gun functions essentially as a linear dc motor. The plasma behaves as an armature while the parallel rails serve as a single turn field, winding in series with the armature. The current J flowing in the rails generates a magnetic field B between the rails and this magnetic field interacts with the current flowing in the armature. The resulting Lorentz force ($J \times B$) acting on the armature accelerates the plasma along the rails. If the plasma is confined behind a projectile made of dielectric materials, the pressure of the plasma will also accelerate the projectile. The confinement of the plasma can be provided by the conducting rails on two sides and the dielectric materials on the other two sides. The peaking loads are supplied by a capacitor energy storage system and the current is discharged through a pulse-shaping network containing an inductor.

MPD Thruster

The self-field MPD thruster consists of a discharge chamber made of an annular anode ring and a centrally located cathode. After a suitable gaseous propellant, such as argon, is injected into the discharge chamber, a large current pulse (kiloamperes) is passed from the anode to the cathode ionizing the propellant. A magnetic field B is induced inside the discharge chamber by this azimuthally symmetric current flow. It interacts with the current J to produce a Lorentz body force ($J \times B$) on the propellant gas. This Lorentz body force has an axial component which moves the plasma downstream and a radially inward component which confines the plasma. The plasma expelled from the discharge chamber provides the thrust.

The self-field MPD thruster is a low voltage (hundreds of volts), high current device which is well suited for operation in an intermittent, quasisteady mode.

Free Radical Thruster

This device operates on the principle of continuous creation of atoms dissociated from molecules of light gases, such as hydrogen, and recombining them in a chamber to obtain the heat of recombination of free atoms. The free radical thruster represents the ultimate chemical system yielding the highest specific impulse for 100% dissociation and recombination.

The input electrical energy is converted to microwave radiation and fed into a resonant cavity. Molecular hydrogen gas flows through the cavity and a fraction of the molecules are dissociated by the microwave energy. The mixture of molecular hydrogen and dissociated hydrogen atoms then flows out of the cavity into a recombination chamber where the hydrogen atoms recombine, releasing the energy absorbed in dissociation as heat. The hot recombined gas is expanded through a nozzle to produce thrust.

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Mercury Ion Engine

In these thrusters, neutral mercury atoms are fed to an ion source and the positive ions generated are accelerated by an electrostatic field. These positive ions are formed in a discharge chamber by electron bombardment, where electrons are emitted from an electrically heated cathode filament and are attracted by a surrounding cylindrical anode. The electrons are made to spiral through mercury vapor by applying an axially divergent magnetic field to improve ionization efficiency.

The positive ions are extracted and accelerated by a multiple-aperture dished accelerator screen grid system. After being expelled from the thruster, the positive ion beam is neutralized by the addition of an equal number of negative electrons.

Results

Of the five electric propulsion systems evaluated, the mass driver, rail gun, and MPD thruster are pulsed devices, whereas the free radical thruster and ion engine are continuous thrust devices. For a comparative evaluation, the electric propulsion systems are characterized by specific impulse, overall efficiency, input power, average thrust, power-to-average thrust ratio, and average thrust-to-dry mass ratio. Additionally, there are several important physical characteristics such as dry system mass, accelerator length, bore size, and current pulse requirement and these are also evaluated in appropriate cases. Dry system mass represents the masses of all components except propellant. In the case of propulsion systems that operate in a pulsed mode, the input power represents the average power.

The efficiency of the power conditioning system has been assumed to be 0.9 in all cases except for the ion engine. The powerplant specific mass is assumed to be 10 kg/kW. For mass driver and rail gun, the radiator specific mass is assumed to be 10 kg/kW and the power conditioning system mass is assumed to be 5 kg/kW of input power. It is to be noted that these values are quite optimistic. The propellant utilization efficiency is assumed to be 100% in all cases except for the ion engine where it is taken to be 95%. It should be further pointed out that the mercury ion engine is the most highly developed of all electric propulsion systems. Hence, their mass and performance characteristics are best known and therefore most realistic.

The equations and data used to calculate the characteristics of the electric propulsion systems are provided in Ref. 6.

Mass Driver

Projectile mass and specific impulse are used as the variables in mass driver calculations. The mass of the projectile is varied from 1-30 g for two values of specific impuse, 1000 and 1500 s. Mass driver characteristics are determined for several combinations of projectile mass and specific impulse.

Overall efficiency of the mass driver is plotted in Fig. 1 against projectile mass for the specific impulses. It is observed that the efficiency is quite low for smaller projectile masses. However, it rapidly rises to a high value (greater than 50%) and begins to flatten out thereafter. The efficiency is higher when the mass driver is operated at a higher specific impulse.

For the mass drivers, the input power requirement ranges from a megawatt to tens of megawatts and the average thrust varies from tens of newtons to thousands of newtons. These devices are extremely long (tens of kilometers) and hence, very massive ($\sim 10^5$ kg).

The power-to-average thrust ratio (Fig. 2) is rather high at low projectile masses and approaches an asymptotic value (~ 9 kW/N at $I_{sp} = 1500$ s and ~ 6 kW/N at $I_{sp} = 1000$ s) as the mass of the projectile is increased. Figure 2 also shows the average thrust-to-dry mass ratio of the mass driver. For a fixed specific impulse, the ratio increases with increase in projectile mass. This ratio decreases when specific impulse is increased.

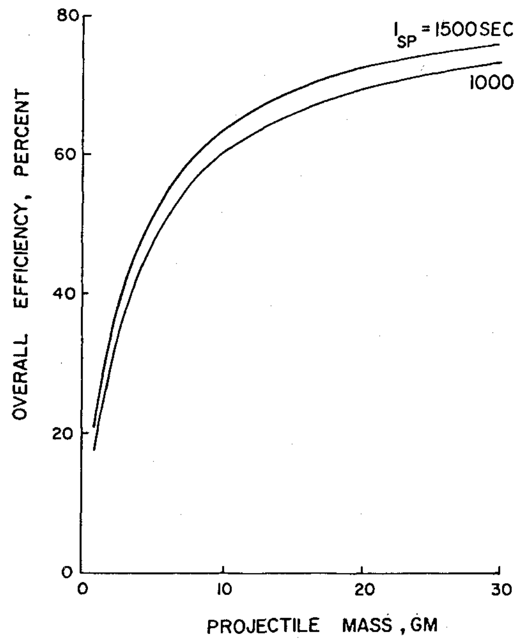

Fig. 1 Mass driver overall efficiency.

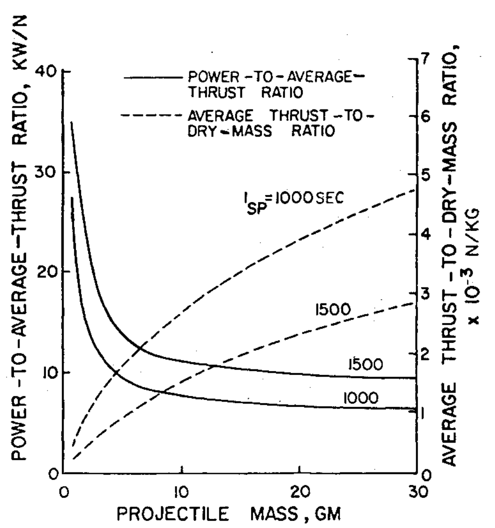

Fig. 2 Mass driver power-to-average thrust ratio and average thrust-to-dry mass ratio.

Rail Gun Thruster

Projectile mass and specific impulse are used as the variables in rail gun calculations. The mass of the projectile is varied from 0.1-1.0 g for specific impulses of 1000, 1500, and 2000 s. Characteristics of rail guns are evaluated for several combinations of projectile mass and specific impulse.

Figure 3 shows the overall efficiency of the rail gun against projectile mass for the three specific impulses. It can be seen that the efficiency is rather low; the upper limit is close to 34%. At a fixed specific impulse, the efficiency increases with the increase of projectile mass; however, the efficiency progressively decreases as the specific impulse is increased.

When the rail gun is operated at a low specific impulse and with a small projectile mass, the input power requirement is hundreds of kilowatts and the average thrust is tens of newtons. For gram-size projectiles at higher specific impulse, the input power requirement quickly climbs to the megawatt level and the average thrust increases to hundreds of newtons. To achieve higher efficiency, rail guns should be operated at a low specific impulse and a high average thrust (hence, a high input power).

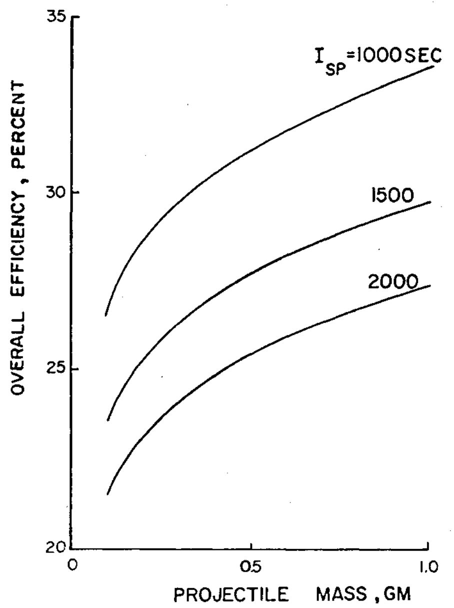

Fig. 3 Effect of projectile mass on overall efficiency of a rail gun.

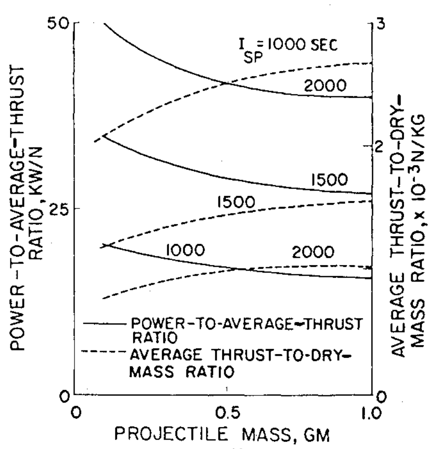

Fig. 4 Rail gun power-to-average thrust ratio and average thrust-to-dry mass ratio.

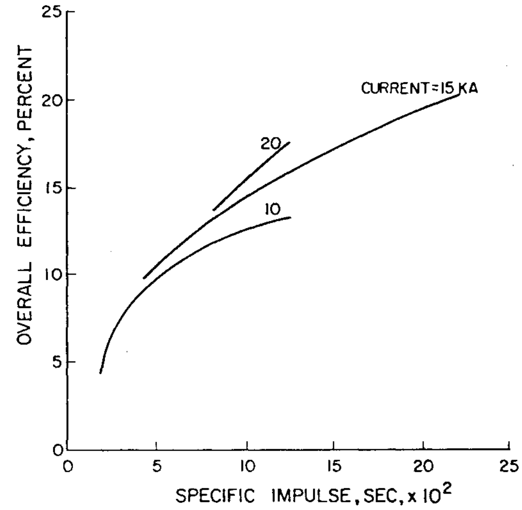

Fig. 5 Overall efficiency of an MPD thruster.

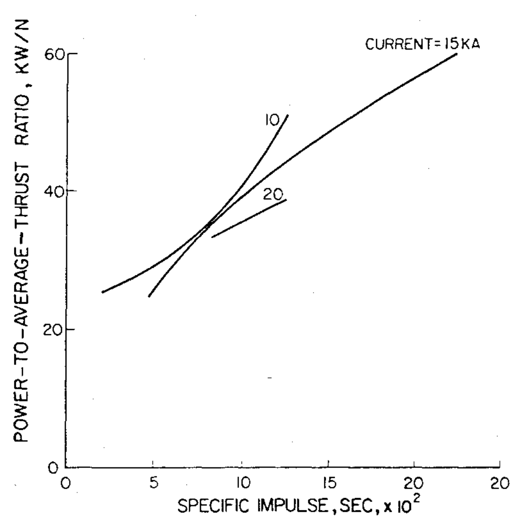

Fig. 6 Power-to-average thrust ratio of an MPD thruster.

The length of the rail gun varies from tens to hundreds of meters to provide a specific impulse of 1000 s or more. Current pulse required in rail guns varies from 35 kA for launching a mass of 0.1 g to 75 kA for launching a mass of 1.0 g. From a practical point of view, masses less than 0.1 g cannot be launched as the bore width has to be less than 4 mm for a 20-m-long accelerator. For a given projectile mass, changing specific impulse has no significant effect on the length and bore size of the accelerator and the current pulse needed. The dry system mass of the rail gun thruster varies from 10^4-10^5 kg.

Due to low efficiency of the rail gun, the power-to-average thrust ratio of this device is rather high, particularly at specific impulses of 1500 and 2000 s (Fig. 4). For a given specific impulse, this ratio decreases slowly as the projectile mass is increased. The average thrust-to-dry mass ratio is also presented in Fig. 4. For a given specific impulse, it increases slowly with increase in projectile mass. This ratio decreases when specific impulse is increased.

MPD Thruster

The MPD thruster characteristics are evaluated by using the experimental data obtained from an argon self-field MPD device.[3] Current pulses in the 10-20 kA range and average gas flows in the 1.5-9.0 g/s range have been used in these experiments to provide specific impulses from 200-2200 s. The thruster terminal voltage ranged from 40-155 V. The data used represent the operating range before the onset of voltage fluctuations.

Overall efficiency of an MPD thruster is plotted against specific impulse in Fig. 5. These thrusters are currently characterized by low efficiencies. The input power requirement is several hundreds of kilowatts and the average thrust is a few newtons. Due to low efficiencies, the power-to-thrust ratios of these devices are rather high, particularly if they are to be operated at higher specific impulses (in excess of 40 kW/N, Fig. 6). Due to insufficient design information about the thrust chamber, MPD thruster system mass could not be determined.

Free Radical Thruster

To obtain free radical thruster characteristics, the molar ratio of H_2 and H in the recombination chamber is varied from 0:1 to 10:1. Due to lack of sufficient experimental or design information about the plasma cavity, the microwave energy conversion efficiency needed to produce the desired H_2:H molar ratios is assumed to be 0.3 and 0.6 to reflect two possible designs. The H_2 flow rate is assumed to be 1 g/s.

All of the energy released due to recombination of the free radicals cannot be converted into kinetic energy of the ejected matter. A large portion of the energy of the exhaust gases leaves the nozzle as residual enthalpy. In this study it was

Table 1 Specific impulse of a hydrogen free radical thruster

Free radical molar composition, H_2:H	Specific impulse, s
0:1	1493
1:1	860
2:1	665
5:1	448
10:1	325

assumed that 50% of the energy input into the combustion chamber is available for conversion into kinetic energy. Under these conditions, the specific impulse of the hydrogen free radical thruster varies from 325 (for H_2:H=10:1) to 1493 s (for H_2:H=0:1), as shown in Table 1.

The thrust produced in these devices is tens of newtons and the input power ranges from tens to hundreds of kilowatts. The power-to-thrust ratio is high for low H_2:H molar ratios (Fig. 7) which implies higher specific impulses. Due to insufficient information about the design of dissociation and recombination chambers, the mass of the free radical thruster could not be determined.

Mercury Ion Engine

The characteristics of a 50-cm-diam mercury electron bombardment ion engine are evaluated for specific impulses ranging from 2000-4000 s. For specific impulses of 2000 and 3000 s, the total accelerating voltage is assumed to be 2000 V, which provides net-to-total accelerating voltage ratios of 0.25 and 0.56, respectively. For the specific impulse of 4000 s, the total accelerating voltage is assumed to be 2500 V, which provides a net-to-total accelerating voltage ratio of 0.79.

Overall efficiency of the ion engine is presented in Fig. 8 against specific impulse. These thrusters operate at quite high efficiencies, 55-68% for the range of specific impulses concerned. The thrust developed is a few newtons, whereas the input power requirement is tens of kilowatts. The power-to-thrust ratio changes from 18-30 kW/N (Fig. 9) and the dry system mass is several hundred kilograms. Thrust-to-dry mass ratio remains practically constant at 2×10^{-3} N/kg (Fig. 10).

Comparative Evaluation

Each type of electric propulsion system can be operated over a certain range of specific impulse. The characteristics of mass drivers have been calculated for specific impulses varying from 1000-1500 s, but even at $I_{sp}=1000$ s, this type of propulsion system demands a power of several megawatts and a length of several kilometers. Since the efficiency of rail guns decreases as the specific impulse is increased, rail gun characteristics have been calculated for $I_{sp}=1000$-2000 s. Due to their ability to accelerate macroparticles, both mass drivers and rail guns can produce relatively high average thrusts (tens to hundreds of newtons). Thus, mass drivers and rail guns are basically high power, high thrust devices.

From the experimental data of the benchmark MPD thruster it can be seen that the maximum specific impulse is 2200 s before the onset of voltage fluctuations. In hydrogen free radical thrusters the specific impulse is expected to stay below 1500 s. Only ion engines can operate well beyond this range, from 2000-4000 s. All of these thrusters produce low thrust (~ newtons) and require low input power (hundreds of kilowatts).

Overall efficiencies of the five electric propulsion systems against specific impulse are shown in Fig. 8. For mass drivers, overall efficiency is plotted on the basis of a projectile mass of 15 g, for rail guns a projectile mass of 0.5 g. For MPD thrusters, overall efficiency presented is for a current pulse of 15 kA.

Mass drivers are found to have the highest efficiency of all electric propulsion systems. However, these efficiency values may be too optimistic, because for such a small linear accelerator, the energy losses are expected to be higher than those obtained from the equations used in this study. Rail guns are observed to have low efficiencies due to large amounts of energy loss in the rails.

There is an appreciable amount of power loss associated with the electromagnetic plasma acceleration process which currently makes the MPD device a low efficiency thruster. However, there are indications that the characteristics of MPD thrusters can be improved. By replacing the 10-cm-diam anode orifice of the benchmark thruster with one 6 cm in diameter, the specific impulse was increased to 3000 s and the thruster efficiency was increased to over 30%[3].

The efficiency of dissociation of H_2 in a plasma cavity is extremely low. In recent experiments, dissociation efficiencies ranging from 1.5-6.0% have been observed.[7] Dissociation efficiencies have been arbitrarily assumed in this study and for a dissociation efficiency of 60%, the overall efficiency of the free radical thruster is 27%. Ion engines operate at reasonable high efficiencies because electrostatic acceleration of ions is essentially a loss-free process.

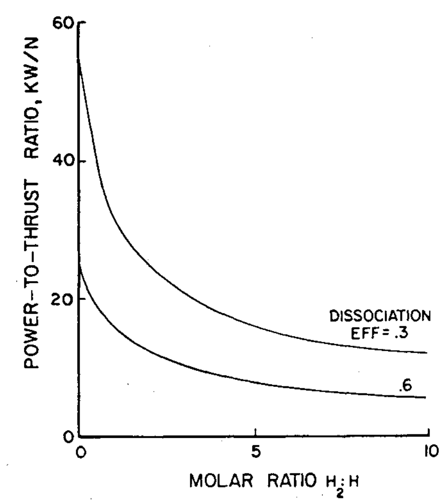

Fig. 7 Free radical thruster power-to-thruster ratio.

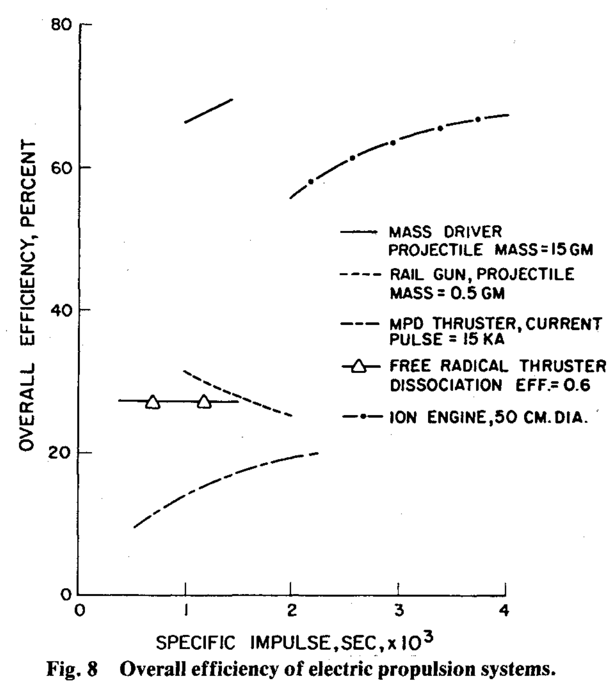

Fig. 8 Overall efficiency of electric propulsion systems.

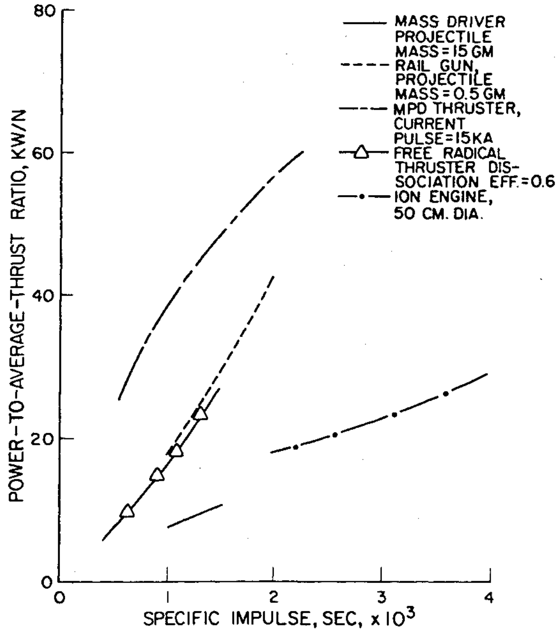

Fig. 9 Power-to-average thrust ratio of electric propulsion systems.

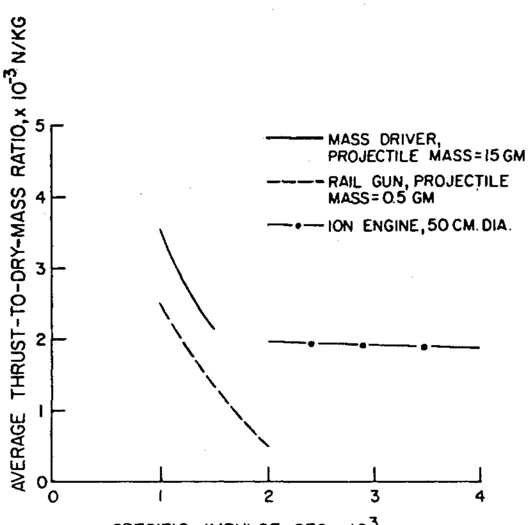

Fig. 10 Average thrust-to-dry mass ratio of mass driver, rail gun, and ion engine.

Power-to-average thrust ratios are presented in Fig. 9 against specific impulse. Mass drivers are found to have the lowest power-to-thrust ratio among all electric propulsion systems. Rail guns and MPD thrusters have relatively high power-to-average thrust ratios due to their low efficiencies. Free radical thrusters also have a high power-to-thrust ratio if a large percentage of H_2 can be dissociated in the plasma cavity, i.e., if they can be operated at a high specific impulse.[12] The power-to-thrust ratio of ion engines is low although they operate at considerably higher specicic impulses.

Average thrust-to-dry mass ratio is shown in Fig. 10 for mass drivers, rail guns, and ion engines. Mass drivers have the highest thrust-to-dry mass ratio followed by ion engines and rail guns. Thrust-to-dry mass ratios of MPD thrusters and free radical thrusters could not be determined due to insufficient design information about these thrusters.

Conclusions

Judged solely on the basis of efficiency, power-to-average thrust ratio and average thrust-to-dry mass ratio, mass drivers appear to be the best of all electric propulsion systems. Mercury ion engines offer reasonably high efficiencies. Their thrust-to-dry mass ratio is comparable to those of mass drivers. The power-to-thrust ratios of ion engines are somewhat higher than those of mass drivers. Yet these values are low enough despite the fact that ion engines operate at considerably higher specific impulses. Ion engines do not have the drawbacks of mass drivers such as large power requirements or excessive length. Although ion engines produce low thrust, several of them can be put together in a module to provide higher thrust. In view of these observations, it is concluded that overall, ion engines have somewhat better characteristics than the other electric propulsion systems.

Acknowledgments

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