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ELECTRIC PROPULSION IN SPACE

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ELECTRIC PROPULSION IN SPACE

by

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A B S T R A C T

In the past twenty years electrical methods of propelling space vehicles have developed from the speculative stage to practical reality. A brief description of current achievements in this evolving field is given.

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C O N T E N T S

1. INTRODUCTION

Two decades ago expressions like ion engine and plasma rocket were more familiar to the aficionados of 'Astounding Science Fiction' than engineers. Today these terms are commomplace jargon in the Aerospace Industry. The current annual expenditure on electric propulsion in the U.S.A. alone is approximately $ 15,000,000 and experimental ion engines have been tested on satellites.

Electric propulsion uses electric energy to achieve exhaust velocities greater than those possible with chemical rockets. Higher exhaust velocities mean potentially more effective rockets or thrustors for the following reason. A manoeuvre or change in velocity of a space vehicle involves discharging mass, in the form of rocket exhaust; because the total momentum of the system is conserved the vehicle moves in one direction while the exhaust or propellant moves in the opposite direction. From this simple premise the basic rocket equation can be derived, namely:-

$$M \frac{dv}{dt} = v_e \frac{dM}{dt}$$

$$\therefore \Delta v = v_e \log_e \left(\frac{M_o}{M_o - \Delta M} \right) \qquad \ldots (1)$$

where M_o is the initial mass of the vehicle plus propellant. ΔM is the mass of propellant expelled, v_e is the exhaust velocity and Δv is the increase in velocity of the vehicle. Equation (1) shows that, to order of magnitude, it is impractical to accelerate the vehicle to a velocity of more than a few times the exhaust velocity. All else being equal, the velocity increment Δv increases as the exhaust velocity is increased.

In a chemical rocket the fuel is both the energy source and the propellant but with electric propulsion a separate energy source is needed as well as a supply of propellant aboard the vehicle. To use the energy from a chemical reaction by converting it to electrical energy (e.g. with a fuel cell) is pointless as the mass of the convertor and propellant will always make the system less efficient than one using the chemicals directly in a chemical rocket. The limiting figure-of-merit in a rocket is the energy available for expelling the exhaust divided by the total mass of the propulsion system. Electric propulsion only comes into its own when high energy sources, such as fission reactors, are used or when an external source of energy (e.g. solar radiation) is used to produce electrical power. In the latter case the energy available increases directly as the lifetime of the vehicle. As the useful lifetimes of satellites and other space vehicles increase so electric propulsion using solar energy becomes more and more competitive with chemical propulsion. Electric propulsion using fission power however, still awaits a long-life lightweight reactor.

2. TYPICAL USES FOR ELECTRIC THRUSTORS

Before describing different types of electric thrustors some typical manoeuvres of a space vehicle will be discussed to illustrate the potential advantages electrical propulsion has over chemical propulsion, but first it should be noted that the thrust of a rocket is given by

$$F = v_e \frac{dM}{dt} \qquad \ldots (2)$$

and the minimum power required is given by

$$P = \frac{v_e^2}{2} \frac{dM}{dt} = \tfrac{1}{2} F \, v_e \qquad \ldots (3)$$

The exhaust velocity from a chemical rocket is typically a few km/sec; higher velocities cannot be obtained from chemical reactions. A chemical rocket capable of launching even a small satellite (100 kg) into a low orbit around the earth uses hundreds of kilograms of fuel a second and works at a power of thousands of megawatts; these prodigious flows are necessary to give enough thrust (about 10^6N) to overcome gravity during 'lift-off'. It is inconceivable that an electric thrustor could ever approach this performance or even produce enough thrust at the Earth's surface to lift the weight of its power supply and propellant.

Once in orbit the situation is different; the vehicle is now in an essentially friction-free environment and even a minute thrust will produce a corresponding reaction and movement. For instance a thrust of one tenth of a newton (about 1/40 lb weight) can be obtained for a power of 2·5 kW by a mass flow rate of 2×10^{-3} gm/sec and an exhaust velocity of 50 km/sec (see Fig.1). In one month this thrust could accelerate 100 kg to 2 km/sec for the expenditure of 5 kg of propellant.

Detailed analysis is necessary before a proper comparison can be made between competing propulsion systems; this exercise is known as mission analysis and is a subject in its own right. However it is possible to make a few generalizations. For most missions the best compromise arises when the mass of the power supply and thrustor, the propellant mass and the payload mass are of the same order of magnitude. The optimum exhaust velocities for missions within the Solar System and using existing technology lie in the range 10 - 100 km/sec; higher exhaust velocities call for excessively massive power supplies while lower velocities require too much propellant mass and usually are not competitive with chemical rockets. As longer and longer journeys are considered electric propulsion becomes increasingly attractive until a stage is reached when chemical rockets are impractical. Recent estimates (e.g. see ref.1) show that with existing technology, 1,800 lb of scientific instrumentation could be placed in an orbit around Mars using a Saturn 1B/Centaur launch vehicle if electric propulsion were used between Earth and Mars; this payload is reduced by nearly a factor four if chemicals alone are used. It is also estimated that the cost of orbiting 6,000 lb around Mars could be halved by using electric propulsion with a saving of some $ 100,000,000!

Electric propulsion is particularly suited to missions where a source of electric power must be available for some other function. For example if an atomic reactor has to be transported to the Moon for a permanent space station then there are obvious attractions in using the reactor for propulsion during transit. Similarly a space probe to Jupiter might need 100 watts of power from solar panels for sending information back to earth; the power from these panels is available for propulsion during the journey. One mission, in which electric power is already available, has recently attracted the attention of engineers at R.A.E. Farnborough. Communication satellites have most scope when placed in a synchronous or geostationary orbit. (An altitude of 36,000 km.) A launcher capable of putting useful payload into a synchronous orbit is several times bigger than the rocket needed to place the same payload into a low orbit (say 500 km). An electric propulsion system using the power finally needed for relaying messages could in principle spiral the satellite from the low orbit to a synchronous orbit without a drastic reduction in payload, thus allowing the smaller launcher to be used.

The uses for electric propulsion mentioned so far come under the heading of primary propulsion where the need is to transport payload from one point to another. Electric propulsion shows more immediate promise in attitude control and station-keeping. Often a satellite must maintain its attitude with respect to the Sun or the Earth; this need arises when directional aerials or an array of solar panels are used. Very small but precise thrusts are required for maintaining attitude. Although the environment of space is friction-free by most terrestrial standards finite perturbing torques and forces exist due to pressure from the Sun's radiation, local variations of the Earth's gravitational field, outgassing from the satellite, interaction of the satellite with the Earth's magnetic field and other effects; the torques disorientate the satellite while the forces change its orbital position. At present jets of gas, inertia-wheels or passive techniques relying on the gradient in gravitational potential may be used for attitude control while gas jets or sophisticated chemical systems allowing precise control are used for station-keeping and the final placement of the satellite into its exact orbit (e.g. see ref.3). The thrusts required for satellite control are often no more than a few dynes (about 1 mg weight) and the power a few watts. With cold gas systems the energy per unit mass of propulsion system is very low and electric propulsion starts to be competitive once the planned lifetime of the satellite extends into years, (e.g. ref.4). The use of electric propulsion for satellite control is already a practical possibility (ref.5).

3. TYPES OF ELECTRIC THRUSTOR (Ref. 6, 7 and 8)

The following section gives a brief description of the main types of electric thrustors and indicates the state of development reached.

RESISTOJETS

The resistojet is the simplest of electric thrustors; it consists of a jet in which the gas is passed through an electrically heated duct and raised in temperature to $1000^{o}C$ or more before expanding through a nozzle (see Fig.2). Exhaust velocities lie in the range 1 - 10 km/sec. Although resistojets using 3 - 30 kW have been built they are usually much smaller being about a millimetre in diameter and using some tens of watts; their main attractions are simplicity, reliability and high efficiency. Resistojets have excellent prospects for satellite control and have already been used operationally. Low molecular weight propellants are preferred because they give the highest exhaust velocities. The other main constraints on the choice of propellant are that it is easy to store and does not decompose to leave a solid residue at its operating temperature.

ARCJETS

Like the resistojet the arcjet is classed as an electrothermal accelerator but the incoming gas is heated by an electric arc, instead of a heating element, before passing through an expansion nozzle (see Fig.3). The arcjet can achieve higher temperature and hence higher exhaust velocities than the resistojet. Power levels are in the range 30-300 kW and 50% or more of the electrical energy supplied can be turned into kinetic energy in the exhaust. (The rest of the energy is dissipated in electrode losses, radiation, ionization and thermal energy.) Much development work has gone into arcjets in the last decade and considerable progress has been made in reducing electrode erosion and increasing life but for many applications interest is moving from the thermal arcjet to the M.P.D. arc.

M.P.D. (MAGNETO-PLASMA-DYNAMIC) ARCS

M.P.D. arc thrustors have developed from two sources, firstly from high power arcjets and secondly from the d.c. plasma accelerators which use an externally produced magnetic field in the same fashion as the liquid metal electromagnetic pumps used for cooling fission reactors. The general term M.P.D. arc is applied to a variety of devices which include Hall Current accelerators, magnetic annular arcs and high impulse arcs. M.P.D. arcs operate at high power (tens to hundreds of kilowatts) and use the magnetic force derived from currents interacting with magnetic fields to accelerate partially or fully ionized gas. In appearance they resemble arcjets with external coils or magnets. The thrust from M.P.D. arcs is typically measured in kilograms and exhaust velocities lie in the range 10 - 100 km/sec; they show most promise as a means of primary propulsion. Typical propellants are hydrogen, nitrogen, ammonia and lithium. (Alkali earth metals are attractive as propellants because they have a small first ionization potential coupled with a large subsequent excitation potential.) In common with the arcjet, electrode erosion is a problem but life tests lasting for days at 200 kW and more have been reported.

PULSED PLASMA THRUSTORS

Plasma thrustors are essentially high power devices; pulsed operation offers the attraction of arbitrarily low mean power levels to suit available power supplies and a variety of missions. The price paid is increased complexity and mass of the associated equipment; storage capacitors and fast switching systems for both electric power and propellant are required. A wide variety of pulsed thrustors giving exhaust velocities in the range 10 - 100 km/sec have been investigated in the last decade. Recently the accent has moved from devices using energies of the order of a hundred joules per pulse to thrustors for satellite control using a few joules per pulse. A prototype flight system has been made in which the thrustor is a spark which ablates a capillary-fed liquid propellant (ref.9).

ION ENGINES

To date ion engines have absorbed about three quarters of the United States effort on electric thrustors and consequently have reached a highly developed state.

Ion engines use electrostatic fields to accelerate ions. They are like the electron guns used in travelling-wave tubes and klystrons except ions, rather than electrons, are accelerated. Just as an electron gun needs a thermionic cathode to supply electrons so an ion engine must have some method of ionizing the propellant to produce a steady flow of ions available for acceleration. One of two methods is commonly used, namely surface ionization or ionization by a gas discharge. Surface ionization is used in the contact engines where the propellant (caesium vapour) diffuses through a slab of porous tungsten heated to 1200^{o}C or more. The caesium atoms become ionized at the surface of the tungsten and are accelerated by one or more negative grids (see Fig.4). The electron bombardment engine uses a gas discharge to ionize the propellant. Mercury or caesium vapour is fed into the gas discharge and ions are extracted by a negative grid and then accelerated.

If an ion gun, isolated in space, emits only positive ions it will become increasingly negative until the escaping ions are attracted back to the gun. To prevent this occurrence electrons are injected into the beam of accelerated ions thus neutralizing their charge. Fortunately neutralization of the ion beam has proved to be quite simple in practice but, because of the difficulty of simulating the situation in the laboratory, flight tests were necessary before the last lingering doubts about its efficiency were removed.

Complete ion engine units have been developed and flight-tested. Lifetimes ranging into thousands of hours have been achieved in the laboratory. Mass-to-power ratios as low as 8 kg/kW for 70% overall electrical efficiency have been achieved. These figures include the propellant feed system with its boiler and valving and the electrics for converting the d.c. voltage from solar cells into the various supplies needed by the ion engine. This last operation is known as power conditioning and represents a major part of ion engine development; not only must the supply voltages be changed but logic circuits are needed for controlling start-up, shut-down, propellant flow rate, and fault diagnosis and correction.

In spite of the complexity of the power conditioning for an ion engine it accounts for only a small fraction of the power losses which determine overall electrical efficiency. The major energy loss occurs in ionization. Although typical ionization voltages are about ten volts or less the average energy expended for each ion formed usually amounts to 500 electron-volts or more. The maximum efficiency of an ion engine is given by

$$\eta_{max} = \frac{\frac{1}{2} M v_e^2}{\frac{1}{2} M v_e^2 + E_I}$$

where E_I is the average energy per ion expended in ionization and $\frac{1}{2} M v_e^2$ is the average kinetic energy of the accelerated ions. At exhaust velocities much less than 30 km/sec, where for typical propellants, E_I and $\frac{1}{2} M v_e^2$ are comparable, existing ion engines are inefficient.

4. POWER SUPPLIES

Finally, no matter how efficient, light and compact electric thrustors become their success as a viable method of propulsion depends on the existence of light-weight sources of electrical energy.

The source of electrical energy on practically every long-life satellite launched to date has been solar panels incorporating silicon photovoltaic cells. They have proved to be highly reliable; their main disadvantage is that they are cumbersome. In the vicinity of the Earth's orbit solar panels can supply 0·1 kW/m^2 (10% efficient) with a mass-to-power ratio of 30 kg/kW. Consequently a kilowatt solar cell array is large and needs some kind of unfurling mechanism. In spite of their size and expense solar panels of tens of kilowatts are feasible.

For higher power still, and for missions remote from the Sun a fission reactor appears to be the most promising energy source. Present estimates indicate that 20 kg/kW is possible, however it will be many years yet before the first fission powered space probe leaves the Solar System.

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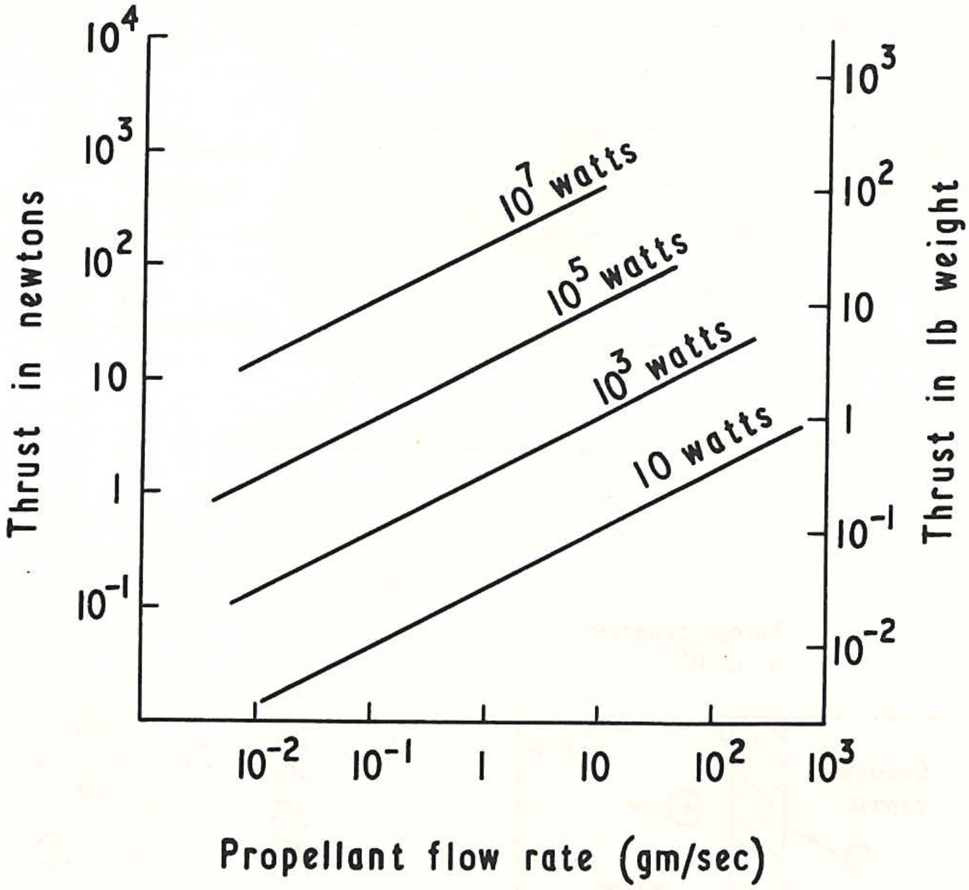

Fig. 1 (CLM-P 148)
Thrust as a function of power and propellant flow rate

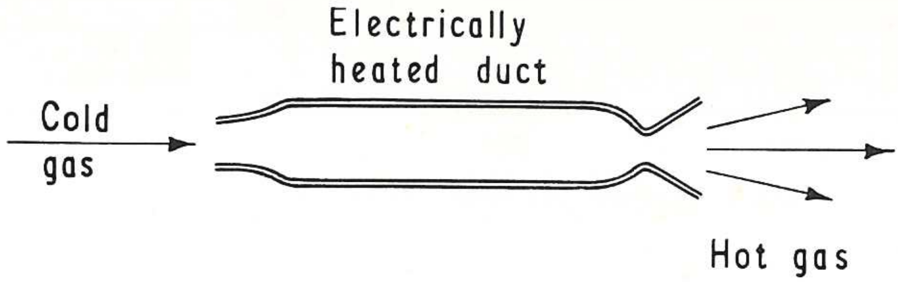

Fig. 2 Schematic of a resistojet (CLM-P 148)

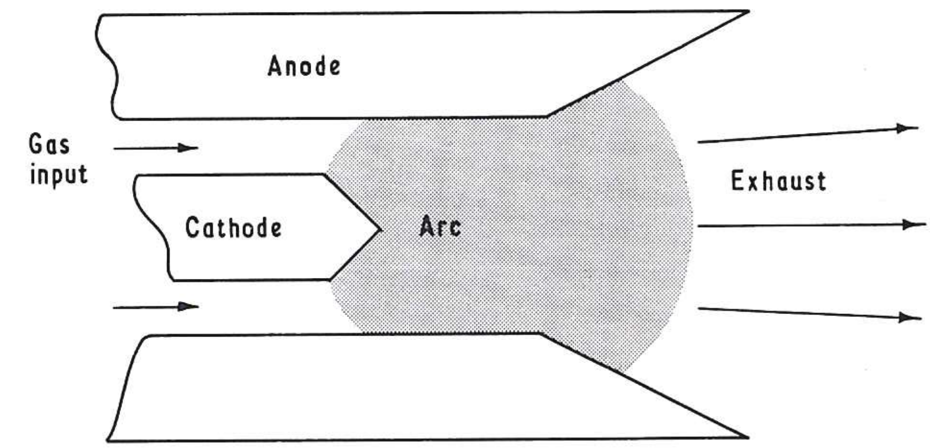

Fig. 3 Schematic of an arcjet (CLM-P 148)

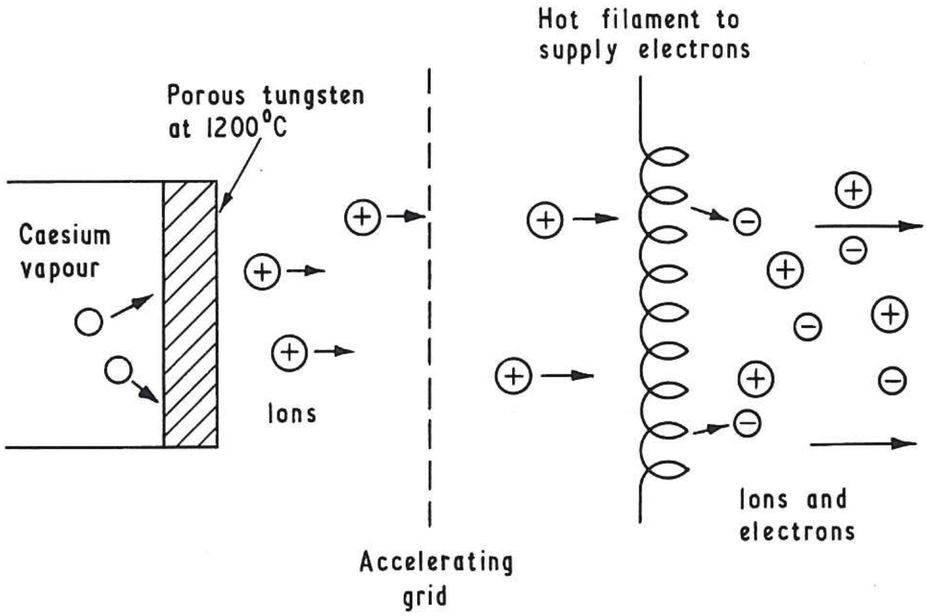

Fig. 4 Schematic of a contact ion engine (CLM-P 148)