Electric Propulsion for Small Spacecraft

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Electric Propulsion (EP) is that in which electrical energy, rather than chemical energy, is used to accelerate a propellant to produce thrust. This paper surveys the EP technologies applicable for use on small spacecraft, paying attention to the unique constraints imposed by this application. The very high specific impulse that can be generated by an EP system offers the potential of greatly expanding the scope of missions that can be achieved by small spacecraft. The paper considers the various missions already identified, and outlines a promising small deep space probe using ion propulsion.

Introduction

While many small satellite missions can be accomplished with simple spacecraft, without propulsive capability (and even without attitude control,) the range of missions that can be accomplished with a given size of spacecraft can be greatly enhanced if the spacecraft is able to manoeuvre.

Any kind of propulsion system obeys the principle of conservation of momentum (a manifestation of Newton's third law.) If the spacecraft's momentum in a given direction is to be increased, there must be an equal and opposite change in the momentum of the propellant, such that overall momentum of the spacecraft-propellant system is conserved. Since momentum is the product of mass and velocity, it follows that if a given spacecraft velocity change (delta-v) is required, a lower propellant mass requirement can be achieved if the exhaust velocity of the expelled propellant is high.

In conventional chemical rocket propulsion, the propellant is given thermal energy by a violent chemical reaction. By expanding the hot exhaust gases through a nozzle, the temperature and pressure of the gases is reduced, this energy being converted into the kinetic energy of a jet. In electric propulsion, the propellant's kinetic energy is derived from electrical energy.

Types of Electric Propulsion

There are various ways of converting electrical energy into kinetic energy. one method that is closely allied to chemical propulsion is the simplest form of EP, the resistojet. Here, ohmic heating caused by an electric current through a heater raises the temperature of the propellant stream. Again, the hot exhaust gas is accelerated aerodynamically in a convergentdivergent nozzle. The performance of this type of thruster is limited by the properties of the propellant, and by the temperature that can be attained in the thruster.

A particular type of resistojet is the Power-Augmented Electrothermal Hydrazine Thruster (PAEHT) - here the energy of the exhaust gas comes both from electrical heating and from the decomposition of hydrazine (which may be triggered catalytically, thermally, or both.)

In the arcjet, the gas is again heated and expanded through a nozzle. The heating mechanism this time is an electric arc, through which the propellant passes before being exhausted. The performance of an arcjet can be higher than that of a resistojet since higher temperatures can be obtained.

A further refinement is the MPD (magnetoplasmadynamic) thruster. This is essentially an arcjet which exploits the fact that a gas heated to extreme temperatures will ionise. The charged ions are again accelerated (in part) aerodynamically, but also through the interaction with a magnetic field, generated by the high currents in the thruster. Such thrusters are most efficient when operated at the Megawatt power level - frequently therefore such thrusters are operated in a pulsed mode.

One type of MPD thruster particularly appropriate for small satellites is the plasma rail gun. Here an electric arc is struck between two long electrodes across the surface of an insulating propellant (usually Teflon) - a small quantity is vapourised and ionised. It therefore conducts a current between the two electrodes and the combined magnetic fields of the currents accelerate the conducting plasma away.

A rather less violent method of acceleration is electrostatic acceleration. Here charged droplets or ions are generated and simply accelerated through an electric field. While the thrust levels of electrostatic systems are very much lower than the thermal or MPD systems, the exhaust velocities that can be attained are very kigh - of the order of 30km/s. This high specific impulse (specific impulse Isp equals thrust per unit weight flow, i.e. exhaust velocity divided by gravity) implies that to achieve a given velocity change, a very small propellant mass is needed.

The charged species that are accelerated in electrostatic propulsion can be generated in a number of ways. The American, Japanese and British ion thrusters are of the so-called Kaufman type, the ions being produced by electron bombardment. The German ion thruster uses radio frquency radiation to excite the ionisation of its propellant. In the colloid thruster, unfortunately abandoned by the USA and Europe in the early 1970s, a glycerol-based solution is 'sprayed' from sharp edges, slits or needles (under the influence of the intense electric field at the edge, the liquid can no longer sustain its meniscus and tiny multimolecular droplets are emitted. A similar process occurs to produce caesium ions in the Field Emission thruster under development in Europe.

Reference (1) gives a useful introduction to the various types of EP.

A final type of EP worth mentioning, is the electrolysis thruster. Here, water is stored as a liquid and dissociated electrolytically in orbit to produce hydrogen and oxygen which are then combusted as in a chemical rocket motor. Such a thruster, if it could be made to operate efficiently, reliably and safely, would be very useful for a range of missions. However, such a thruster has yet to be developed successfully.

Advantages of Electric Propulsion

While some types of electric propulsion (e.g. low power resistojets) have lower specific impulse than chemical systems, an obvious generic advantage of electric propulsion is the very high exhaust velocity, enabling large manoeuvres with low propellant mass. For large manoeuvres, then, the overall propulsion system mass is lower. The low propellant requirement also means that the volume allocation for propulsion is reduced.

Most EP systems use (or can use) fairly inert propellants. Ion thrusters are being weaned off mercury and now use Xenon as propellant. Arcjets and resistojets can use a variety of fluids - Freons, Ammonia, Propane and even water. As ground processing costs are often a large budget item, the avoidance of highly toxic, corrosive, flammable, explosive and carcinogenic fuels simplifies matters greatly. In addition, several launch options (e.g. STS GAS) would prohibit the use of reactive fuels.

Most electric propulsion systems can be easily throttled - by simply varying flowrate and/or voltage or power, the thrust and specific impulse can be varied. For example, the UK-10 ion thruster has been demonstrated over a thrust range of 10 to 70 mN. This flexibility is useful if, for example, power budget fluctuates throughout the mission, or delicate manoeuvres such as stationkeeping are to be performed.

Spacecraft charging, particularly at high (e.g. geosynchronous) altitudes is a problem that can cause many spacecraft anomalies and even failure. The beam from an ion thruster can be used to electrically couple the spacecraft to the space plasma, thereby leaking any charge build-up.

An important fact is that EP systems, many of which have been ready or in development for decades, are technologically interesting. The economics of a technology demonstration mission can be greatly improved if the propulsion system can be regarded as a payload.

Constraints on Small Satellites

The principal constraints on a small spacecraft are cost, volume, mass and power. While obviously the propulsion system for any given application must be considered individually, it is possible to make some generalisations.

For very low mass spacecraft (10s of kg) a simple chemical propulsion system (e.g hydrazine monopropellant) will have a lower total mass than any electric system of an equivalent impulse. Here, the electric system either requires a larger propellant mass because of its low specific impulse (in the case of low-performance devices such as resistojets) or in the case of higher performance systems, the large dry mass of the system offsets the small propellant requirement.

In volumetric terms the problems are again the same - offsetting the overheads of larger electric thrusters and their power processing electronics against a lower propellant requirement. (Here propellant density becomes an influence in propellant selection.)

Power is (perhaps not surprisingly) a crucial constraint - there is a lot of kinetic energy in a rocket exhaust. It is for this reason that EP systems as a rule are low thrust systems. The power available on a spacecraft (a function of the solar array size and geometry, and of spacecraft orbit and attitude) must be shared among the various systems and payload. The power requirement of many thrusters is such that they could not be operated continuously - power would have to be stored in a battery. There are then effectively two constraints on thruster operation: first the total energy generated by the solar arrays during (say) one orbit must be sufficient to operate the thruster for the required burn time; second, the burn time will be limited by the energy that is stored in the battery.

Note that because many thrusters need peculiar power requirements, e.g. high currents and/or voltages, a large amount of power conversion and conditioning electronics is needed. This introduces mass and volume overheads, and also leads to losses in overally system efficiency. One approach being looked at (by, for example, the Japanese(2)) is to wire solar arrays to produce high voltages, running ion thrusters from them directly (of course, this approach limits thrusting to sunlit periods.)

Cost is a very difficult design driver to quantify. However, it is the author's belief that cost is not (at present) a problem. The technology of resistojets is such that low-performance devices can be built by virtually anyone. In-house development of a resistojet (and perhaps even an arcjet) should be quite possible with modest facilities. As for ion thrusters, these have been in development for some time by universities and research establishments, but actual flights are rare. Consequently there is, from a technology demonstration point of view, a reasonable demand for the flight of these devices, such that the system could be regarded as a payload.

The mission itself will pose constraints. In general, the thrust of electric propulsion systems is orders of magnitude below that of chemical systems. The impact of this feature must be considered in the spacecraft design. The thrust level (when scaled by the duty cycle as determined by attitude and power constraints) must be adequate for the mission. On low altitude spacecraft, the average thrust must exceed the atmospheric drag to prevent orbital decay. If orbit-raising is to be attempted, the thrust must exceed the drag by a factor of 2-3 if large drag penalties are to be avoided. In addition, the transfer time to accomplish the manoeuvre may be important. For example in spiral orbit raising, say to lunar or geosynchronous altitudes, the transfer time can be of the order of years. On such missions, the time spent in the Van Allen radiation belts can be crucial in sizing the solar arrays of the craft.

Previously-Identified Missions

It is now appropriate to review the missions that have already been identified as benefitting from the application of EP.

T-SAT (UK) There was, for a couple of years, a project which involved many UK universities and research establishments. The Technology Satellite (T-SAT) was to have demonstrated a wide range of spacecraft technologies and conduct mobile communications experiments(3). The spacecraft was to have been placed into a Molniya orbit, i.e. one in which the spacecraft loiters at apogee roughly above the UK. However, the Molniya orbit is not a truly repeating one, so stationkeeping is necessary to prevent a drift in the longitude of the apogee. The required impulsive Delta-Vs are 0.0618 m/s and .0070 m/s at apogee and perigee respectively. Thus over one year, the total velocity increment is about 100 m/s, requiring only 2kg of Xenon propellant (4) for an on-orbit mass of 600kg.

A chemical (hydrazine) propulsion system was to have been carried for the purpose, but an ion thruster was also to have been carried. This was to have space-qualified the UK ion thruster. If the thruster failed, the 'safe' chemical system would have operated for the required mission life. In the event that all systems performed well, the use of the ion thruster after the chemical propellant ran out would have significantly extended the effective life of the spacecraft.

AMSAT Phase 3D (West Germany) AMSAT-Deutschland was largely responsible for the successful OSCAR 10 and OSCAR 13 communication satellites. These used bipropellant motors to change their inclination from about 7 (Ariane GTO) to 59 degrees to improve high latitude coverage. This manoeuvre involves at least two burns, amounting to a total Delta-v ofabout 1500 m/s.

The motors used were virtually museum pieces, being modified left-over vernier thrusters from the abandoned ELDO launch vehicle 'Europa'(5). The supply of these motors is exhausted, and AMSAT wishes to avoid the safety problems associated with using unpleasant rocket fuels. AMSAT-DL considered developing a water electrolysis rocket, but was wary of the dangers of such thrusters (indeed, development attempts have resulted in at least one fatal accident (6)). Consequently AMSAT-DL is developing its own plasma thruster, using a water-based propellant (7).

PACSAT (UK/US) Pacsat was an AMSAT/VITA/UoSAT project to develop a store-and-forward communications satellite to service relief workers in isolated areas (VITA is Volunteers in Technical Assistance.) The spacecraft was to be deployed into polar orbit from a shuttle GAS canister (6). However, orbital lifetime at 350km is very limited, so the vehicle was to have raised its orbit to 800km (Delta-v 300m/s.) The vehicle was to have been magnetically stabilised such that its axis pointed along the orbit twice each orbit. The thruster duty cycle would be in the range 2-10%, sizing the thruster at 189 mN for Isp 89s. Thruster power would be around 60W, using Freon 114 propellant. (Note that ammonia would normally be used in preference, but a GAS satellite has very tight volume constraints so the higher density of F114 led to its selection over ammonia.)

UoGAS (UK) This study (8), conducted by the author at the UoSAT Unit, University of Surrey, re-examined the PACSAT concept. It was calculated that a satisfactory lifetime could be obtained by raising the orbit from STS deployment at 350km to 500km (Delta-v 100 to 140 m/s, depending on atmospheric conditions.) An aerodynamic stabilisation system was devised whereby the the long axis of the spacecraft could be kept continuously within, say, 10 degrees of the velocity vector, allowing continuous operation of the thruster. A resistojet was identified as the best thruster option, however, no propellant selection was made, as the optimum propellant depends to a great extent on what is permitted for safety reasons. For GAS and some other launchers, these were unclear. However, a useful feature of resistojets is that they can be fed virtually anything - hydrocarbons, Freons, ammonia, water and so on. The thrust would be in the millinewton range, with power of the order of ten watts for a specific impulse of the order of 100 seconds.

LGAS (US) The Lunar Get-Away Special was a JPL study which really got people thinking about small satellites, and electric propulsion for small satellites in particular. The 150kg satellite (9) was to be deployed from an extended Get Away Special canister on the Space Shuttle into a low orbit. After unfurling long (17m) arrays and spinning up (spin axis along sun vector) the spacecraft would use ion thrusters (firing on two 90 degree arcs per orbit) to raise the orbit to lunar altitude - over the period of two years. The craft would then insert into a polar lunar orbit and use a gamma ray spectrometer to locate water on the lunar surface - the total delta-v is of the order of 8 km/s, using only 36kg of xenon propellant.

One interesting feature of this mission is that phasing orbits would be required. After raising its orbit to just below that at which radiation effects occur, the spacecraft would coast for one to three months waiting for favourable sun angles before making a headlong dash through the radiation belts. High doses of radiation reduce the efficiency of power conversion electronics and (more importantly) the efficiency of the solar arrays.

A UK team (Ryden, Herrington and Wallace) have considered a similar mission. Their proposal (10) is for a 300kg spacecraft to be launched into a low circular orbit, from where it would use ion thrusters to climb to lunar altitude (over about 1200 days!) The spacecraft would rendezvous with the Kordylewski clouds, 'patches' of luminosity about 6 degrees wide as seen from the Earth. These clouds move around the L4 and L5 libration points in the Earth-Moon system and are an analogue of the Trojan asteroids in the Sun-Jupiter system. they are though to contain material derived from meteoric collisions with the moon.

STRV (UK) The Royal Aerospace Establishment in the UK (one of two centres, the other being the Atomic Energy Authority's Culham Laboratory, where the UK ion thrusters are developed) has suggested an ion propelled mission for technology demonstration(11). As well as space-proving the ion thrusters, other technologies such as on-board data processing systems, power systems (such as new Nickel Hydrogen batteries and GaAs solar cells) would be flown. The Space Technology Research Vehicle would raise its orbit to some thousands of kilometres, thus exposing the craft to different radiation environments - the craft could also return useful science data: a plasma diagnostic package would monitor the effect of the ion thruster on the spacecraft environment, while other sensors would detect incident cosmic particles and would measure the total radiation dose received by the satellite.

ASAP (UK) The author conducted a study at the UoSAT Unit, University of Surrey, to see what can be accomplished with very small satellites (of order 40kg - the size that can be accommodated on the Ariane Structure for Auxiliary Payloads ASAP.) It was found (12) that adventurous missions (e.g. GTO to Molniya) were virtually impossible. While the ion thruster system required only a few kg of propellant, its dry mass was about 20kg, leaving only 20-30kg for the rest of the spacecraft. Also the transfer time would be of the order of 2 years. Some less adventurous missions such as raising the apogee of a 1000km orbit to 2000km (for radiation studies, for example) would be possible with a limited payload using a resistojet system, but for all practical purposes, a hydrazine monopropellant (chemical) system is best for this size of spacecraft.

A Proposed New Mission

One of the most exciting areas of the aerospace world is that of planetary exploration, which expands the frontiers of both our knowledge and the technology we employ to get it. Deep space missions are generally characterised by large distances (causing communications difficulties and leading to long mission durations) and by large delta-v requirements.

The combination of long mission durations and large delta-v lends itself nicely to the small but persistent thrust of high-performance electric propulsion systems. Indeed, a number of missions can **only** be accomplished with present technology if electric propulsion is used (among examples are interstellar precursor mission, Neptune orbiter and Saturn ring rendezvous (13))

However, another useful function of EP is to facilitate missions that would otherwise be merely difficult, rather than impossible. There is much interest in expanding our knowledge of the minor, primitive bodies of the solar system, in particular the asteroids. While flyby and rendezvous missions are quite possible using chemical propulsion, these missions are still in the 'big science' category, with price tags in the hundreds of accounting units (one accounting unit approximately equals one US dollar.)

On the other hand, more adventurous missions are proposed by the advocates of electric propulsion. An example is a comet nucleus sample return mission proposed by German scientists (14). This spacecraft would use a dedicated Shuttle launch and a Centaur G-Prime upper stage. The 9600 kg spacecraft would unfurl 60m solar arrays generating 50kW to power 8 35cm 200mN thrusters. While a mission of this sort would be a great engineering achievement and of immense scientific value, we again find the cost of the mission unacceptable.

However, a small, electrically propelled probe could have the delta-v capability of performing a rendezvous with one of the nearer asteroids, and yet still be able to be launched as a secondary payload on a GTO launcher such as Ariane. The study of such a mission is to be the subject of the author's final year project for an Aerospace Systems Engineering B.Eng. degree at Southampton.

Consider a 260 kg spacecraft (recall that such trailblazing missions as Pioneer 10 and Mariner 4 were performed using spacecraft of this mass (15)) with modest solar arrays generating 1-2 kilowatts. An instrument payload of about 50kg would be carried, probably including a visible imaging camera, an infrared spectrometer and a gamma ray spectrometer.

Such a spacecraft would also carry about 40kg of Xenon propellant, allowing a post-launch delta-v of over 4km/s. After launch into GTO, the spacecraft would use an off-the-shelf solid rocket motor (say Thiokol STAR-24) to achieve escape velocity.

Thus the launch mass would be well under 700 kg, meaning that the spacecraft could be accommodated in the payload mass increment obtained by upgrading the booster suite on an Ariane 4 (e.g. Ariane 40 to 42P.) The total launch costs therefore should be under 10 MAU (16). A total mission cost of 20-50 MAU should be quite feasible.

As with other small spacecraft, the use of a system for more than one function can greatly enhance the capability of the spacecraft. Among possibilities being examined are the use of the communications antenna for ranging measurements prior to rendezvous and the use of the imaging camera to acquire the asteroid for navigational information.

Another possible 'trick' is the use of the ion thruster system as part of a remote chemistry experiment. One of the mechanisms by which ion thrusters 'wear' out is by sputtering of the molybdenum acceleration electrode. The impinging high-energy ions knock out atoms from solids they impact upon. By directing the exhaust of the ion thruster at the asteroid surface, atoms from the surface will be 'blown off'. These emitted atoms can be analysed in a mass spectrometer to determine the elemental composition of the asteroid surface, and any absorbed solar wind. (An experiment of this type was flown on the unfortunate Soviet Phobos probe. The 'DION' experiment was to have used a krypton ion beam accelerated through 2-3 kV : an ion thruster would have a 1-2.5 kV xenon beam.)

Another potential mass-saving area is attitude control. Modern CCD cameras can act as small, cheap star sensors and fibre-optic gyros are becoming inexpensive and are very small. As for actuators, the precise pointing of a spacecraft requires thrusters with a very low impulse bit, such that frequently hydrazine thrusters cannot be used and an additional cold gas propulsion system must be carried. On this spacecraft, the Xenon propellant for the ion thrusters can be used in cold gas jets for attitude control (slightly lower impulse bits, but greater specific impulse could be obtained if heated thrusters 'resistojets' were used.)

Note that if the asteroid is only a few tens of kilometres in diameter, the surface gravity would be low enough that the thrust from an ion engine would be sufficient to enable a soft landing (although this would greatly complicate the mission.)

During the author's literature search for the project, it was found that a group incorporating AMSAT-Deutschland had proposed a very similar mission (17) (incorporating several of the above 'tricks') for the Ariane Apex 401 flight (on which AMSAT Phase 3C eventually flew.) Interestingly, the mission was not funded because the appropriate authorities could not believe how inexpensive it would be(18).

Conclusions

Electric Propulsion offers the possibility of much more technologically and scientifically exciting missions with small spacecraft. In addition, the constraints placed on small satellites mean that some more standard missions may benefit from the use of electric propulsion owing to the safer propellant and lower propellant mass requirement.

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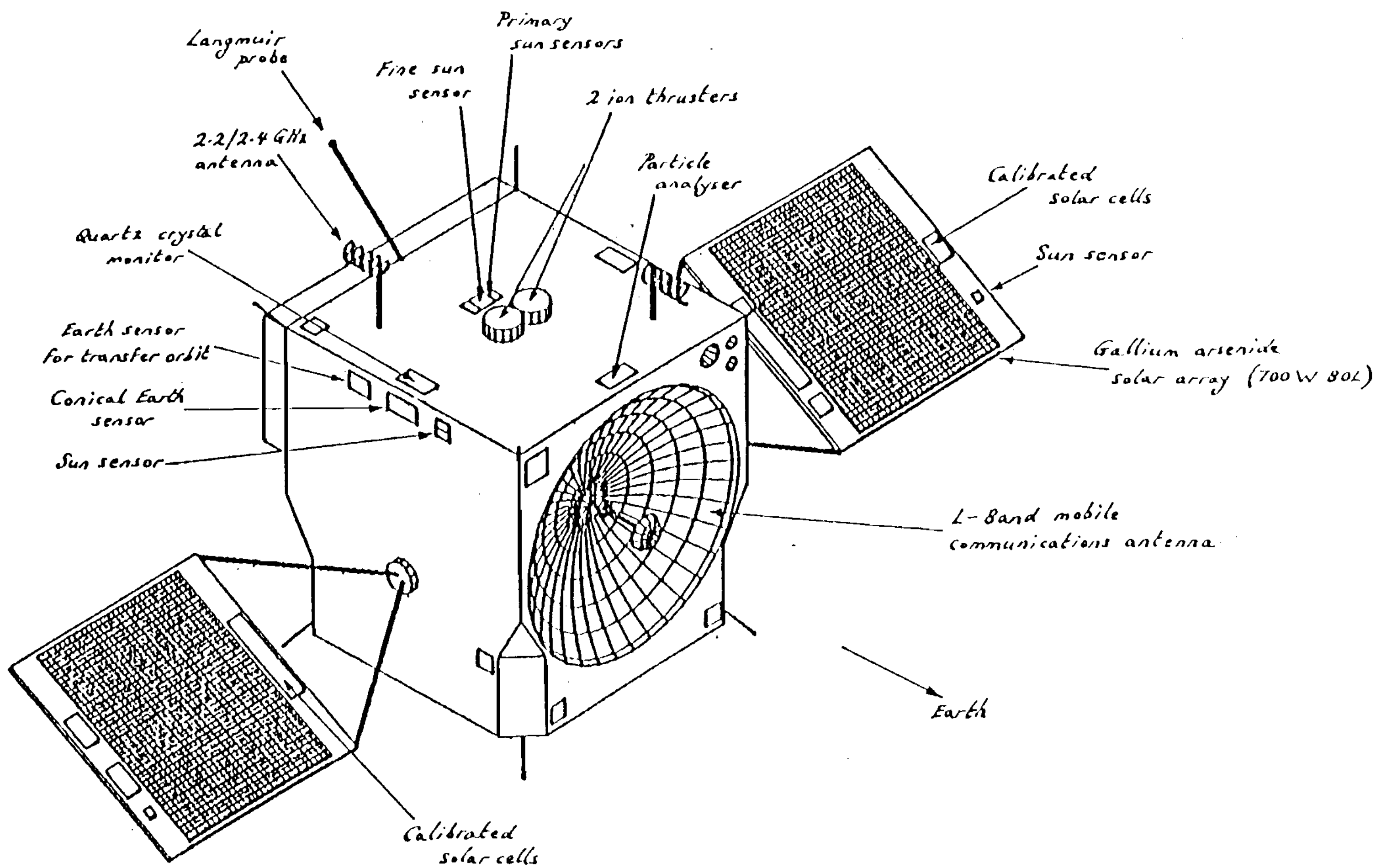
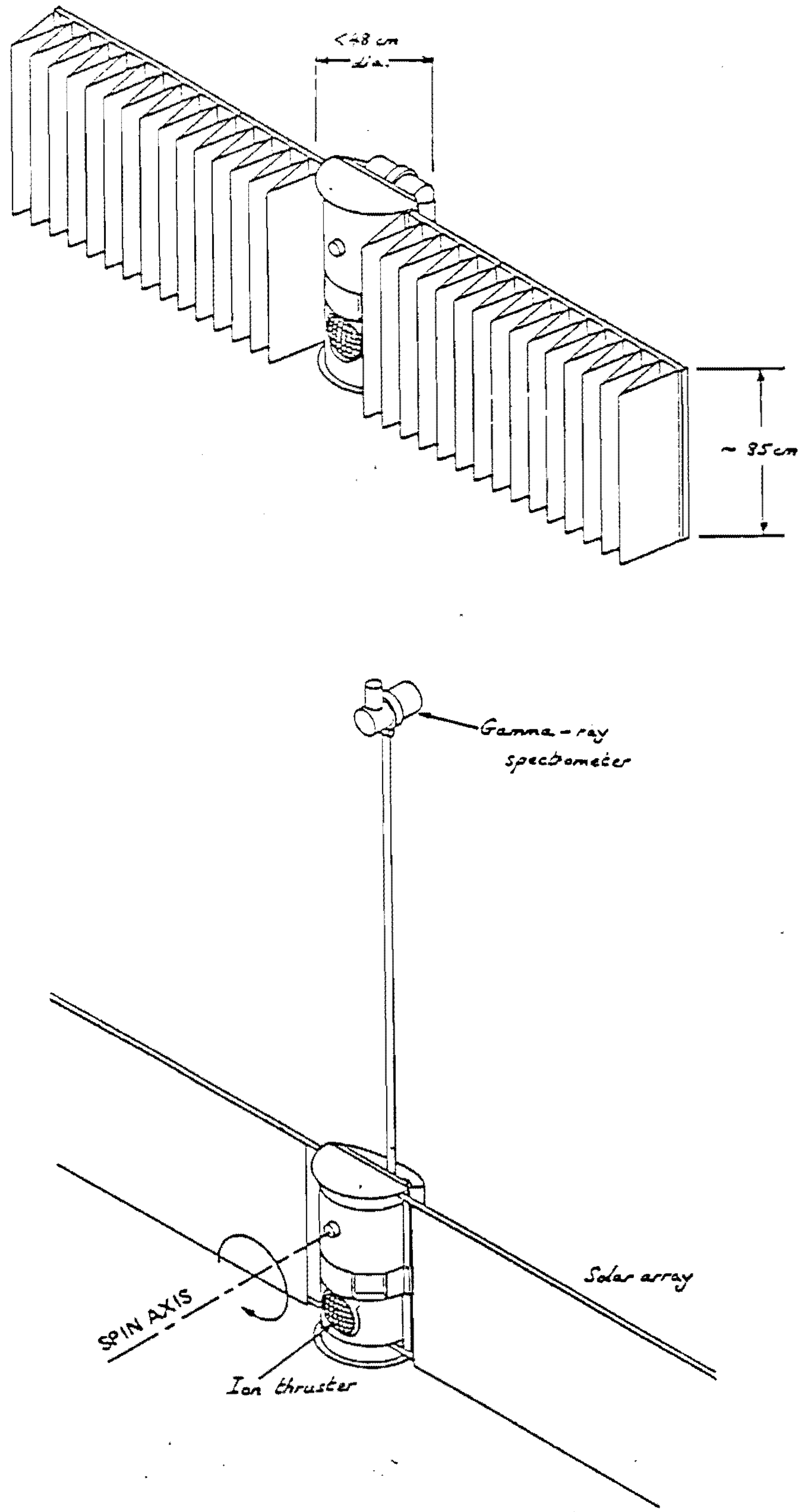
Table 1. Nominal Parameters For various Electric Thrusters Suitable for Small Spacecraft

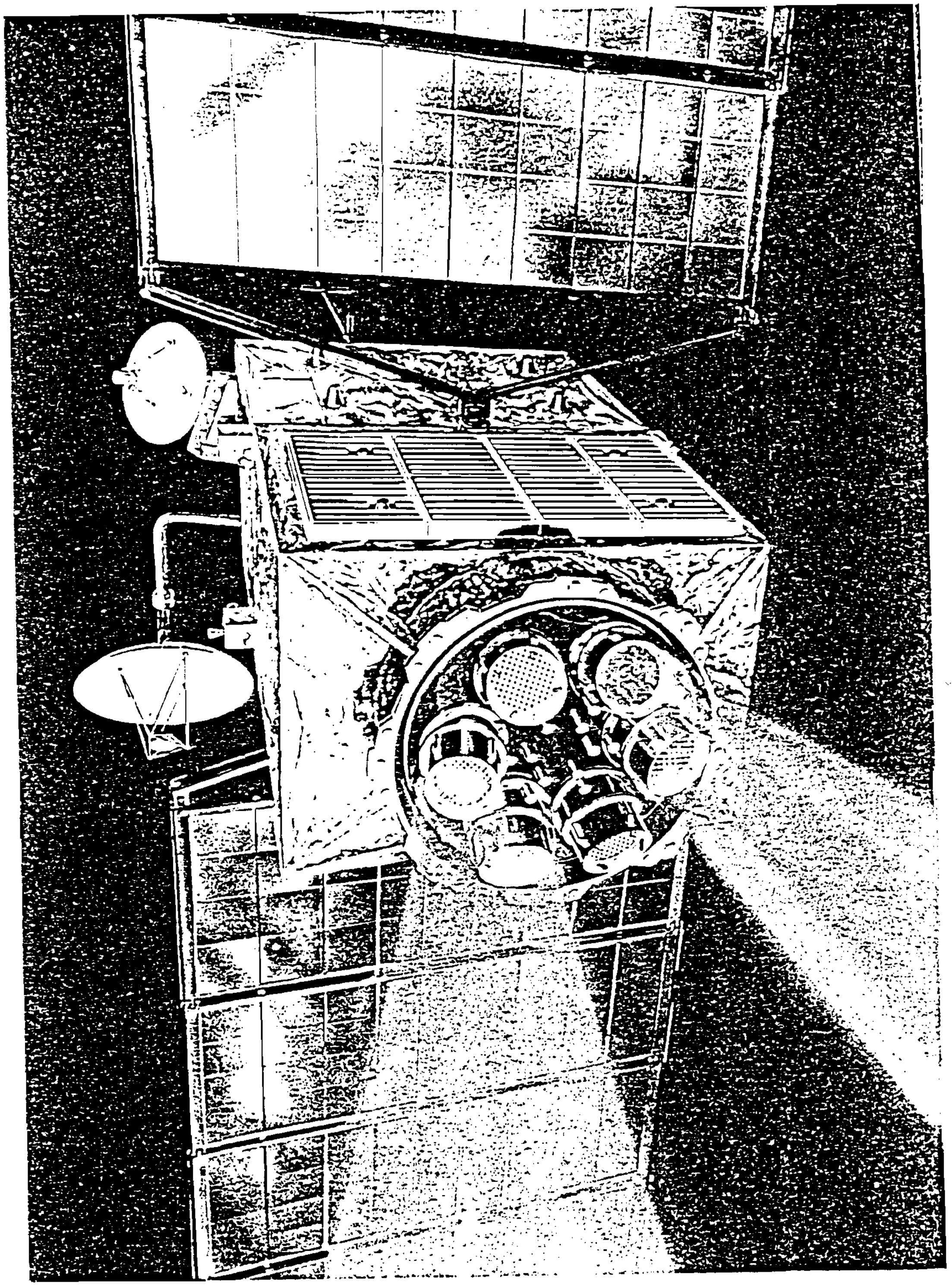
SYSTEM	THRUST	PROPELLANT	POWER	Isp	Mission
UK-10 Ion Thruster	11.4mN	Xe	275W	3033s	STRV, T-SAT
US Thruster (modified SERT II)	42mN	Xe	1420W	4493s	LGAS
AMSAT-DL Plasma Thruster	95mN	water	300W	320s	AMSAT P-3D
PACSAT Thruster	189mN	Freon 114	60W	89s	PACSAT
NASA resistojet	2.2mN	Ammonia	12W	140s	(ref.19)
NASA resistojet	170-360mN	water	443-192W	192s	(ref.20)
Japanese MPD	2mN?	Ammonia	820W	2000s	(ref.2)
Colloid Thruster	0.5mN	Glycerol/NaI	10W	1500s?	(ref.1)
Field Emission	2.5mN	Caesium!	160W	9000s	(ref.1)



The configuration of the (abandoned) UK Technology Satellite



JPL's Proposed LGAS Spacecraft would be launched as a compact cylinder and would then unfurl large solar arrays to power its two ion thrusters



Previous electrically propelled deep-space missions have had an unfortunate tendency to be big and nasty