Abstract

The prospects for a wider utilisation of ion propulsion are outlined as a prerequisite for assessing their possible impact upon spacecraft systems. A manifest is made of all effects which could be detrimental to spacecraft or payload performance and each is examined in terms of the probable risk and available safeguards. In-flight monitoring of the effects will be essential to demonstrate the viability of any particular ion thruster unit and various diagnostic instruments are discussed. Computer simulation provides a valuable tool for estimating plasma interaction effects and some initial results from NASCAP are presented. Problem areas are identified and solutions proposed. In some cases, special measuring techniques are being developed, and these are described in outline.

1. INTRODUCTION

Spacecraft engineers are now increasingly considering ion propulsion for long term station-keeping and orbit changing and the UK rare gas thruster [1,2] is being developed to meet their needs. Ion propulsion has definite advantages in respect of low total system mass and long-term stability of performance; the relatively low thrust can be offset by increasing the period of operation.

However, there is some concern that the use of an ion thruster could give rise to effects which might degrade spacecraft performance due to contamination of spacecraft surfaces, perturbation of the surrounding space plasma, or direct electromagnetic interference. Ion thrusters do have a reputation of being 'dirty', but this really dates back to anxieties over mercury and caesium; with the successful substitution of xenon as the propellant [1], a reassessment of the problem is warranted.

Any thruster must be 'on trial', but the present climate seems to point towards a verdict of 'guilty until proved innocent'. Three possible sources of evidence should be considered:

(1) data from laboratory tests
(2) results from computer simulations
(3) data from in-flight demonstration.

The proof of a negative result is never easy, but the last witness is likely to be the most convincing. For this reason, it is important to consider what diagnostic instruments could be included in a thruster demonstrator satellite. This paper is an interim report by a design study team formed in 1986; the long-term aim being to establish an environmental impact statement for the UK-10 thruster.

2. THE ROLE OF ION THRUSTERS

Putting aside a few spectacular failures, conventional rocket motors have generally been very reliable and their inherent limitations have not introduced serious restraint in the space programme. The potential benefits of electric propulsion (EP) have long been recognised but perhaps their 'Star Trek' image has been unhelpful; the development of thrusters has been slow but the trend towards commercial space activities, with long duration, might now produce the necessary incentives. Many applications have been studied and considered, including attitude control for large distributed over a spacecraft and integrated into spacecraft and very different regimes of space. Any possible 'side-effects' will obviously depend upon spacecraft and very different regimes of space. Any possible 'side-effects' will obviously depend upon

The baseline orbit chosen was Molniya with critical. Increased currents to exposed conductors raising at heights greater than 500 km, north-south station-keeping in GEO, change of orbit plane to comet or asteroid rendezvous and interplanetary navigation. These applications can cover a large range in the size and complexity of spacecraft and very different regimes of space. Any possible 'side-effects' will obviously depend upon the ambient plasma environment, but also the susceptibility of the spacecraft systems to be employed. The baseline orbit chosen was Molniya with inclination 63.4°, apogee 38746 km, and perigee 1610 km; this effectively covers all conditions likely to be encountered on a demonstration mission. Figure 1 illustrates a typical in-flight configuration of the thruster on a representative satellite.

3. POSSIBLE HAZARDS - DIAGNOSTICS

Any hazards due to thruster operation must be put into proper context because the space environment is relatively hostile anyway: conditions of high vacuum, zero g, ultra-violet illumination, thermal stress and penetrating radiation are damaging enough. The following list of additional real or imagined threats needs to be considered:

- condensation of propellant (if Hg or Cs are used)
- electron emission from extraction grids
- change in spacecraft potential
- change in potential of sensitive surfaces
- damaging currents
- damage to local electric fields and ambient plasma
- switching transients → current spikes (e.g. inter-grid arcs)
- inter-grid arcs
- operating fault could enhance (a) to (h)

Opportunities to test fly an ion thruster are hard to find, and chances of adding a comprehensive package of diagnostic instruments are likely to be strictly limited. It is important to decide on the key measurements and then to minimise demands for payload mass, volume, power and telemetry. The localised nature of the problem implies the need for a number of sensors, but compromise will be driven by payload capacities. Instruments will fall into two categories, (A) those designed for routine monitoring - almost a thruster housekeeping function, and (B) those appropriate to a full demonstrator payload - part of the research and development programme.

The choice of xenon as propellant, rather than the mercury or caesium of yesteryear, should remove the hazard of direct metallic condensation on spacecraft surfaces. The potential benefits of electric propulsion have long been recognised but perhaps their 'Star Trek' image has been unhelpful; the development of EP has been slow but the trend towards commercial space activities, with long duration, might now produce the necessary incentives. Many applications have been studied and considered, including attitude control for a spacecraft and integrated into actual solar array panels: since their calibration is temperature dependent, thermists have to be incorporated.

All spacecraft are subject to electrostatic charging due to photo-emission and the incidence of charged particles which make up the natural plasma environment. Large potentials (< 1 kV) can be developed although the charging currents are relatively small (~ 10 nA/m²). The thruster with a beam current of some 225 mA must upset the current balance of the satellite, but an ion thruster cannot work without a neutralising electron emitter and it is the operation of the latter which will be critical. Increased currents to exposed conductors could present problems e.g. solar cell junctions with high potentials would suffer a loss of efficiency if the attracted current got too high: destructive arcing might occur in extreme cases. The extent of any differential charging should be much reduced by the stabilising source of low energy electrons from the neutralizer; however, the ion and electron emissions must not be too far apart and there could be some undesirable consequences. Surface erosion due to increased ion fluxes may be a problem. Since the thruster will not operate continuously, its turn-on might trigger arcing if high potential differences had been established previously.

The ion thruster has an input power of ~ 275 W and uses an electro-magnet, solenoid valves, pressure transducers, heater coils etc. It is necessary to show that the whole system can be kept safe for transients or transient interference, either conducted or radiated. Work is being initiated in this area and will be reported at a later date.

4. KEY MEASUREMENTS - NEW INSTRUMENTS

The ion thruster will emit xenon ions with energy ~ 900 eV but this is only one component of the surrounding plasma population. Close to the source of the thruster beam, the neutralizer supplies ample cold ions and electrons; the latter are carried away to create an overall neutral beam which should not return to the spacecraft. Not all the ionized thruster gas will be accelerated through the grid and a small fraction will leak out with lower energy. Some accelerated ions will strike the extraction grids and sputter molybdenum atoms which will ionize quickly; having low energy (a few eV), these ions will not escape and will add to the deposition on spacecraft surfaces. The low energy neutralizer ions (probably xenon but helium might be preferred) will interact with emitted photoelectrons and form a cold plasma cloud around the spacecraft. Such a cloud should prevent differential surface charging but, given the source asymmetry, this is difficult to guarantee. Neutral atoms due to outgassing or leakage, if ionized and accelerated in the beam, could return to the spacecraft and cause damage. Thruster operation will change the interaction of a satellite with the ambient plasma to such an extent that meaningful measurements of the latter become impractical, beam-particle interactions and the generation of wave instabilities may also be significant.
A full investigation of these effects is a considerable undertaking but work is progressing on all (i) to (iii) avenues listed above. A plasma simulation facility situated at the UKAEA Culham Laboratory [7], will be utilised for the testing of both the thruster and the diagnostic instruments. Four other aspects are now discussed in more detail because they appear to hold the key to the full accreditation of a user-friendly ion thruster.

4.1 Electrons - Langmuir Probes

Probes and retarding potential analysers have been successfully flown on a variety of space missions; usually the objective has been to escape or nullify the influence of the spacecraft. Here there is a conflicting requirement to investigate the 'local plasma'; multipoint sampling is essential and the number and placing of sensors becomes critical. The size and geometry of the probes will depend upon the orbit of the satellite and the range of ambient plasma characteristics. For the Moliya orbit, the Debye length ranges from 20 mm to 2 metres while the random electron current density (Ie) could be 200 µA/m² at perigee but some four orders of magnitude smaller at apogee. The choices of spherical or cylindrical collectors, probe radius/length, and boom length are difficult because the need for sensitivity opposes that of spatial resolution. At this time, the available options are being examined (8) with an assessment of the relative merits of simple D.C. and A.C. modulation techniques and a critical look at the problems of boom mounting. Since the monitoring of 'space potential' is more important than accurate measurement of electron temperature or concentration, the feasibility of appropriate on-board processing will be a vital factor in the eventual choice.

4.2 Ions - A Thomson Parabola Analyser

Acknowledging that it is impossible to cover the complete ranges of ion mass, energy and incident direction, MSSL are endeavouring to optimise the properties of a Thomson analyser (9) for this application [10]. Figure 2 illustrates the basic properties of parabolic deflection as an ion enters a region of parallel electric (E) and magnetic (B) fields [11].

\[
\begin{align*}
\vec{x} &= qE/m \\
\vec{y} &= qvB/m
\end{align*}
\]

(1)

for an ion of mass m, charge q, and velocity v. For a particular ion species (m/q), different energies give a parabolic locus of points on a two dimensional imaging detector.

\[
y^2 = \frac{B^2 d^2}{2E (m/q)} \cdot x
\]

(2)

where d is the depth of the field region. For singly charged ions, the x deflection depends only upon the energy but the y deflection depends upon energy and mass, both of which can therefore be determined.

Suitable selection of E and B field strengths and geometry (d) should permit detection of ions with energies up to 100 eV and m/q ratios up to 132. This would cater for Xe⁺, Xe²⁺ and plasmaspheric ions (H⁺, He⁺, O⁺) but could only sample the low energy tail of plasmasheet populations.

Although the most compact arrangement (12) has coincident fields, this is not necessary. Figure 3 schematically shows the instrument proposed for a non-spinning spacecraft when the field of view must be scanned to observe all possible angles of incidence. The entrance aperture includes two pairs of electrostatic plates which are swept in voltage like the plates of a cathode ray tube; the deflection depends upon particle energy. Once through the aperture, particles encounter two grids: the first uses a retarding potential to exclude ions with less than a selected threshold energy (1 eV); the second accelerates the ions into the Thomson Analyser, in order to achieve a more uniform energy resolution. Thomson analysers are not focussing instruments, the mass and energy resolutions are directly proportional to beam cross-section. The beam is collimated by another aperture before entering the field region. Permanent magnets with small pole separation can produce a high B with no power penalty. The applied potential (V) is relatively easily adjusted for ion energy range selection. The microchannel plate detector amplifies the signature of incident ions by providing an avalanche of '10' electrons per ion, while retaining positional information. These electrons strike a wedge-and-strip anode array configured to encode their position.

Fig.3: Schematic of MSSL Thomson analyser.
electric field, is being investigated in order to overcome these disadvantages, a different principle of measuring charge, or more strictly an electric field, is being investigated at RAE. The proposed method utilizes the change in refractive index which occurs in some crystals (e.g. lithium niobate) when an electric field is applied across them; this is known as the Pockels effect [15]. The variation in refractive index is detected by measuring the change in polarization state of a laser beam propagating through the crystal. The basic configuration of the device is shown in figure 4. The input laser beam is linearly polarized and may be considered in terms of its x and y components. When an electric field is applied across the crystal, the internal field $E_i$ will change the refractive index and cause the two components to travel at different velocities. Consequently, a relative phase shift $\Delta \phi$ between the components will appear, causing the light to become elliptically polarized.

$$\Delta \phi = \tau E L$$

where $\tau$ is the relevant Pockels coefficient and $L$ is the length of the crystal in the propagation direction.

The polarization of the output beam can be measured by the polarizer-detector combination. Since the Pockels coefficients are small ($10^{-10}$ m/V), electric fields of order $10^5$ V/m are required to achieve 180° phase change, i.e. complete extinction of the light emerging from the analyser. Potentials of several kilovolts can appear on spacecraft surfaces, so, by choosing a crystal of suitable dimensions, a practical device for spacecraft applications becomes feasible. The use of a semi-conductor diode laser and a silicon PIN diode detector provides the necessary sensitivity, consuming power of only a few milliwatts. The effects of temperature variation on the operation of the device have been analysed theoretically and a change in calibration of less than 2%, over a -150°C to +60°C range, is expected for certain crystal orientations. Work continues on the development of such devices which can be located in sensitive areas such as on solar array panels.

### 4.4. NASCAP Simulation

The emphasis on flight hardware is essential but the development of instrumentation and the interpretation of space data will both be greatly assisted by simulation exercises. NASCAP (NASA Charging Analyser Program) is a computer code which performs a dynamic, fully three dimensional simulation of electrostatic charging processes, either in space or in a test-tank environment [16]. It is ideal for simulating the effect of emitted ions on spacecraft potential and tracing the trajectories of particles in the electric field of a charged satellite. The behaviour of the thruster beam, the trajectories of the neutralizer ions and ions created in the beam, can be investigated but there is a difficulty. NASCAP neglects particle-particle interactions which could be crucial when emitted currents are as high as those of the thruster.

A NASCAP simulation was performed with the very simple model of figure 5. Low energy (0.4 eV, 0.8 A) proton and electron emitters (conductors 3 & 4) representing the neutralizer are flanked by two 900 eV ion emitters (conductors 1 & 2), each with a current of 0.2 A. All the conductors are aluminium and separated by a resistance of 2 ohms, the ambient plasma is taken to be 1 cm$^{-3}$ at 1 eV. With the neutralizer OFF, all parts of the surface charged to -900 V in less than 0.01 sec and stayed at that level as expected; however, the thruster ions could not be tracked back to the spacecraft. With the neutralizer ON, conductor 3 charged up to cut off the emission of cold ions and conductor 4 stayed at a few volts negative; conductors 1 and 2 started to charge rapidly but then stabilized at -120 V, as a potential barrier prevented further escape of electrons. Although this simulation demonstrates that the neutralizer lessens spacecraft charging, and thus allows the thruster beam to be maintained, 120 volts is an unreasonably high charging level. It is difficult to apply NASCAP to low Debye length plasmas and the imposed resistance between the conductors is unrealistic; a better representation must be developed.

![Fig.5: Simple NASCAP model of thruster and neutralizer.](image-url)
5. FINALE

* An inert gas (Xe) will be chemically less reactive than conventional thruster propellants (hydrazine), but sputtered metals (Mo) may be a real hazard.

* Ionized molecules will not return to the spacecraft more readily than neutrals if a positive satellite potential can be maintained.

* Deposition must not significantly reduce the efficiency of solar cells but, given the relatively high duty cycle, this might impose a significant constraint in long duration missions.

* The 'neutralizer' plasma source must dramatically modify the surrounding plasma, but this need not be a bad thing.

* The cold plasma should inhibit 'differential charging', but if it does not, the 'arching' triggered by this current source could be more damaging.

* A set of simple Langmuir probes seems to offer a feasible in-flight method of monitoring local plasma variations.

* Low energy ions hold the key to charging susceptibility and the Thomson analyser promises a suitable measurement, but a single instrument may not achieve appropriate range and resolution in terms of energy, mass, angle and time.

* Direct measurement of surface charging on satellites is difficult and the performance of the Pockels device justifies further study and development.

* Computer simulation is a useful tool but the modelling of high current beams has yet to be validated.

References

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