# Electric Propulsion: Which One For My Spacecraft?

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#### 1.0 Introduction

Electric propulsion has become a cost effective and sound engineering solution for many space applications. Two of the main reasons why are its increased commercial availability and the opportunity it affords to perform the same task as conventional chemical propulsion systems while reducing the portion of the spacecraft's mass required for that task. Electric propulsion systems have been tested on ground and in space since the 1960s, and a wide variety of system types are available or have flown.

In this survey systems compatible with solar electric propulsion and that are commercially available are emphasized, however other types are mentioned for completeness. Blind pursuit of completeness can be a never ending endeavour and therefore some techniques will not be broached such as solar photon sailing, fusion, railguns, and laser propulsion. Included are summaries of the principles, advantages, disadvantages, ground based test experience, spaceflight experience, and descriptions of electric propulsion systems currently available. The reader should use this article as a pointer to other documentation sources as it is not meant to be an authoritative source of principles, design requirements, constraints, or data. Be also cautioned that research for the article tapped the resources of the world wide web extensively, and many of the references point to pages which have half-lives shorter than academic cycles. Occasionally, more conventional references are cited alongside URLs.

With a control systems engineer in mind, an attempt is made to provide enough information for making preliminary choices about which type of electric propulsion might be suitable for an application. In this regard, the tables provide much of the "meat and potatoes" content. According to the Chemical Propulsion Information Agency, over 300 electric thrusters had flown on over 100 spacecraft as of 1997<sup>1</sup>. In 1998, at least 78 more spacecraft used some type of electric propulsion device. By latest counts, 388 electric thrusters are aboard 152 spacecraft<sup>2</sup>. Electric propulsion research is an active field going as far back as the 1920s. Flight and test experience is mentioned briefly where the literature provides data.

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<sup>1.</sup> Filliben, J. D., Johns Hopkins University, http://www.jhu.edu/~cpia/electhsys.html .

Snyder, J. S., Aerospace America, v. 38, no. 12, Dec., 2000.

# 2.0 Classification of Electric Propulsion Types

With the wide variety of electric propulsion types, classification is in order to better understand them. Many primary authors have attempted to classify electric propulsion systems. It should be noted that not all authors agree on how each type of electric propulsion system is classified. For example, some authors classify Hall effect thrusters as electromagnetic while others classify it as electrostatic. The most common classification scheme is by the *means* in which the working fluid is accelerated up to exhaust velocity. However, alternate schemes divide the techniques by the means for ion production (for those that rely upon plasma generation) or by the propellant composition. Since different techniques can quite often each use various propellants, the latter scheme is not widely used. Although we discuss primarily solar electric propulsion, some systems work more efficiently at high power input and therefore operate better with nuclear or thermonuclear power sources.

We adopt the conventional classification scheme wherein the primary category is how the working fluid is accelerated, while the secondary category is how the fluid (ionization in the case of plasmas) is generated. This scheme is fairly standard, and the three major categories of electric propulsion are:

- Electrostatic
- Electromagnetic
- Electrothermal

Within these categories, subdivision by the techniques for ion generation (for those where plasma is generated) or by propellant heating is made.

#### • Electrostatic

- Ion Bombardment
- Colloid ion
- Contact ion
- Field Emission (FEEP)
- Microwave or Radiofrequency ion
- Plasma separator ion
- Radioisotopic ion
- Hall Effect:
  - SPT
  - $\bullet$  TAL

#### • Electromagnetic

- Magnetoplasmadynamic
  - Steady state vs Quasi steady state
  - Self-field vs Applied-field
- Pulsed plasma
- Helicon plasma
- Inductive pulsed plasma
- Electron-cyclotron-resonance
- Variable specific-impulse plasma

#### Electrothermal

- Resistojet
- Arcjet
  - DC vs AC vs Pulsed

#### • Electrothermal

- Electrothermal hydrazine
- Microwave electrothermal
- Pulsed electrothermal

Table 1 shows the major techniques which have been researched, tested, and/or flown. Current developmental and historical information on the various types of electric propulsion systems is given.

Table 1: General Features and Development Activity on Various Electric Propulsion Systems

Propulsion Type	Working Propellant	Flight Experience	First Flight	Commercial Level	Manufacturers or Test Labs		
Electrothermal DC Arcjet	N2H4, H2, NH3, Teflon	7+	1993	Off-the-shelf	Centrospazio, IRS, Primex		
Electrothermal AC Arcjet		never	-	Experimental	?		
Electrothermal Pulsed Arcjet		never	-	Experimental	?		
Electrothermal Hydrazine	Hydrazine	multiple		Off-the-shelf	TRW, Primex, GRC		
Microwave Electrothermal	N2	never	-	Laboratory	Penn State, Michigan State, JPL, GRC		
Pulsed Electrothermal		never	-	Developmental	?		
Resistojet	H2, N2H4, N2, Teflon, NH3, H20, N2O	dozens	?	Off-the-shelf	Primex, Moog, EPL		
Ion Bombardment	Xe, Ar, Ne, Cs, Hg	multiple	1970, SERT-II	Off-the-shelf	Hughes, GRC, JPL, AEA/ RAE, MMS, Japan		
RF/Microwave Ion	Xe, Kr	1+	1993 EURECA	Experimental Flight Test	DASA, Japan		
Colloid Ion	Glycerine	never ?	-	Developmental	U.S., U.K.		
Radioisotopic	Ce	never	-	Theoretical	U.S.		
Plasma Separator	Ce	never	-	Discontinued	U.S.		
Contact Ion	Ce	7	1962	Discontinued	Hughes, LeRC, USAF		
FEEP	liquid metal, Ce, Ru, In	5+	1991 MIR	Available	Centrospazio, SRI, ESA, ARC		
Hall: SPT	Xenon	dozens	1972	Available	Centrospazio, Fakel, AFRL,		
Hall: TAL	Xenon	dozens	1972	Available	TsNIIMASH, NIITP, IST, RIAME		
Electron-Cyclotron Resonance	Ar, Kr, Xe	never	scheduled 2002 MUSES-C	Laboratory / Verification	GE, JPL, GRC, U. Tokyo, ISAS		
MPD Arcjet Steady State	Nobles, H2, CH4, N2, N2H4, NH3, Li, K, Na	never	-	Experimental / Developmental	Centrospazio, EPPDL, IRS, MAI, ISAS		
MPD Arcjet Quasi-Steady State	Nobles, H2, CH4, N2, N2H4, NH3, Li, K, Na	?	EPEX on SFU 1985	Flight Tested	ISAS		
Pulsed Plasma	Teflon, Xe	multiple	1964, Zond 2	Available	EPPDL, Primex, NASA/ LeRC, SRL, Russia		
Helicon Pulsed Plasma		never	-	Laboratory	U. Wisconsin		
Pulsed Inductive	N2H4, CO2, NH3, Ar	never	-	Developmental	TRW		
Variable Specific Impulse Plasma	Hydrogen	never	-	Laboratory	JSC, MIT		
MEMS	Pb-styphnate/Nitrocel- lulose	never?	-	Laboratory / Developmental	EPPDyL, AFRL		
Mini-Magnetospheric Plasma (M2P2)	Solar Wind	never	-	Laboratory	U. Washington		

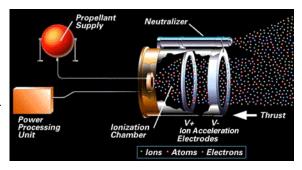
<sup>&</sup>quot;Commercial Level" must of course be considered in the context that some systems may be at more

advanced levels than indicated, and the list of providers is not intended to be complete. The preferred, tested, or commercially used propellants are shown, though quite often other options exist. Any noble gas can replace any other, although particular ones are preferred due to the need to match elemental properties with thruster performance. Cesium and mercury were tested and even flown in the 1960s in types of electrostatic systems that currently employ noble gases. Teflon can be replaced by other soft solids. Though not mentioned further here, C60 fullerenes are being considered as propellant, though significant problems remain with their use.

# 3.0 Electrostatic Propulsion

Electrostatic propulsion uses a high voltage electrostatic field to accelerate ions to large exhaust velocities. Most development work has been on systems using positively charged ions as the primary working fluid with some means for neutralizing the ions after they reach the exhaust.

Many electrostatic systems rely on a gridded system at the exhaust port for containing and producing the high electric field needed to accelerate the ions (*ion bombardment, RIT, and colloid thrusters*). In a typical gridded thruster, a DC potential difference (~ 1 kV) between an inner grid anode on the plasma chamber and an exit-plane cathode is used. Multiple grids are employed at the exhaust port to divide the functions of propellant containment, ion acceleration, and beam divergence control<sup>3</sup>.



**Figure 1**: Conceptual illustration for Hughes XIPS ion thruster showing major subsystem components.

Radiative heat losses from the propellant heating/
ionization chamber limit efficiency in most systems. The power conditioning requirements are considered to be complex depending upon the method used for propellant ionization. Grid-type electrostatic systems have been lifetime limited by grid and cathode erosion. Material improvements, particularly with carbon-carbon composite grids are in development and expected to increase the performance and life expectancy of these units.

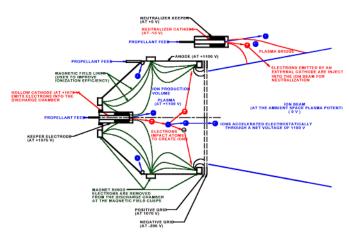
#### 3.1 Ion Bombardment

Electron bombardment or ion-bombardment thrusters produce positive ions by bombarding neutral propellant atoms in a discharge chamber with thermionically excited electrons. The discharge chamber is typically a cylindrical anode, with a centrally located axial hollow cathode. Heating of the axial

<sup>3.</sup> XIPS Figure 1 is from http://www.hughespace.com/factsheets/xips/nstar/ionengine.html .

cathode produces thermionic emission of electrons at a low amperage (1 to 15 Amps) and low voltage (25 to 30 V DC) which discharge toward the outer anode. A magnetic field is typically applied in the discharge chamber to increase the electron path length and residence time allowing a higher collision probability and propellant utilization efficiency<sup>4</sup>. Grids held at different potentials near the exhaust port allow the plasma to be accelerated to exhaust velocities. The ions are then neutralized in the exhaust by a spray of electrons from a neutralizer cathode to prevent a potential difference from pulling ions back to the engine.

Ion bombardment systems have a test and flight history stretching over 30 years in



**Figure 2**: Line diagram showing functional elements, fields, and propellant paths of a gridded electrostatic ion bombardment thruster.

space and 40 on the ground. Several NASA and Air Force low Earth-orbit missions in the 1970s helped demonstrate and troubleshoot the basic design. Intelsat VII employs 25 mN UK-10 north-south station keeping units. Higher thrust units have been flight qualified for use as east-west station-keeping motors on geosynchronous satellites (about 20 times the  $\Delta$ -V per year is required for east-west versus north-south stationkeeping at geosynchronous altitudes).

Perhaps the most prominent mission to date has been Deep Space-1 which uses a 30-cm diameter NASA/Hughes xenon-ion engine. Ground units have been tested at thrusts over 1 N, with power consumptions of 50 W - 200 kW. Many countries and organizations have been involved with development work and production of flight equipment including Glenn Research Center (GRC, formerly Lewis Research Center-LeRC), JPL, Hughes, and centers in Japan, German, France, UK, and Russia.

Gridded acceleration can sometimes be tempermental as evinced with even the recent systems. DS-1's engine had to initially be cycled hundreds of times before any thrust occurred to remove contaminants which were producing shorts in the acceleration electrodes. The initial flight of an electron-bombardment test system (27mN SERT II mission in 1970) suffered similar problems.

In addition to the drawbacks of gridded accelerators, the discharge chambers can be subject to sputtering and spalling. In spite of these problems, the relatively high performance, extended development heritage, and potential long lifetime of the thrusters make the systems attractive. Ion bombardment systems are capable of delivering the highest integrated lifetime impulse of any currently flying electric propulsion technique and are therefore excellent candidates for not only station keeping but for primary propulsion. Plans for commercial use are extensive. Tiny microthrusters which use a hollow cathode have been under test<sup>5</sup>.

<sup>4.</sup> Electrostatic gridded element diagram Figure 2 from http://sec353.jpl.nasa.gov/apc/Electric/06.html

<sup>5.</sup> Katz, I., Davis, V. A., et. al., http://apc2000.jpl.nasa.gov/proceedings/Micr\_PR1.pdf.

## 3.2 Radiofrequency (RIT) & Microwave Ion

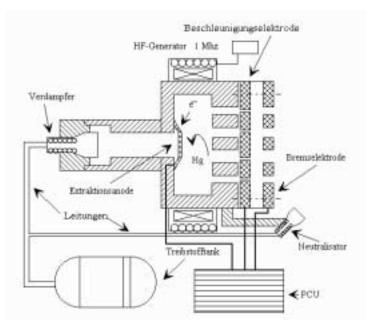
Radiofrequency ion thrusters rely on ion creation by pumping a cavity with radio frequency radiation,

usually in an insulated discharge chamber. The ions are then extracted through the exhaust port by an accelerator grid similar to that in gridded electrostatic propulsion. Like other systems which eject a charged plasma, an external neutralizer cathode is used to balance the current in the exhaust.

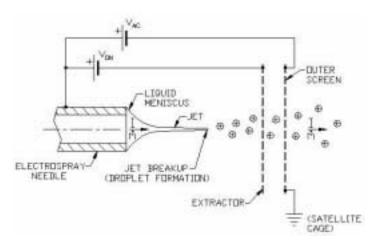
Thrust levels in the range of tens of milliNewtons have been demonstrated with the RIT-10 developed by the University of Giessen<sup>6</sup> and Daimler-Benz Aerospace (DASA). The RIT-10 was flown aboard the EURECA test satellite in 1993. Larger models with 15-cm and 35-cm grids have been developed. ESA is pursuing investment in radiofrequency electrostatic engines for use as north-south station keeping for geostationary satellites. Two RIT-15s are being integrated for launch with the ARTEMIS satellite. RIT systems show lifetimes nearly equivalent to those achievable with the ion bombardment technique.

#### 3.3 Electrostatic Colloid

With an electrostatic colloid thruster, droplets of a conductive liquid such as glycerol or sodium iodine are pumped through a needle at a high potential (~5-10 kV). An negatively charged extractor (several kV negative potential) pulls the liquid into a thin continuous stream until positively charged droplets separate from the stream<sup>7</sup>.



**Figure 3**: Conceptual diagram of the RIT thruster series showing propellant flow and main thruster elements.



**Figure 4**: Gridded acceleration of colloid droplets is shown in the above layout sketch.

<sup>6.</sup> Figure 3 showing the RIT design from http://www.irs.uni-stuttgart.de/RESEARCH/EL\_PROP/ION/e\_ion.html .

Alternate propellant schemes rely upon condensing a supersaturated vapor, such as mercury or aluminum chlorides into a liquid. A drawback with the technique is that energy is required to condense the vapor, thereby reducing efficiency. Another is that droplet size is non-uniform resulting in inefficient drop mass/charge ratios.

Studies in the 1960s and 1970s were performed in the U.K. and U.S., but development lagged until the late 1990s, largely because other systems appeared more promising. Busek Corporation is developing a colloidal thruster system in the 25 microNewton class for the SBIR Air Force early warning satellite system. Stanford University is also involved in testing small colloid thrusters<sup>8</sup>.

#### 3.4 Contact Ion

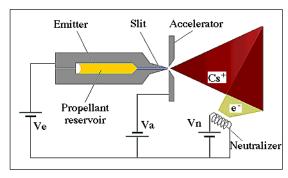
The contact ion engine creates ions by passing liquid cesium through a heated bed of porous tungsten. The higher electron work function of tungsten relative to cesium results in electron transfer from the cesium atoms to the tungsten. The cesium ions vaporize from the tungsten bed and are accelerated by an electrostatic field.

Structural and fabrication problems prevented the successful design of contact ion engines above the 20 kW power range. Excessive thermal management requirements, cesium toxicity and contamination of the engine, and the high system complexity made the technology unattractive. After about 7 orbital and sub-orbital U.S. flight tests spread across the 1960s and termination of a French program in the mid-1970s, pursuit of contact ion thruster development has apparently disappeared<sup>9</sup>.

### 3.5 Field Emission Ion

Field Emission Electric Propulsion (FEEP) relies on a strong electric field, typically 8 - 15 kV, to directly ionize the surface of a working fluid, typically a liquid metal. This technique differs principally from colloid ion thrusters in that individual ions are produced rather than droplets. Slit or pinhole diameters are typically about one micron in size<sup>10</sup>.

The technique has an inherently high efficiency because no heat is lost in ionization since the fluid is directly accelerated after ionization and extraction



**Figure 5**: FEEP concept showing the ion flow, thruster elements, and application of electric potentials.

<sup>7.</sup> Line diagram of colloid thruster elements Figure 4 from http://www.busek.com/.

<sup>8.</sup> Mahoney, J., Perel, J., http://apc2000.jpl.nasa.gov/proceedings/Micr\_PR2.pdf.

<sup>9.</sup> A flight history can be found at http://sec353.jpl.nasa.gov/apc/Electric/08.html#UK.

<sup>10.</sup> Figure 5 diagram of field emission ion concept from http://www.centrospazio.cpr.it/FEEPPrinciple.html .

from the bulk material/fluid. One of the advantages from a spacecraft control point of view is the reproducibility of short pulse times and small impulse bits. Thrust units can be quite small and have comparatively high specific impulse. For space missions which require counteracting the effects of atmospheric drag and solar radiation pressure, FEEPs are well suited. Centrospazio<sup>11</sup> and Austrian Research Center<sup>12</sup> have produced flight units used on numerous missions for testing, and is marketing them for science-sensitive station keeping missions such as LISA and TPF.

## 3.6 Plasma Separator Ion

The plasma separator ion thruster uses high density cesium vapor which is pumped through an array of hollow cathodes having converging-diverging nozzles. Ions are created by discharge between the cathodes and annular anode ring at the end of the nozzles. After ionization, a conventional electrostatic acceleration system produces high exhaust velocities. Nonuniform plasma flow from the cathode array was noted in lab tests. Development work in US was discontinued in the 1960s with no space tests<sup>13</sup>.

# 3.7 Radioisotopic Ion

Unlike the name's implication, thrust is produced with charged colloidal particles. A thin layer of fuel containing beta-decaying radioisotopes is spread over a large emitting surface with a net positive charge produced by the decaying radioisotope fuel (typically conceived as Cesium 144). A large potential difference between surface and space (~500,000 - 1,500,000 volts) is produced as a result. Electrons emitted from this surface are collected by a shield, and the potential difference and current are used to operate a high-energy colloidal accelerator.

In many respects, this was more of a technique for using radioisotopes to produce a large potential difference and drive an engine, and is thus a power source. No working model was produced and safety considerations have probably prevented the idea from being developed due to extreme radiation hazards and complexities.

#### 3.8 Hall Current

R. G. Jahn<sup>14</sup> has identified a number of different fundamental ways in which the Hall current or Hall effect can be used for electric propulsion. All Hall thrusters are gridless accelerators which use the

<sup>11.</sup> Centrospazio: http://www.centrospazio.cpr.it/Centrospazio6FEEP.html.

<sup>12.</sup> Austrian Research Center: http://www.arcs.ac.at/E/EM/ultra.

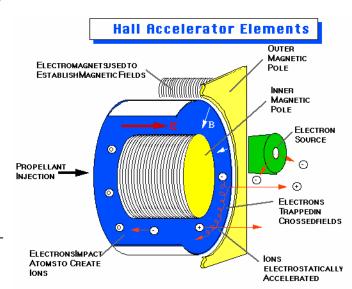
<sup>13.</sup> What little information is available was found at http://sec353.jpl.nasa.gov/apc/Electric/08.html .

<sup>14.</sup> Jahn, R. G., Physics of Electric Propulsion, McGraw-Hill, 1968, pp.219-227.

body forces on charges in crossed electric and magnetic fields. The most common configurations in use have an axisymmetric cavity in which a radial magnetic field is generated by electromagnets with the field pointing to (or from) the surrounding coil/chamber body from (or to) an inner magnetic pole.

Lower potential differences are required to reach specific impulses close to those of ion bombardment systems. Some of the exhaust energy is not produced by the electrostatic field and therefore some authors classify the system as electromagnetic rather than electrostatic.

Hall thrusters research and development is being pursued widely by in Europe, Japan, the U.S., and Russia. Russia has been a long-time leader in the field of Hall thrusters. Typical usage is for orbit raising and station keeping maneuvers.



**Figure 6**: Concept diagram for SPT-type hall device showing magnets (yellow), cathode (green), and plasma chamber (blue).

Two types of Hall thrusters exist:

- Stationary Plasma Thruster (SPT)
- Thruster with Anode Layer (TAL)

#### 3.8.1 Stationary Plasma Thruster

In the stationary plasma thruster, or "closed-drift" a DC electric field is established along the axis of the device with the anode located at the non-exhaust end of the ionization chamber and with the cathode located externally or at the exhaust end of the chamber. Electrons emitted from the cathode are pulled into the chamber by the applied electric field and have their circulation lifetimes increased through a force produced by **E** x **B** drift<sup>15</sup>. As a result, they are available to ionize the propellant injected from the non-exhaust end of the chamber through collisions for longer times. The applied electrostatic field then accelerates the ions into the exhaust flow. Additional electrons from the cathode flow into the exhaust stream to neutralize the charge flow. Russian built Fakel SPTs have had over 10,000 hours of space operation<sup>16</sup>.

<sup>15.</sup> Figure 6 concept diagram from http://www.grc.nasa.gov/WWW/onboard/EPO/sld011.htm . Other good diagrams are available on the web at http://ncst-www.nrl.navy.mil/HomePage/EPDMHall.html, http://www.stanford.edu/group/pdl/EP/Hallcut/HallCut.html and from http://www.busek.com/.

<sup>16.</sup> Choueiri, E., Aerospace America, v.37, no. 12, Dec. 1999, p.68.

#### 3.8.2 Thruster with Anode Layer (TAL)

"Thruster with anode layer" or "thruster with external layer" devices are configured somewhat differently in that the anodes are located downstream. The ion production region is positioned more externally than in SPT units. Most are generally smaller and have a lower erosion rate. TAL type Hall thrusters typically have twice the thrust-to-power ratio of ion-bombardment electrostatic systems, yet require only 300 - 400 V electric field potentials.

The USSR had been using both SPTs and TALs for decades with thrusters flying on Meteor weather, military surveillance, and Express telecommunications satellites. With the waning of the cold war, Russian Hall thrusters have even been used on U.S. military research projects, such as STEX, launched in October 1998. A successful marketing campaign in partnership with companies in the U.S. has been undertaken.

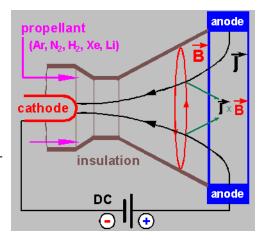
# 4.0 Electromagnetic Propulsion

A principle advantage of electromagnetic techniques over electrostatic ones is that plasmas with higher temperature and density (typically by several orders of magnitude) can be confined and directed. This results in higher exhaust velocities and therefore more efficient use of propellant mass. All electromagnetic techniques rely upon production of a plasma which is accelerated to exhaust velocity by interaction with electromagnetic fields within and around the plasma production chamber.

# 4.1 Magnetoplasmadynamic (MPD)

The MPD arcjet evolved from electrothermal arcjets and magnetogasdynamic technology and is sometimes referred to as a Lorentz Force Accelerator. The general configuration is an axisymmetric chamber with a cathode running the length of the ionization region which carries a large current (typically ~ kiloAmperes). The potential difference between electrodes ionizes inflowing neutral gas. Once ionized, the plasma is accelerated by both Joule heating and electrodynamic forces. The current carrying plasma interacts with a magnetic field resulting in a Lorentz acceleration which expels the plasma. The Lorentz force provides the dominant acceleration mechanism. There are two different ways the magnetic field is produced:

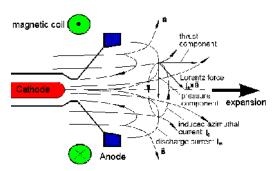
- Self Field
- Applied Field



**Figure 7**: Self-field MPD schematic showing electric and magnetic fields in addition to cathode, anode, and nozzle.

In both types, the cathode-anode is charged with a DC power supply. The high temperature cathode produces most of the current through thermionic emission. An azimuthal magnetic field is generated by the current flowing along the cathode bar, helping to initiate the  $\bf J$  x  $\bf B$  force on the plasma.

With the self-field system<sup>17</sup> acceleration of the plasma occurs as a result of the magnetic field produced by the high current flow along the cathode. With an applied field technique<sup>18</sup>, an external solenoidal magnetic field is applied to enhance acceleration and plasma confinement. For higher temperature and energy plasmas, applied azimuthal fields are preferred for plasma confinement. With



**Figure 8**: Applied-field MPD thruster showing the additional solenoid (green) plus fields and charge flow.

the addition of the applied field, a lower plasma current is required to produce the same propulsive power. Depending upon the architecture, an MPD thruster can be operated in either a steady-state or pulsed mode with demonstrated durations as short as a millisecond. The design of magnetoplasma-dynamic thrusters allow operation in one of two different modes:

- Quasi-Steady State Operation
- Steady State Operation

With pulsed (quasi-steady state) operation, a capacitive system discharges across the arc allowing for higher currents and higher magnetic fields for a given average power level. Arc erosion is more severe in the pulsed arcjets.

Unfortunately for low-power applications, efficiency has been a function of power input. Cathode lifetime is a limitation as with many systems employing high velocity plasmas. No steady state units have flown as these generally require higher input power. High thrust and specific impulse are achievable. The Japanese ISAS satellite SFU tested the general operation of quasi-steady state MPD thrusters.

# 4.2 Pulsed Plasma (PPT)

In a pulsed plasma thruster  $^{19}$ , plasma is created by an arc discharge from a capacitor across a pair of electrodes. The ions in the plasma are then accelerated by the  $\bf J$  x  $\bf B$  Lorentz force in the induced magnetic field. Their use stretches back to the mid-1960s, and a resurgence in popularity has been seen in the 1990s. In a teflon pulsed plasma thruster, ablation of a solid block of teflon propellant. In these thrusters, propellant delivery is by quite a simple device: a spring! Teflon PPTs are currently

<sup>17.</sup> Self-field concept diagram (Fig. 7) from http://www.irs.uni-stuttgart.de/RESEARCH/EL\_PROP/MPD/e\_mpd.html .

<sup>18.</sup> Applied field concept diagram (Fig. 8) from http://www.irs.uni-stuttgart.de/RESEARCH/EL\_PROP/AFMPD/e\_afmpd.html .

<sup>19.</sup> Figure 9 teflon PPT cross-section diagram from http://www.lerc.nasa.gov/WWW/RT1997/6000/6910curran.htm .

being used on EO-1 for momentum wheel replacement<sup>20</sup> in pitch-axis control. Teflon PPTs are also a leading candidate for DS-3, an experimental space interferometer which requires precision formation flying. Use as orbit-raising, attitude control, station keeping, and fine pointing and positioning control will no doubt continue.

Another type of pulsed plasma system under development uses a gas feed system with xenon or water as a propellant. This system has not yet flown but has been shown to be capable of over 2 million cycles at a power consumption rate of 40 W and 0.02 second pulses using water as a propellant.

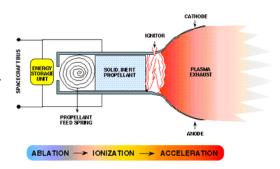


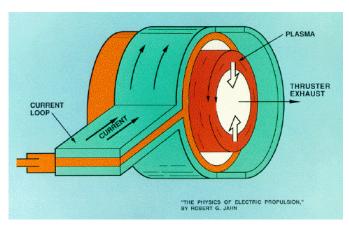
Figure 9: Teflon pulsed plasma thruster cross-sectional diagram. Relative locations of the capacitance, propellant, ignition, and electrode positions are shown.

#### 4.3 Helicon Plasma

A Helicon thruster<sup>21</sup> is similar to pulsed plasma thrusters in that acceleration of a plasma occurs through a Lorentz force interaction. However, a helicon tube is instead used to produce a travelling electromagnetic wave down the center of the plasma chamber to maintain the high magnetic field strengths. Helicons have also been proposed for use in other electromagnetic thrusters, such as in the variable specific impulse plasma thruster.

# **4.4 Inductive Pulsed Plasma (PIT)**

In a pulsed inductive thruster<sup>22</sup>, a bank of high voltage (~ 10 kV) capacitors is discharged into a flat induction coil strip surrounding a cylindrical chamber. Immediately before discharge, a fast valving system injects neutral propellant into the chamber. Before the propellant can escape the chamber by diffusion, the discharge pulse creates a high magnetic field within the chamber which both Figure 10: PIT conceptual diagram showing the inductive curionizes and accelerates the plasma away from



rent strip (green), the insulating chamber (orange) and the plasma (red).

<sup>20.</sup> Burton, R. L., Aerospace America, v.36, no. 12, Dec. 1998, p.62.

<sup>21.</sup> Source info for the Helicon Plasma Thruster is available at http://rigel.neep.wisc.edu/~ifs/neep533.lect31.99/plasmaProp.html, and information about helicons at http://www.anutech.com.au/asi/helicon.htm.

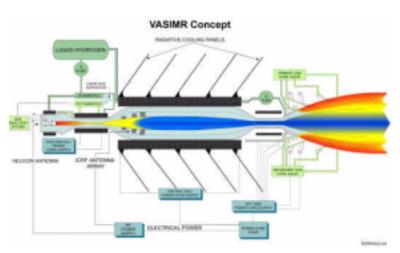
<sup>22.</sup> Figure 10 cut-away diagram from http://sec353.jpl.nasa.gov/apc/Electric/16.html.

the coil. Since the chamber is closed on one end, the propellant plasma is confined and squeeze out of the exhaust end of the chamber.

Shielding transient magnetic and electric fields may be an issue. Development work by TRW has been performed, but no space tests have been conducted.

## 4.5 Variable Specific Impulse Plasma

The technique relies on an electrodeless cylindrical chamber in which the functions of ionization, plasma heating, and conversion to a directed exhaust. In the forward portion of the chamber, hydrogen is injected and ionized. The ions diffuse into the mid-section of the chamber and are further heated by electron and ion cyclotron heating and whistler wave heating. Moving downstream, the plasma enters the nozzle section where the shape and field strength and configuration converts the plasma's thermal energy into propulsive kinetic energy. The chamber walls are kept cool by injecting neutral hydrogen



**Figure 11**: Diagram showing relationship of the VASIMR propulsion and control elements.

radially near the nozzle, with the bonus of disrupting the connection between the plasma and the contained magnetic field at low specific impulse (high plasma densities). At higher specific impulses, a high frequency AC ripple field is instead used to disrupt the magnetic field - plasma connection.

The variable specific impulse plasma thruster is currently only in the laboratory testing and development phases. Johnson Space Center is currently exploring a version suitable for manned space missions called VASIMR<sup>23</sup>.

# **4.6** Electron-Cyclotron-Resonance (ECR)

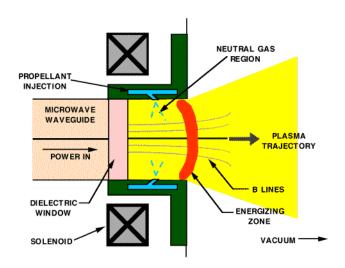
ECR is an electrodeless technique using a microwave waveguide to deliver the energy for ionizing a gas. Circularly polarized transverse-electric mode radiation is absorbed by the small population of free electrons constrained to move in cyclotronic paths within the plasma chamber in a magnetic field produced by an external surrounding solenoid<sup>24</sup>. Collisions between neutral gas atoms and the circu-

<sup>23.</sup> VASIMR Figure 11 diagram from http://spacsun.rice.edu/aspl/vasimr.htm .

<sup>24.</sup> Figure 12 ECR cross-section diagram from http://sec353.jpl.nasa.gov/apc/Electric/17.html .

lating electrons ionize the gas. The circulating electrons preferentially align their magnetic dipoles along but opposite to the externally applied magnetic field. Divergence of the solenoid field toward the exhaust port accelerates the plasma to high velocity.

A unit (whose engineering model passed an 18,000 hour life test<sup>25</sup>) is slated for launch after 2002 aboard the Japanese asteroid sample return mission MUSES-C<sup>26</sup>.



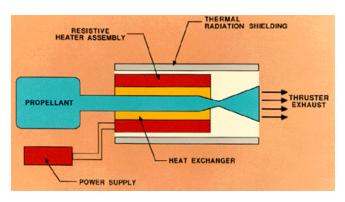
**Figure 12**: ECR diagram showing the waveguide, window, solenoid, field and propellant flow.

# 5.0 Electrothermal Propulsion

Electrothermal propulsion relies on thermal heating of the propellant to increase the exhaust velocity. Unlike electrostatic and electromagnetic propulsion, exhaust velocities are primarily a product of thermodynamics of the gas and not from interactions with applied or induced electric and or magnetic fields.

## 5.1 Resistojets

Resistojets operate by direct ohmic heating of the propellant. In a typical resistojet<sup>27</sup>, the propellant is heated in passing over a tungsten heating element within a heat exchange chamber before being exhausted. Although the electrical heating requires a more complex interface than chemical propulsion, these systems have power conditioning and feed systems often compatible with conventional chemical monoor bipropellants. In addition to being compact and light-weight, relatively high thrust levels are achievable with voltages of ~ 100V and



**Figure 13**: Above are shown the basic elements of a resistojet thruster.

<sup>25.</sup> Choueiri, E., Op. Cit.

<sup>26.</sup> From http://www.aiaa.org/information/technical/rev-prop.html .

<sup>27.</sup> Figure 13 resistojet cross-section from http://sec353.jpl.nasa.gov/apc/Electric/02.html .

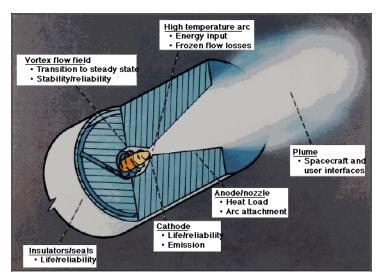
high current. Hydrazine resistojets were used on Iridium satellites for orbit-raising maneuvers. Suited for multi-hour burns.

## 5.2 Electrothermal (Augmented) Hydrazine

With the electrothermally augmented hydrazine thruster, a hybrid of a conventional electrothermal thruster (using hydrazine) and a monopropellant chemical hydrazine thruster is employed. In the first stage of the device, conventional chemical decomposition of hydrazine is achieved to liberate the chemical energy stored in the molecular structure. In the second stage, the propellant is passed through a heating chamber where ohmic heating further raises the temperature and is then exhausted. Because of the time constants required to bring the heating elements to high temperature, longer, steady burns are needed to yield precise pulse control. A 30% increase in specific impulse over conventional hydrazine is achievable. Although these units have lower thrust than conventional hydrazine units, they are becoming standard replacements as station keeping thrusters. One example of a flight unit is Intelsat V.

## 5.3 Arcjets

Many different kinds of arcjets have been designed, tested, and built. All electrothermal types create thrust through the thermodynamic expansion of a hot gas or plasma through a nozzle. The primary methods of propellant heating are DC current heating, AC current heating, RF heating, as well as laser-thermal heating. Arcjets also have been designed using either alternating or direct current. The devices are relatively simple<sup>28</sup>, but suffer from both cathode and anode erosion. As a result, their optimal operating mode is to minimize the number of starts (thousands) rather than use them for fine control with small impulse bits (millions).



**Figure 14**: Arcjet concept cutaway showing helical propellant injection.

DC arcjets use sub-kV arcs with high current between a cathode tip and diverging conical anode nozzle walls, with the propellant flowing through the inlet at the base of the cone around the cathode needle. Thrust is limited by power available, and specific impulse limited by nozzle materials. A 30 kW orbit-raising ammonia arcjet (ESEX) was flown on ARGOS in February 1999. A lower power

<sup>28.</sup> Basic arcjet configuration in Figure 14 from http://www.grc.nasa.gov/WWW/onboard/EPO/sld006.htm . More information on arcjets can be found at http://www.irs.uni-stuttgart.de/RESEARCH/EL\_PROP/ARC/e\_arcjet.html .

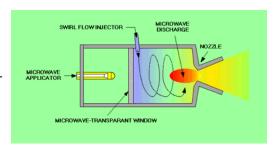
ammonia arcjet is used on AMSAT for orbit-raising and inclination control. Hydrazine arcjets are in use aboard Lockheed Martin geosynchronous satellites for station keeping.

AC arcjets are similar to DC arcjets, but have a shorter lifetime. Power conditioning requirements are simpler than with DC systems. Because of their shorter lifetimes, no space test has been done and development was discontinued after the 1960s.

Pulsed arcjets are similar to DC arcjets, except that instead of a steady current, it pulses resulting from charge and discharge of the input capacitance. The discharge pulse occurs at the breakdown voltage of the gaseous propellant flowing between the cathode and anode. Discharge pulses are typically in about 5 microseconds. Propellant flow is continuous and not pulsed. A disadvantage of the pulsed arcjet is its lower specific impulse compared with DC arcjets, and as a result, no space tests have been done.

## **5.4 Microwave Electrothermal (MET)**

Standing wave microwave radiation is fed from a waveguide into a plenum chamber through a dielectric window. The microwave radiation accelerates electrons in the high-field regions of the chamber which collide with injected neutral propellant. Mixing within the chamber heats the propellant which is expelled as exhaust. METs can function in both steady state and pulsed modes. Since this is an electrodeless technique, erosion is less of a problem, and these thrusters are likely to show significantly longer lifetimes than arc-type electrothermal systems. Laboratory tests have shown that specific impulses as high as 1300 are achievable<sup>29</sup> using helium, although



**Figure 15**: Microwave electrothermal thruster cross-section showing elements and propellant flow.

heavier molecules produce lower specific impulses. To date, no units<sup>30</sup> have been flown and the design is still in the lab test phase.

#### **5.5** Pulsed Electrothermal

Pulsed electrothermal thrusters (PET) eject pulsed plasma through a conventional supersonic nozzle which forms the anode of a propellant chamber. Plasma breakdown in the propellant is achieved by discharge of a capacitor across the inner electrode which heats the gas admitted to the cylindrical chamber. Liquid hydrogen has a predicted theoretical specific impulse of ~ 2900, with other propel-

<sup>29.</sup> Penn State Web News Bulletin: http://www.engr.psu.edu/news/Publications/EPSspr00/thruster.html .

<sup>30.</sup> Figure 16 diagram from http://sec353.jpl.nasa.gov/apc/Electric/04.html . More information on METs can be found at http://alfven.princeton.edu/html/projects.htm .

lants scaling as the inverse root of the molecular mass. Electrode erosion limits the lifetime of the thrusters and no space tests have been performed.

# **6.0 Future and Alternate Propulsion**

As noted in the introduction, there are other forms of electric propulsion under study that rely on fusion, lasers, solar sailing, antimatter, railguns, and other exotic means and their place is beyond the scope of this article. However, as a final excursion, we briefly examine several new and novel techniques not for reasonas of their usefulness, but out of a desire to keep this article from being totally confined in a box and to break up the monotony! We look at two systems, one useful in the commercial and scientific fields (MEMS), the other only for narrow mission class (M2P2).

## **6.1 MEMS: Thrusters on a Chip.**

MEMS is a propulsion type which may be of interest to attitude and dynamics control engineers. MEMS (Micro Electro-Mechanical Systems) Propulsion<sup>31</sup> uses current pulses to ignite tiny cells of lead styphanate which in turn ignite the main propellant of a nitrocellulose mixture. Technically, this is probably best classified as a technique other than electric propulsion, however the pulses are set off by current ignition. The feature of interest here is the ability to generate microNewton-second to milliNewton impulse bits with as little as 10 milliWatts over a hundredth of a second. Arrays have been manufactured containing over 256-squared elements using advanced semiconductor manufacturing technology. The thruster clusters appear to be a conventional semiconductor VLSI chip in their appearance. Specific impulses are in the range of 100-300 seconds.

# 6.2 Mini-Magnetospheric Plasma (M2P2): Bubbles to the Stars.

Although technically solar sailing is not a form of electric propulsion, a research group headed by R. Winglee at the Redmond Plasma Physics Laboratory<sup>32</sup> in Washington have proposed inflating a magnetic bubble around a spacecraft and using the interaction with the solar wind to push the spacecraft on interstellar trajectories. Using solar electric power, a solenoid coil would generate a large magnetic dipole bubble. Charged particles are injected into the bubble and their motion helps to inflate

<sup>31.</sup> Some information about MEMS is available at http://sec353.jpl.nasa.gov/apc/Micropropulsion/01.html . A recent paper SSC00-X-2, "MEMS Mega-pixel Micro-thruster Arrays for Small Satellite Stationkeeping ", D. Youngner, S. Lu, et.al., on the MEMS thruster given at the 14th AIAA/USU Small Satellite Conference, North Logan, UT, August 21-24, 2000 is available at http://alfven.princeton.edu/html/abstracts/MMMAabstext.htm .

<sup>32.</sup> See the news note: http://www.geophys.washington.edu/Space/SpaceModel/M2P2/.

the up to 10 - 20 kilometres across. The solar wind, streaming at 400 - 600 kilometres per second from the sun interact with the bubble and accelerate it up to the speed of the solar wind. Bye-bye solar system!

**Table 2: Expected Performance Parameters for Different Types of Electric Propulsion** 

Propulsion Type	Specific Impulse (s)	Specific Power (kW/kg)	Electric Power/ Thrust (kW/N)	Energy Conversion Efficiency	Propellant Utilization Efficiency	Impulse Bit (mN-s)	Thrust Level (mN)	Lifetime (N-s)
Electrothermal Arcjet	280 - 2,300	10 <sup>-3</sup> - 1	9	30 - 50 %	>30 %	0.3 - 1	50 - 5000	860,000
Pulsed Electrother- mal			14 - 20			0.3 - 1	~ 35	
Microwave Electro- thermal	300 - 1300		~ 3	40 - 70 %	50 - 70 %	< 1 - 2	< 1000	
Electrothermal Hydrazine	299 - 304	0.62 - 0.79	1.37 - 1.74	300 % <sup>a</sup>			330 +	300,000
Resistojet	150 - 700	10 <sup>-3</sup> - 10 <sup>-1</sup>	1 - 3	35 - 90 %			5 - 5,000	300,000
Ion Bombardment	1,200 - 10,000	10 <sup>-3</sup> - 1	25 - 50	75 - 90 %	80 - 95 %		0.005 - 500	5 x 10 <sup>6</sup>
Radiofrequency & Microwave	3,000 - 4,000	0.03	25	56 - 75 %	71 - 80 %		15	
Electrostatic Colloid	1,100 - 1,500	0.002	9	~ 75 %			0.001 - 0.5	> 10 <sup>3</sup>
Contact Ion	3,500 - 8,000		30 - 100	55 %			< 600	
Field Emission Ion	4,000 - 6,000		60	80 - 98 %		5x10 <sup>-7</sup>	.001 - 1000	
Hall-effect	1,500 - 2,500	0.2	17 - 25	40 - 60 %			< 220	2.3 x 10 <sup>6</sup>
Electron Cyclotron Resonance	2,000 - 4,000							
Variable Specific Impulse Plasma	3,000 - 30,000	0.15	~ 30	< 60 %				
MPD Arcjet Steady State	1,000 - 11,000		0.5 - 50	10 - 40 %			20 - 200,000	
MPD Arcjet Quasi- Steady State								
Pulsed Plasma	1,000 - 1,500	0.04	50 - 90	5 - 15 %		0.01 - 1	0.005 - 20	200 - 200,000+
Pulsed Inductive	1,000 - 7,000		20 - 100	20 - 60 %			2,000 - 200,000	

a. Efficiency > 100% due to chemical energy making up substantial fraction of exhaust energy.

# 7.0 Summary

A large variety of electric propulsion techniques have been designed, investigated and tested. Table 2 shows many of the expected properties of such systems that are of interest to a spacecraft engineer. Table 3 is a similar compilation with data for systems that have flown or will fly in the near future. The data is a compilation of material scattered throughout the references. Where values could not be computed or found in the literature, cells have been left blank, rather than insert possibly erroneous values<sup>33</sup>. Because of the non-uniform nature of the data in these tables, they should only be used as a guide and a starting point for further investigation.

Table 3: Performance Parameters for Various Electric Propulsion Systems that Have Flown

Propulsion Type	Specific Impulse (s)	Thrust/ Weight (N/kg/g)	Specific Power (kW/kg)	Electric Power/ Thrust (kW/N)	Energy Conversion Efficiency	Propellant Utilization Efficiency	Typical Thrust (mN)	Impulse Bit (mN-s)	Total Impulse (N-s)
Electrothermal Arcjet	480 - 810	0.003 - 0.005	0.25 - 0.5	6 - 15	91 - 95 %	27 - 37 %	100 - 2000		12,000
Augmented Hydrazine	294-304	0.018 - 0.036	0.5	1.5 - 3			180 - 300		
Resistojet	280 - 305	0.02 - 0.05	0.4 - 0.8	1.3 - 2	60 %	35 %	180 - 500		300,000
Ion Bombard- ment	2500 - 3310	0.0001 - 0.0006	0.03 - 0.12	22 - 36	87 - 91 %	46 - 66 %	10 - 160		>3x10 <sup>6</sup>
Radiofrequency Ion	3000 - 3150	0.00017	0.07	39	64 %	71 - 80 %	15		
Contact Ion									
Field emission Ion	4,000 - 11,000			33 - 60			.001 - 1000	1x10 <sup>-6</sup>	
MPD	600	0.00005	0.01	10 - 19		15 %	23	<500<	> 1,000
Pulsed Plasma	830 - 1200	0.000004	0.003 - 0.005	83 - 100	80 %	7 - 9 %	0.3 - 0.75		15,000 - 20,000
Hall Effect	950 - 1950	0.0006 - 0.003	0.1 - 0.45	16 - 19	91 - 93 %	42 - 67 %	11 - 512		2.3x10 <sup>6</sup>

Electric propulsion, although not a new form of propulsion, is certainly an alternative worthy of consideration given the increased commercial profile it has achieved. If a system requires a propulsion system that is at the low end of the chemical thrust regime, then electric propulsion may be a way to save spacecraft mass and/or increase the payload deliverable.

<sup>33.</sup> Including from the AIAA <u>Aerospace Design Engineers Guide</u>, 4th ed., AIAA, 1998, p. 10-40, and Sackheim, R. L., Wolf, R. S., Zafran, S., "Space Propulsion Systems", <u>Space Mission Analysis & Design</u>, Table 4.

# 8.0 Bibliography & Additional References

Design Guide Subcommittee of the Design Engineering Technical Committee, <u>AIAA Aerospace</u> <u>Design Engineers Guide</u>, 4th ed., AIAA, 1998.

Finke, R. C., ed., <u>Electric Propulsion and Its Applications to Space Missions</u>, *Progress in Astronautics and Aeronautics*, v. 79, AIAA, 1981.

Jahn, R. G., Physics of Electric Propulsion, McGraw-Hill, New York, 1968.

Moss, J. B., "Propulsion Systems", ed. Fortescue, P. and Stark, J., <u>Spacecraft Systems Engineering</u>, 2nd ed. J. Wiley & Sons, 1995, UK, pp.171-180.

Sackheim, R. L., Wolf, R. S., Zafran, S., "Space Propulsion Systems", <u>Space Mission Analysis & Design</u>, 2nd ed., eds. W. J. Larson & J. R. Wertz, Space Technology Library, Microcosm Inc. & Kluwer Academic, 1992, pp.644-645, 653-655.

Stuhlinger, E., <u>Electric Propulsion Development</u>, *Progress in Astronautics and Aeronautics*, v. 9, AIAA, Academic Press, 1963.

Stuhlinger, E., Ion Propulsion for Space Flight, McGraw-Hill, New York, 1964.

#### **Electric Propulsion Websites:**

Frisbee, R. http://sec353.jpl.nasa.gov/apc/index.html.

Advanced Space Propulsion Research Workshop May 31 / June 2, 2000 - JPL. Proceedings papers may be found at http://apc2000.jpl.nasa.gov/.

A somewhat out of date compilation of electric propulsion sites may be found at http://www.irs.uni-stuttgart.de/SURF/ep\_sites.html .

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