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IN-SPACE ELECTRIC PROPULSION SYSTEMS – THE FUTURE OF SPACECRAFT PROPULSION TECHNOLOGIES

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ABSTRACT

This specific paper explores how the in-space ‘Electric Propulsion Systems’ can turn out to be one of the most promising futuristic spacecraft propulsion technologies, possessing unique advantages over the chemical and other propulsion technologies. The propulsion systems for in-space spacecrafts and air-crafts are different, although sharing certain similarities, and the strategic and systematic approach of exploring the possibilities from the lower atmospheric to the upper atmospheric level is given a good emphasis here, which although is also brief. Moreover, a brief comparison is done between the conventional propulsion systems and the Electrical propulsion systems in general with regard to the specific Impulse and the Thrust generated. In addition, the different variability conditions in the terrestrial atmosphere is discussed in brief in order to account for the various challenges for the in-space electrical propulsion systems and to look for novel and innovative solutions to these challenges. The different types of applications of Electrical propulsion systems and the various thrusters in the current scenario are also mentioned. The main focus is on the feasibility of the Electric Propulsion systems for the low-altitude earth orbiting satellites which are mostly used for earth observation, land, water resources mappings, climate warning systems, earth science etc. at the present moment and thereby strategically going ahead into the electric propulsion systems and their pivotal role in the upper atmosphere of the earth. Although, the Various other applications of the In-Space Electric Propulsion Systems like the Medium Altitude Earth Orbiting satellites mainly used for Navigational purposes, Geostationary satellites used for Telecommunications etc, the Space Transportation – Launcher kick stages, Space Science - Interplanetary Space Exploration etc are beyond the scope of this particular paper, nevertheless these exciting aspects will be explored consecutively. Nevertheless, the various advantages like the reduction of weight of the satellite, Decrease in the launch cost, increase in the lifetime, efficiency and functionality of the satellite, reduction of the quantity of the space debris, the usage of the non-toxic green propellant etc will also be discussed consecutively and are presently beyond the scope of this paper.

Keywords: In-Space propulsion systems, Electric Propulsion systems, Non-toxic green propellant, Gridded Ion Engine (GIE), Hall Effect Thruster (HET) , High Efficiency Multistage Plasma Thruster (HEMPT), Pulsed Plasma Thruster (PPT), Magneto Plasma Dynamic (MPD) Thruster, Rayleigh-Taylor and Kelvin-Helmholtz instabilities.

1. THE FUNDAMENTALS

Performing an exciting quantum jump into the details of the futuristic spacecraft propulsion technologies without trying to have a good flavor of the fundamentals is like trying to start a giant ice-cream company without having the basic knowledge of the ingredients and the various flavoring substances used. Enjoying an ice-cream is definitely an exciting activity, but the knowledge of the ingredients and the flavors will enhance innovative ways to do an ice-cream. In a similar fashion, extra-terrestrial and interplanetary, interstellar journeys, travel and itinerary, exploration of the Celestial Universal secrets are the cosmic flavors that can get excited when we try to do Cosmic chemistry with the ingredients used in the space-craft propulsion systems. This will surely enhance the speed of the spacecraft, which is in fact inversely proportional to the time taken to reach a planet or a natural satellite of any celestial object in our immediate space neighborhood or at least in the vicinity of our ‘Solar system’. In other words, the speed of the space-craft should be enhanced multi-fold, while at the same time, the time taken to reach a particular celestial destination should decrease by the same multi-fold times. Following this principle, we need to design our space-craft propulsion systems in such a way to reach say for example, the Red planet within a month or so and the Moon within 12 Hours (!).

Obviously this requires a shift in the existing space-craft propulsion technologies to newer ones, by conquering over the various limitations posed by the existing space-craft technologies ensuring a smooth transition to the futuristic space-craft propulsion technologies. Of Course, the targets do not seem so simple as newer challenges try to make us stumble on the innovative path. Moreover, by utilizing the same futuristic propulsion technologies, we also need to take into account the propulsion technological requirements of the space-crafts or the satellites that orbit the earth in various zones like the LEO, MEO, GEO etc. In these cases, the speed and time factors need to be balanced with more finer precision accuracies as these

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satellites are used for various purposes such as civilian, military, natural resource mapping, climate warning systems, Communication and navigation systems, interstellar, interplanetary data processing purposes such as collecting the data from far-off interstellar space (in case of HST and ISS) , exploration for extra-terrestrial life etc, whereas the space-crafts utilized for the formerly mentioned interplanetary and interstellar exploration purposes can sometimes perform programmed (using AI and ground controlled) and calculated risky maneuvers in space by increasing or decreasing their speeds in space depending on the various imminent dangers posed by cosmic debris in the form of rocks, dust etc in space, during the course of interplanetary missions. This is highly evident in the case of NASA’s planetary missions to other planets like Jupiter, Saturn etc which must cross the vulnerable Asteroid belt between Mars and Jupiter.

Space-craft propulsion plays a pivotal role in any kind of in-space maneuvers of all kinds of space-crafts intended for all purposes. Moreover, space-craft propulsion technology can greatly influence the aerospace propulsion technology as well, wherein air-crafts can get the benefits from in-space propulsion technology systems too, when it comes to maneuvering in earth’s lower atmosphere - Troposphere, Stratosphere etc in which the conditions are highly varied in terms of temperature, pressure, fluid and gas dynamics, magnetic field and radiation effects etc. The upper limit for the military jets traveling at supersonic speeds is around 22 miles or 35 km which falls in the stratosphere region of the earth’s lower atmosphere. There is a much higher concentration of the atmospheric gases such as Nitrogen, oxygen forming the major portion of the Troposphere and the other gases extending into the Stratosphere with minor proportions. The Troposphere is very much a dynamic layer and an all time busy layer with winds, aerosols, climate activity like thunderstorms, temperature and pressure gradients changing all the time , when it comes to the Troposphere layers above oceans and continents etc.

2. DISCUSSION AND ANALYSIS

2.1 Structure of the Earth’s Atmosphere

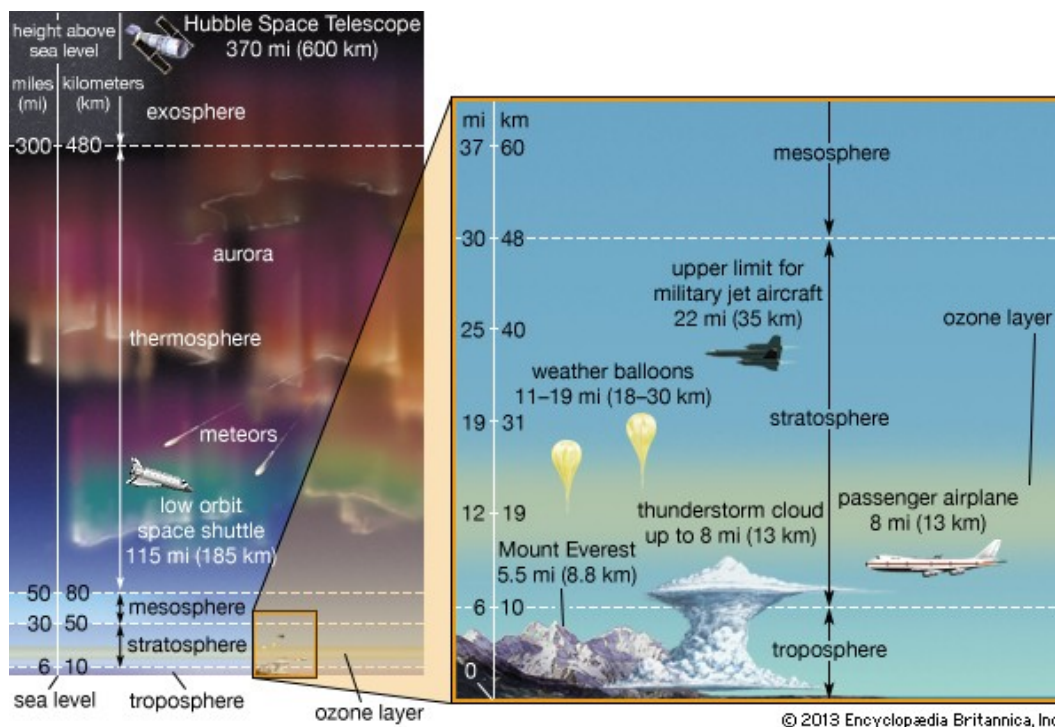


Fig 1 – The Structure of the Terrestrial Atmosphere up-to 600 km, the altitude of the HST (Kind Courtesy : Encyclopædia Britannica)

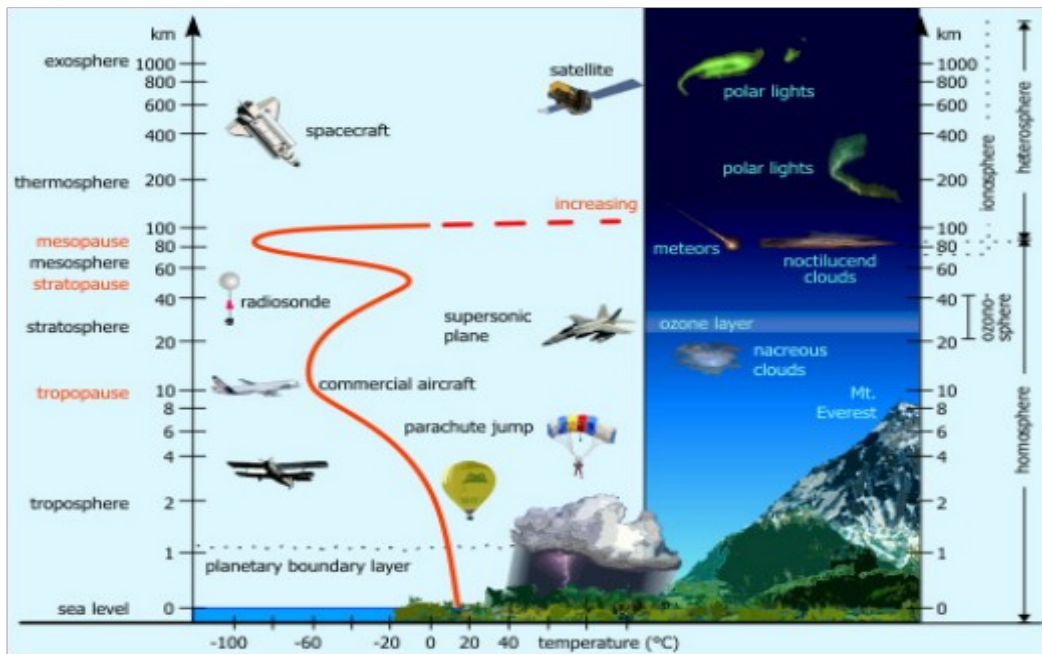


Fig 2 – The Structure of the Terrestrial Atmosphere up-to Exosphere at an altitude of around 1000 km (Kind Courtesy : <https://www.latitudegeography.org/atmospheric-interactions.html>)

2.2. Variability Conditions in the Earth’s Upper Atmosphere – Impact on the Space-crafts

The structure of the earth’s atmosphere is shown in the above figures. The immediate space neighborhood for the terrestrial atmosphere will start from an altitude of around 100 km above the surface of the earth. In other words, the terrestrial atmospheric boundary ending at 100 km above the surface of the earth, known as the Mesopause, marks the beginning of the space boundary technically lying in the Thermosphere-Ionosphere zone, where low earth orbiting spacecrafts used for communication and other specific purposes are designed to orbit at. The various conditions of temperature-pressure, thermal flows, fluid flow instabilities, gaseous current flows are much different for either side of this critical boundary. Moreover, the influx of the highly energetic particles from the earth’s upper atmosphere like the Magnetosphere to the Ionosphere, thereby coupling processes happening in the space – layers at an altitudes above 100 km extending to more than 60,000 km in deep space of the earth, where the earth’s magnetic field lines interacting with the Solar wind’s jumbo pack of energetic charged particles turns out to be much more critical for spacecrafts orbiting in these critical zones. However, the impact of the energetic charged particle influx on the Geo-stationary satellites is much more, when compared with the impact on the Low Earth orbiting space vehicles. Still, the ionospheric turbulent and variability conditions during day time and night time create chaotic effects when it comes to GPS Communication satellites and other space-vehicles even in the lower orbits.

2.3 Impact of the Ionosphere Turbulence on the Space-crafts orbiting in the Low Altitude Earth orbits

The Ionosphere consists of the D, E, F1, F2 layers that exhibit some typically different behavioral dynamics during the Sunlight time and the night times, following the Dissociation and the Recombination phenomena leading to a wide variety of chemical processes, making the ionosphere chemically turbulent most of the time. Whenever a solar storm hits and compresses the earth’s magnetic field lines, forming a bow shock at an altitude of 60,000 km in space beyond the surface of the earth, the effects are clearly noticed in the Ionosphere zone in the form of Aurora, Polar lights (Northern and Southern Lights). This will further impact the communication satellites and the various other space-crafts orbiting at these altitudes in multi-fold ways. The Rayleigh-Taylor, the Kelvin-Helmholtz and other instabilities add up to the turbulent conditions of the Ionosphere too. These all factors severely impact the electromagnetic wave propagation which plays a pivotal role on the GPS Communication abilities of the satellites, thereby reducing the lifetime of the data transmitting satellites, and resulting in severe loss of data.

Since, the main focus is on the propulsion systems, the detailed characteristics of the earth's upper atmosphere – Thermosphere-Ionosphere, Mesosphere, Exosphere, Magnetosphere etc are beyond the scope of this particular paper, nonetheless will be dealt consecutively.

2.4 The Pivotal role of Propulsion systems

Propulsion system of any spacecraft, be it low altitude earth orbiting, medium altitude earth orbiting, Geostationary satellites etc, is like a heart of a human body, constantly in motion for the over-all functionality of the space-craft. For a space-craft to receive, process and transmit the data, it has to maintain a well-defined orbit with a fine accuracy in its maneuvering through space, maintaining approximately the same velocity and angular momentum, balancing the gravity of the planet earth etc, thereby making sure the data is transmitted to the ground stations on the earth with meager disturbances. These adjustments in space are mostly controlled by the propulsion systems, which in turn churn out the energy required for the various components of the space-craft to be in its orbit.

2.4.1. A Brief Survey of the various Propulsion systems – Correlation between Specific Impulse and Thrust

In General, a propulsion system is a machine (Together with the various components) involved which generates a specific amount of thrust to give an object a certain amount of push depending solely on the amount of the specific thrust provided. In the case of air-crafts, the thrust is usually produced by the application of the Third Law of Motion (The Newtonian) involving the action and re-action. A gas or a working fluid with the necessary properties that lead to the capabilities in generating the required thrusts in the framework of the predefined temperatures and pressure conditions is accelerated by the engine (the action part) and the re-action to this acceleration that creates a force on the engine which allows the object (be it a spacecraft or an airplane depending on the various dynamic conditions in the atmosphere) to move in the forward direction exactly opposite to the direction of the motion of the gas or the fluid which has been accelerated by the engine.

While in space, the specific purpose of a propulsion system is to alter the velocity v of a spacecraft, which might result even in even inter-orbital shifts whenever required. Rocket engines using the Chemical mono-propellant or bi-propellants generally have a quite lower specific impulse (~ 300 s), but generate high thrust. The most unique feature of the space propulsion is the absence of indeed a material medium in which vacuum conditions perfectly fit into the scenario. This actually avoids the scenario of ejecting the environmental matter in the backward direction, allowing the vehicle to get accelerated in the forward direction. This has certain consequences listed below.

a. The propulsion under the vacuum conditions requires the backward ejection of on-board mass. The propellants are those which are ejected outwards and the rocket is the engine to force that ejection process and the required energy to power the rocket engine might come from inside the vehicle (say..in the form of combustion) or from outside the vehicle in the form of solar power.

b. Now, the propulsion under vacuum requires the carrying the load of both the fuel and the oxidizer aboard the vehicle. In the burning process of most of the fuels, the stoichiometry demands that every kilogram of fuel requires mostly 15 kg of air. Ironically, we do not need to transport the air, but only the oxygen or any other oxidizer, avoiding combustion for the time-being, making the use of other physical process to accelerate the propellants backwards to achieve the propulsion.

c. Propulsion under the conditions of Vacuum requires the backward ejection of the on-board mass to achieve the deceleration (braking), since there is no air drag in space.

Technically speaking, by the word 'space' in the word 'space propulsion', we understand the 'outer space', where the vacuum conditions predominate, say beyond the 100 km altitude Karman line on earth, until we encounter another planetary atmosphere – mostly called the space environment. We also can safely include the atmospheric flight of space vehicles (launchers and descenders etc) under the category of Space-Propulsion. Contrarily, in the case of aircraft flight, it must be propelled continuously (sailplanes considered aside), spacecraft flight is most of the time unpowered (ballistic motion mostly predominated by gravity forces), with some periods of propulsions based on rocket-engines, that is, on the high speed throwing of some amount of stored mass on board, technically known as the propellant, which is accelerated by the various internal energy sources (can be chemical or even nuclear reactive) or through the external energy sources (mostly the natural solar radiation or the radiation generated from a typical ' power station' spacecraft, originating from a nuclear reactor or **stored solar radiation**, which is being targeted to the receiving space-craft in a Laser or a Microwave radiation beam).

Another unique and distinctive characteristic feature of space-propulsion is that, there are no possibilities left for re-fueling and typically ends up in the end of a space mission, dictated by the run-out of the fuel. (The Historical context of the propulsion system of the rocket engines is certainly beyond the scope of this particular paper and which forms an exciting topic of exploration in another paper). At this juncture, the relative motion under the outer-space vacuum conditions must be generated by the ejection of own mass in a backward direction. A rocket is the typical ‘ engine’ we might be engaging to fulfill this specific purpose, although it can simply act like a reservoir of gas.

The various other means of spacecraft propulsion without necessarily the ejection of mass can be conceived , by making use of environmental material and electromagnetic flows (EM Flows) in outer space (in the case of Solar sail propulsion) or the ejection of electromagnetic radiation – which involves the flow of energy without the rest-mass, but involving the momentum) , but the forces which are involved are too small for the current applications. In fact, Space propulsion is much needed to launch from a planetary surface to orbit (involving the sub-orbital flights), orbit acquisitions and orbit keeping against perturbations, orbit changes (including inter-planetary transfers), de-orbiting (descent and landing process on the surface of another planet or a moon) and attitude control in all the necessary phases of space flight (launch, orbit and de-orbit).

Arriving at the spacecraft propulsion technology part, currently it is categorized into (I) chemical (II) Electric (III) Propellant-less. In addition, the liquid-propellant acquisition and the management devices are also reviewed as one of the most significant components of in-space propulsion systems. A general listing is shown in the below table, consisting of the various in-space technologies, the specific Impulse and the thrusts generated.

Table 4-1: Summary of Propulsion Technologies Surveyed		
Technology	Thrust Range	Specific Impulse Range [sec]
4.6.1 CHEMICAL PROPULSION TECHNOLOGIES		
Hydrazine Monopropellant	0.25 – 22 N	200 – 235
Other Mono- and Bipropellants	10 mN – 30 N	160 – 310
Hybrids	1 – 10 N	215 – 300
Cold / Warm Gas	10 μ N – 3 N	30 – 110
Solid Motors	0.3 – 260 N	180 – 280
Propellant Management Devices	N/A	N/A
4.6.2 ELECTRIC PROPULSION TECHNOLOGIES		
Electrothermal	2 – 100 mN	50 – 185
Electrosprays	10 μ N – 1 mN	250 – 5,000
Gridded Ion	0.1 – 15 mN	1,000 – 3,500
Hall-Effect	1 – 60 mN	800 – 1,900
Pulsed Plasma and Vacuum Arc Thrusters	1 – 600 μ N	500 – 2,400
Ambipolar	0.25 – 10 mN	500 – 1,400
4.6.3 PROPELLANTLESS PROPULSION TECHNOLOGIES		
Solar Sails	TBD	N/A
Electrodynamic Tethers	TBD	N/A
Aerodynamic Drag	TBD	N/A

Fig 3 – A brief summary of the propulsion technologies providing the Thrust ranges and the Specific Impulse (Kind Courtesy : NASA)

In addition, the below figure provides a graphical illustration of the range of thrust and specific impulse for these small spacecraft propulsion devices.

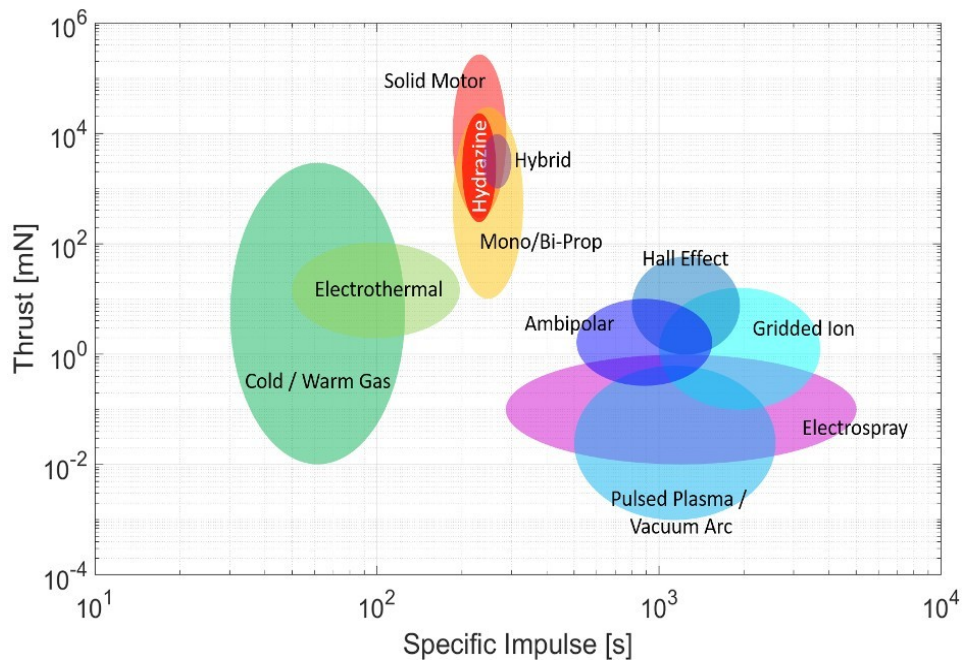


Fig 4 - Typical small spacecraft in-space propulsion trade space (thrust vs. specific impulse).
(Kind Courtesy & Credits: NASA)

The Specific impulse ranges and the thrust provided in the table and the above figure provide us with only a summary report of the performance of the small spacecraft devices and need not necessarily reflect the broader capabilities of the technologies beyond the small spacecrafts and which is indeed possible with the advancement of technology further.

Chemical systems have enabled in-space maneuvering since the beginning of the current modern space-age, which definitely have proved to be highly capable and reliable too. These include Hydrazine-based systems, various other mono or bi-propellant systems, warm/cold gas systems, solid propellants etc. These systems are required whenever there arises a typical necessity of high thrust or rapid maneuvers. In other words, the chemical systems remain the most sought propulsion technology of choice, when it comes to their total specific impulse capabilities which are generally sufficient to meet the requirements of most space missions.

2.4.2 The Electrical Propulsion Systems – EPS Technology

Electric propulsion is a class of space propulsion, which is unique of its kind, which makes the use of electrical power to supply the required acceleration to a propellant by the various possible electrical or magnetic means. In fact, the use of electrical power literally enhances the performance of the propulsion of the Electrical Propulsion (EP) thrusters when compared with the chemically driven conventional thrusters. Unlike the chemical systems, electric propulsion generally requires very little mass than from a conventionally classical chemical thruster and proves to be a certainly much more mass efficient. In Comparison with the chemical propulsion systems, the EPS does not possess any limitation with regard to energy, but is only constrained to the available electrical power on-board the spacecraft. Nonetheless, the EPS is mostly suitable for the low thrust (the micro and milli-Newton levels) lengthy duration applications on-board spacecrafts. Most commonly, the propellant used in the EPS varies with the thruster and can be a rare gas (say xenon or Argon etc), sometimes a liquid metal too.

2.4.3 Applications of Electrical Propulsion Systems and the various types of thrusters in brief

The various applications which currently make use of the Electrical Propulsion systems can be listed below:

- (I) Low Altitude earth orbiting (e.g. Earth Observation , Earth Science etc)
- (II) Medium Altitude earth orbiting (e.g. Mainly for Navigational Purposes)
- (III) Geo-stationary (Mainly for Communications etc)
- (IV) Space Transportation (e.g. Launcher kick stages, space tugs etc)
- (V) Space Science, Interplanetary and Space Exploration.

Different space missions are intended for different purposes. The requirements are diverse and hence, the Electrical Propulsion systems is faced with certain operational challenges in order to be able to cope up with various types of maneuvers such as inter-orbital transfer, inter-planetary cruising, *continuous LEO operations (control over the air drag)* , highly agile attitude control, Long -endurance missions etc.

A number of different types of Electrical propulsion systems exist , based on the following thrusters and are listed below.

- (a) Gridded Ion Engine (GIE)
- (b) Hall Effect Thruster (HET)
- (c) High Efficiency Multistage Plasma Thruster (HEMPT)
- (d) Pulsed Plasma Thruster (PPT)(e) Magneto Plasma Dynamic (MPD) Thruster
- (f) Quad Confinement Thruster (QCT)
- (g) Resistojet
- (h) Arc-jet
- (I) Field Emission Electric Propulsion (FEEP) Thruster
- (j) Colloid and Electro spray Thrusters
- (k) Electrode-less Thrusters
- (l) Hollow Cathode and Neutralizers

The below figure provides a much brief about the basic components of an Electrical propulsion systems

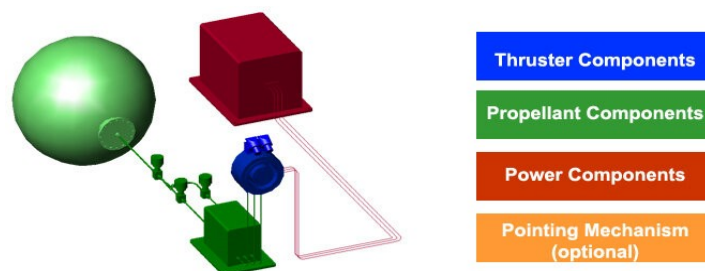


Fig 5 - An Overview of the Building Blocks of the Electric Propulsion Systems

In fact, specially in the European continent, various developments have been carried out in all the various diversified areas of the electrical propulsion systems over the last four decades. As per the survey conducted, the HET, GIE and HEMPT turned out to be some of the most promising technologies. Depending on the specific mission requirements and the field of applications, a particular system level trade off should be performed to identify those thruster systems which can be more or less attractive, depending on the specific thrust capabilities, the electrical power consumption levels and various other factors affecting the performance characteristics.

3. CONCLUSION AND FURTHER SCOPE

Although, the EPS technology has been studied extensively, developed and thoroughly tested for several decades(in Europe etc), certain Electrical Propulsion Systems were not readily employed in the early times of some European space missions mainly due to the lack of availability of adequate electrical power on-board the spacecraft. Since, the onset of the new century, the increasing levels of electrical power on newly developed spacecrafts allows the Electrical Propulsion Systems to be much more realistic and provides us with a serious alternative to the chemical propulsion technology. Electrical Propulsion systems is currently considered by the global space industry and space agencies alike as a key and a revolutionary technology for the next generation of commercial and scientific spaces satellites. It is also noteworthy to see that various initiatives in this specific field all over the globe are targeted at the development of new and innovative generations of the Electrical propulsion systems. Having said this, the application of the electrical Propulsion devices has been historically far more limited in this regard. The challenges are also many in this field. For instance, electrical propulsion systems generally provide a thrust-to-power levels below 75mN/kW. Hence, a small spacecraft which is quite capable of delivering 500 W to an electrical propulsion system may generate around 38mN. While, the total impulse capability of electric propulsion is quite considerable, it needs to operate continually for hundreds of thousands of hours, in comparison to the seconds or minutes that chemical systems necessitate for a similar impulse. Nonetheless, the high total impulse and low thrust requirements of certain applications might be sufficient to utilize the electrical propulsion systems. However, the recent years has seen a steady increase in the exploration of the EPS, and might even crossover the various challenges, thereby can certainly prove to be much more efficient than the chemical propulsion systems. Moreover, some advanced versions such as nuclear in-space propulsion have been surfacing, but are certainly beyond the scope of this paper. Finally, while considering the complete propulsion systems comprising the thrusters, feed systems, pressurization systems, propellant management and storage etc, power processing units, the electrical power supply plays a pivotal role for all of these components for their functionality on board. Depending on the device's intended platform such as NanoSat, MicroSat, etc, the propulsion systems can be either integrated or distributed within the spacecraft.

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