A Study of Low-Power MPD Arcjets for Future High-Power Evolution

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Preliminary concepts of low-power MPD (Magnetoplasmadynamic) arcjets for high-power evolution have been studied in ISAS (Institute of Space and Astronautical Science). There are two categories of these concepts, pulsed-mode and steady-state MPD arcjets. Both are the candidates, because ISAS has several flight experiences of pulsed MPD arcjet, and also R & D experiences of quasi-steady MPD arcjets and low power DC arcjets. This study shows that the cluster of single MPD arcjet will be the reasonable way to realize large-scale high-power MPD arcjet from the viewpoint of ground tests and facility availability. The focal points for such design will be the thermal analysis and electrode erosion for single MPD arcjet that is just a portion clipped out from the cluster configuration. The simple and robust MPD arcjets at high-power evolution will propose a lot of large-scale transportation in the near future.

Introduction

MPD (Magnetoplasmadynamic) arcjet is one of the feasible options for large-scale and high-power electric propulsion which will be requisite for heavy cargo orbit transfers in solar power satellites, massive flights for interplanetary logistics like Mars explorations, and even in the control of extremely large space structures, for example, a space colony in the near future. While electrostatic thrusters attain high exhaust velocity of Xe, Kr or other ions of heavy atomic species, the MPD arcjet will be able to utilize more popular and lighter atomic species of Ar, NH_3, N_2H_4 and even H_2 if its storage innovation is achieved in the future. However, the available electrical power in space is yet so unsatisfactory that the MPD propulsion has never been applied to space missions to date except for a few preliminary space experiments in repetitively-pulsed mode of operation. One of the most important key issues for MPD propulsion realization is feasibility of future high-power evolution such as cluster of single thruster or its extrapolative enlargement corresponding to available electrical power. Another rigorous barrier is facility problem, because high-power electric propulsions always demand huge vacuum system. Therefore, in the course of high-power MPD arcjet development, we need at least a plausible roadmap for upcoming several decades that will enable practical missions using very large-scale electric propulsion exhausting tons of propellant. In this research, two types of low power MPD propulsion techniques, repetitively-pulsed operation and steady-state applied-field operation are discussed for the above first requirement of stepping stones. Based upon space and ground experiments performed in Japan in these years and looking at low power applications on the premise of future high-power applications, a survey of MPD propulsion techniques in our laboratory are discussed from the viewpoint of thermal design, electrode erosion, thrust performance, propellant selection and probable plasma interactions with spacecraft.

Flight Heritage and Ground Experiments

Preliminary space experiments of MPD arcjet were attempted a few times by ISAS (Institute of Space and Astronautical Science) in Japan, for example, on MST-4 satellite in 1981 [1] and on SEPAC (Space Experiments with Particle Accelerators) of the Spacelab-1 in 1983 [2]. Their electrical power was limited lower than 200 W or less and quite unsatisfactory to demonstrate an MPD arcjet as the

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electric propulsion system. In 1995 an MPD arcjet thruster system was integrated on a Japanese reusable free-flyer, SFU (Space Flyer Unit) and launched in order to verify its propulsive function in orbit [3]. The objectives of this space experiment EPEX (Electric Propulsion Experiment) were to verify durability of the system against launch and space environment, repetitively pulsed firing more than several thousands of shots at 430 W maximum, and safe dump of residual hydrazine propellant. All these objectives were successful completed and the accumulated repetitive firings amounted to over 40,000 shots. Also the generated thrust was detected from the momentum wheel control value to be compared with the thrust values obtained on the ground experiment (Figure 1) and the results showed good agreement. However, due to the weight restriction of the SFU experiments, a PFN (Pulse Forming Network) was too small to produce a sufficiently long pulse synchronized with 800 μs propellant puff of hydrazine decomposed gas. From the practical point of view, this was purely an experiment of propulsive function only and apparently the delivered specific impulse was low because of the mismatch of the PFN to the gas pulse duration produced by FAVs (Fast Acting Valve).

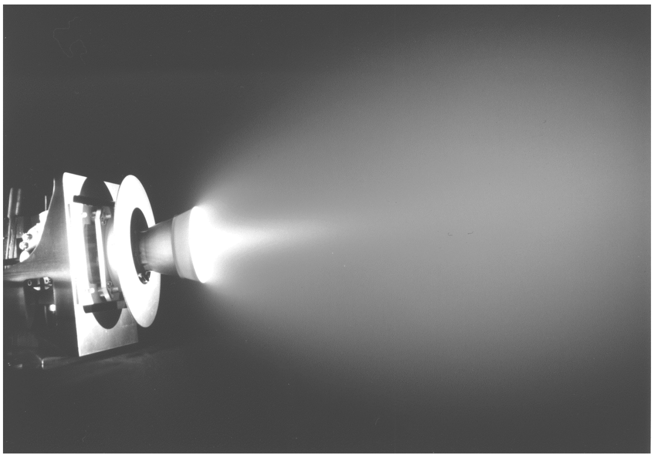

Figure 1 – Pulsed MPD firing used for the EPEX space test on SFU in 1995.

On the ground, an endurance test of 3-million-shot, corresponding to 25 days repetitive firings was successfully finished in 1987 [4]. The repetition rate was 1.4 Hz and the electrical input power to the system was about 1,000 W with longer currents pulse of 600 μs x 6 kA and 800 μs hydrazine decomposed simulative gas pulse. This endurance test was suspended because of the facility maintenance problem and relocation of our institute in 1988. The thrust performance was 34 mN/kW of thrust-to-power ratio at an Isp of 600 s. Prior to this endurance test, we already consolidated a basic design concept of the repetitively pulsed MPD arcjet. The anodes were divided into 8 segments to which a separate PFN (the capacitor bank is 8 segmented and the coil is made by 8-line bifilar windings) is connected so that the arc discharge makes a uniform distribution in azimuth direction, preventing arc localization. Consequently, this configuration realized 2 times higher thrust efficiency than the conventional monolithic anode configuration [5]. The cathode is a single rod without any divisions but short cathode configuration was proved to enhance the aerodynamic thrust generation within the low Isp operation regime.

Discussion of Known Technical Problems

Pulsed MPD Arcjet

There are two types of MPD operations repetitive pulse operation and steady-state operation. Since the MPD arcjet thruster is an electromagnetic accelerator of plasma, a large Lorentz force must be expected for both types operation. In the pulsed mode operation, it is easy to obtain high discharge currents up to several or a few tens of kiloamperes by using a capacitor bank. Instead, the discharge duration is limited by the scale of PFN consisting of capacitor banks and coil stages and the larger the PFN becomes, the longer the discharge duration extends. A typical specific energy of state-of-the-art film capacitor bank is about 25 J/kg and if the coil module should be involved, its value is reduced into 13 J/kg. In this case a film capacitor is assumed, because chemical capacitor has larger capacitance but it is not suitable to thruster application because of low expected lifetime for charge/discharge cycle, for example one million cycles or so. Recently, an electric double layer capacitor is intensively investigated in Japan. This type of condenser consists of separators with activated carbon electrodes in electrolyte and can be applicable to car batteries because of its very large capacitance of several farad order with 50 times higher specific energy to conventional film capacitors [6]. But the output voltage is limited around 1 V of single cell, while its internal impedance is still very high about several tens of milliohms which is inconvenient to the MPD like application of rapid high current extraction in repetitively pulsed mode. If the internal impedance is lowered by two order of magnitude, this will be the promising candidate for the MPD capacitor bank.

As was seen in the EPEX space test, the gas pulse produced by FAVs cannot be reduced shorter than 800 μs and this correspondingly requests a relatively long duration of discharge current. In the EPEX case it was only 150 μs of discharge duration and resulted in low delivered specific impulse, while the ground endurance test employed 600 μs by virtue of 4-staged PFN. This inconvenience should be solved by a sufficient elongation of the current pulse, however the weight penalty due to growth of the PFN also should be accepted at about 10 kg/stage for the time being. Another approach to solve this deficiency is to create a very short gas pulse by non-electromagnetic valves such as the laser FAV which can evaporate a droplet of the liquid phase propellant or a solid state propellant. This concept has not been put into practice yet, but should be a promising candidate especially for the application of small but high power diode lasers. On the other hand at EPPDyL (Electric Propulsion & Plasma Dynamics Laboratory) in Princeton University, an extremely high repetition rate of current discharge up to 7 kHz was attempted during a moderate length gas pulse of 10 ms. It is reported that very high specific impulse of several thousands seconds was successfully achieved [7]. In this case efficiency and/or lifetime of the capacitor bank is a dominant factor of the flight system feasibility.

As for the electrode erosion, the anode erosion can be neglected in any case of the pulsed mode MPD propulsion, however the cathode erosion apparently affected the discharge stability in our endurance test [8]. Figure 2 shows the variation history of erosion rate in the 3-million-shot endurance test performed in 1987. In the very beginning of this endurance test during 25-thousand-shot, a high erosion rate of 18 μg/C was observed while after 400-thousand-shot the erosion rate was kept almost constant at 0.67 μg/C until 3-million-shot was reached. We used a 1-cm diam. Barium oxide impregnated tungsten cathode in the endurance test and this is typically the best value for the MPD cathode compared to 100 μg/C for 2 % thoriated tungsten cathodes. Nevertheless the cathode erosion truncated the electrode length about 1 cm from the tip after the 3-million-shot endurance test as seen in Figure 3. Although the thrust performance scarcely changed before and after the endurance test, the ignition reliability was obviously spoiled to some extent by this cathode truncation. Therefore the cathode erosion must be the problem that will be crucial to the pulsed mode MPD arcjet. The only solution to this problem is to provide a solid cathode or to adopt a dispensable electrode like lithium transpiration cathode [9].

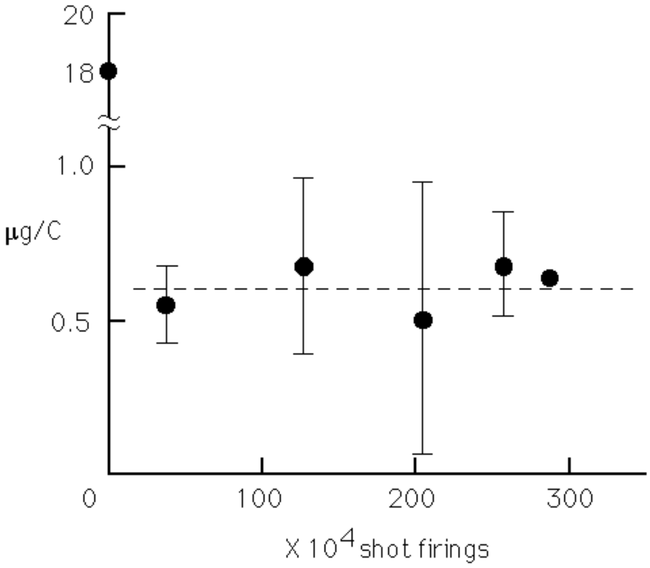

Figure 2 – History of cathode erosion rate during 3-million-shot endurance test.

Figure 3 – Cathode features after 3-million-shot (Top), 25-thousand-shot (Middle) and brand-new (Bottom).

The above mentioned features are unfavorable points of the pulsed mode MPD arcjet. But the largest merit of the pulsed mode operation is the flexibility of electrical power consumption, because the charge/discharge cycle is changeable corresponding to the available power. For example in EPEX, possible repetition rates were 0.5 Hz, 1 Hz, 1.4 Hz, 2 Hz and single pulse along with the power available on the SFU. The upper limit of the repetition rate is determined by the capability and efficiency of the charge control unit and endurance of the PFN against rapid charging by surge current.

Steady-State MPD Arcjet

The steady-state MPD arcjet has a few advantages over the pulsed mode MPD arcjet such as low erosion rate of cathodes and compact electrical power processor. As for the cathode erosion, a steady-state operation always revealed better characteristics than those of pulsed mode. The best erosion rate in the steady-state arc discharge is 1 ng/C for 2% thoriated tungsten in the most of DC arcjets and this value is lower than the pulsed MPD arcjet by 3 orders of magnitude. Another merit of steady-state MPD arcjet is no PFN required and thus the weight penalty is simply owing to the electrical power processor. This should be the important mass saving.

Contrary, in the steady-state MPD arcjet it is rigorously required to enhance electromagnetic Lorentz force for the better thrust performances. The biggest solar panel existing in space is about 140 kW of the space station and even using this electrical power source, the discharge current is only 1.4 kA at a discharge voltage of around 100 V. Reasonable Lorentz force requires several kiloamperes and thus the several hundreds of kW must be prepared for the operation of a self-filed MPD arcjet. This is the most critical and important requirement unless the applied-field MPD arcjet is considered for substitution which is revisited later in this study. A large-scale power source is necessary not only in space but also on the ground for the performance and lifetime verification tests. Especially once an endurance verification is recognized necessary, its facility must be equipped a same or much larger electrical power source and an incredibly powerful pumping system, because insufficient background pressure has a problem of entrainment phenomenon resulted in an overestimation of the thrust performance. The most realistic problem is the financial one rather than these technical problems. The investigator or developer must prepare a huge vacuum chamber with unrealistically large-scale vacuum pumping system and MW-class electrical power source.

Low-Power MPD Systems Design

Based upon the above discussion for both pulsed and steady-state MPD arcjets, possible approaches in ISAS to make the MPD arcjet a vital element of space propulsion is a low-power MPD system which can be promising for the future high-power evolution. In the pulse mode MPD arjet, it is not yet found that there

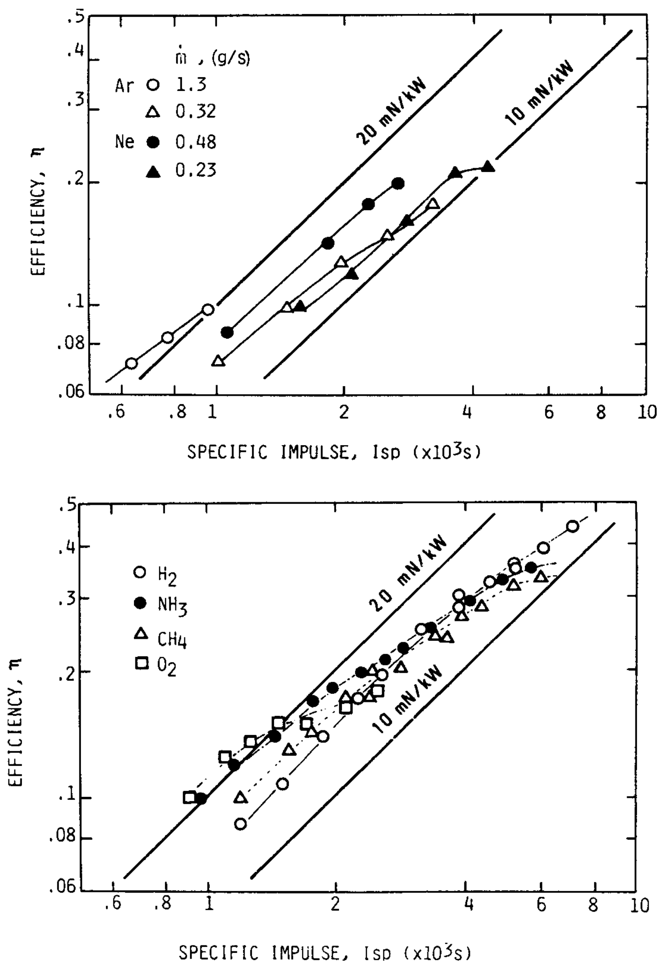

Figure 4 – Thrust performance of pulsed quasi-steady MPD arcjet for rare gas (Upper) and hydrogenous propellant (Lower). [10]

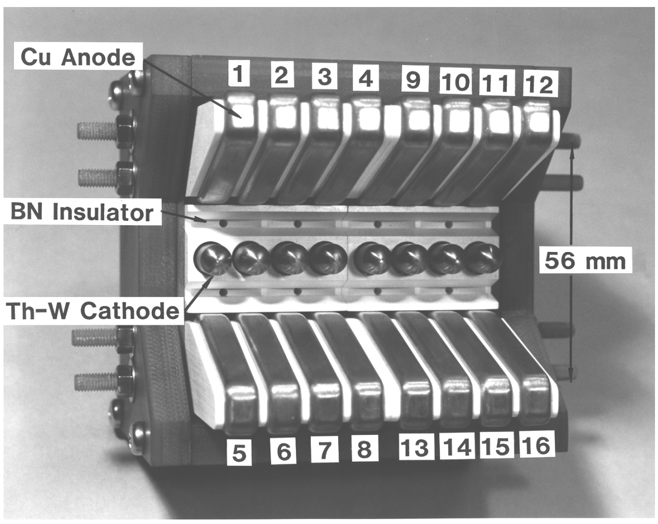

Figure 5 – 2-dimension like MPD arcjet providing flowfield observation window from lateral direction (discharge region is 16 channeled so as to assure uniform arc discharge averaged along the line-of-sight) [11].

should be the optimum electrode geometry maximizing the exhaust speed at given electrical power and thruster size. As shown in Figure 4, the thrust efficiency of the quasi-steady MPD arcjet is improved as high as 40 - 50 % for hydrogen propellant but is limited as low as 10 –30 % for the space storable propellants [10]. The efficiency improvement is our final target of investigation for pulsed-mode MPD arcjet, because it is easier in pulsed or quasi-steady mode than in the steady-state mode to make a trial-and-error approach for the best performance geometry. Our 2 dimension-like MPD arcjet is useful to simulate the MPD flowfields under variety of electrode geometry with operating conditions of propellant species, discharge currents, and mass flow rates (Figure 5) [11]. The experimental results will be compared to the prediction of numerical optimization of the multi-dimensional flowfields in the near future.

Another technical approach is to produce a short gas pulse by using a technique of liquid supply of the propellant, because one of the deficiency of pulsed-mode MPD arcjet is a mismatch of the gas pulse duration to that of the current pulse. The former usually becomes much longer than the latter, whenever the weight limitation is imposed to the system. If the propellant can be supplied in the form of droplet, laser irradiation can instantaneously evaporate it. This approach is being pursued by laser propulsion group in Japan [12], but similar technique is applicable to the propellant supply for the pulsed-mode MPD arcjets.

In the steady-state MPD arcjet, substantially high power is required for satisfactory Lorentz force which in turn requires very high current up to several kiloamperes namely a very high power of several hundreds kilowatts or higher for self-field acceleration. It is obvious that the externally applied-field is necessary for the low-power MPD arcjet in the regime of a few kilowatts, if it is truly applicable to materialization as a thruster system. The discharge current is limited a few tens of amperes, while the discharge voltage cannot vary so much at around several tens of volts or one hundred volts in any case. There are several methods of electromagnetic acceleration deduced by combination of discharge current vector and magnetic field vector in each 3 directions. After eliminating all the trivial combination, we reached 3 possible configurations as the low-power steady-state MPD arcjet as shown in Figure 6. From these cartoons, we selected the most simple configuration Type A as the low-power MPD arcjet, because Type B seems to have lots of dead volume which does not contribute to plasma production nor

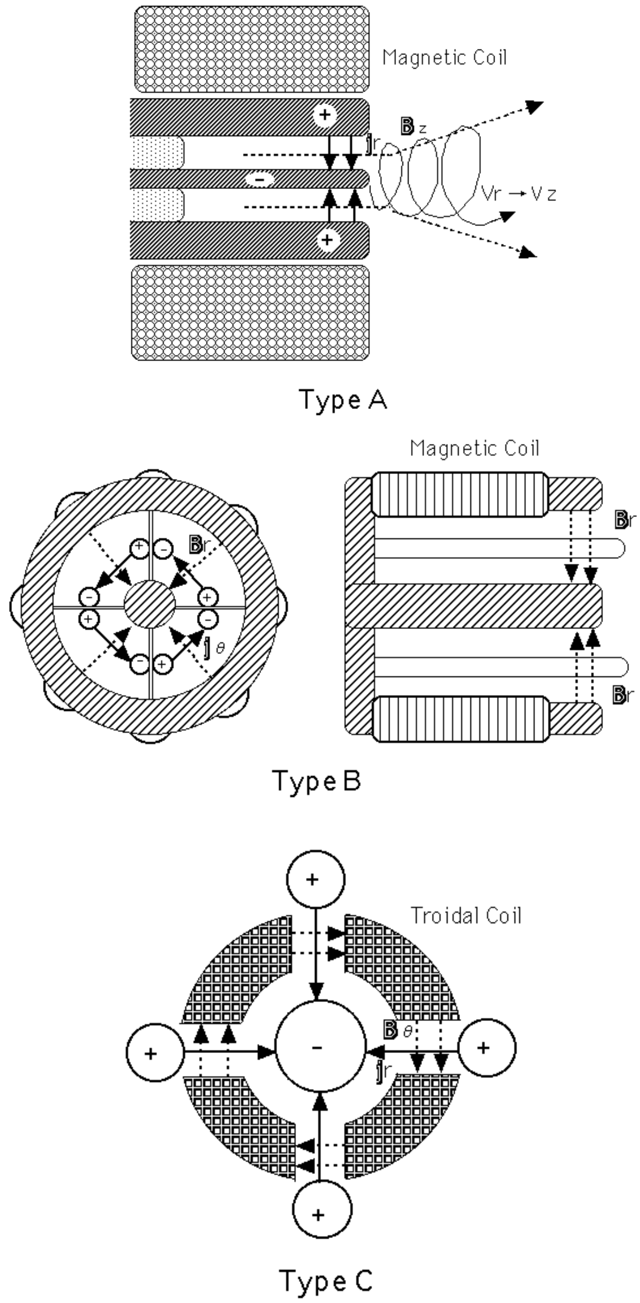

Figure 6 – Three configuration of applied-field MPD arcjets corresponding to Lorentz force (Type A: $j_r \times B_z$, Type B: $j_\theta \times B_r$, Type C: $B_\theta \times j_r$).

thrust generation and type C seems to be just the reverse configuration of Type A in terms of current and magnetic field vectors. Several applied-field MPD arcjets also employed similar configuration as Type A such as University of Tokyo [13] and University of Stuttgart [14], although their power levels are much higher than our concept. However, in Type A we must pay careful attention to magnetic flux leakage from the thruster head, because some sensitive spacecraft should be kept away from any magnetic fields. A magnetic circuit must be formed so that the applied-field lines are enclosed inside the acceleration region by using iron yoke.

Roadmap to High-Power Evolution in ISAS

From the technical point of view, it is the most important step to clarify how to evolve the low-power MPD arcjet into a high-power one without any logical leap in the course of development. In ISAS we will newly begin with a few kilowatt level steady-state MPD arcjet, probably around 1 kW. This implies a cluster configuration is necessary for future high-power evolution. The clustered MPD arcjets must have the same specific impulse and the same or higher thrust efficiency as those of a single MPD arcjet. This condition will be satisfied by just placing MPD arcjets on a common setting plate, however the concept is too much easy-going to give structural merits for scale-up. Before designing single MPD arcjet we must design the final configuration of clustered MPD arcjets. In an ideal case, single MPD arcjet should be just a portion of the cluster configuration as depicted in Figure 7 and the thermal analysis is conducted as a part of cluster MPD arcjets as well as a single MPD arcjet. The former analysis should include boundary conditions of thermal interface surrounded by other exothermic MPD arcjets, and the latter analysis must always take the difference between being isolated and being clustered into account. Figure 8 shows the thruster temperature of 1 m diameter versus the operation power up to 100 MW. From this graph we can understand the upper limit of the input power to a single MPD arcjet having reasonable dimension.

Another biggest problem to be solved is the electrode erosion. It is also very convenient here, if single MPD arcjet is fully analyzed and tested under the known thermal environment without constructing a clustered

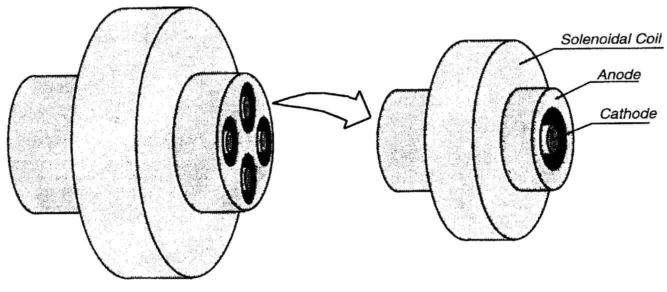

Figure 7 – Concept of single MPD arcjet clipped from clustered configuration.

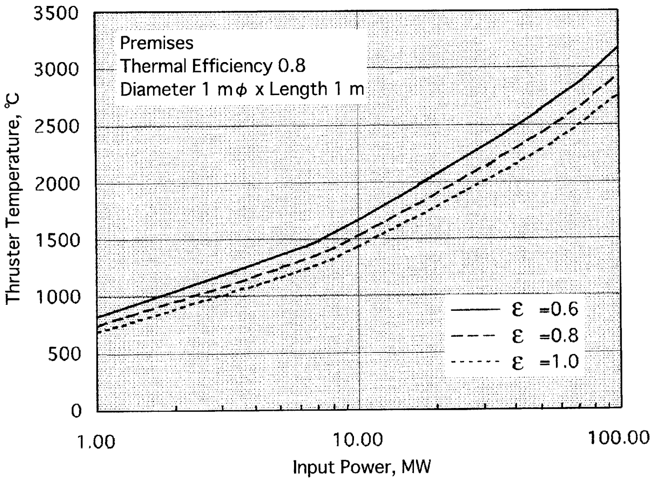

Figure 8 – Temperature evaluation for single MPD arcjet with MW-class power input.

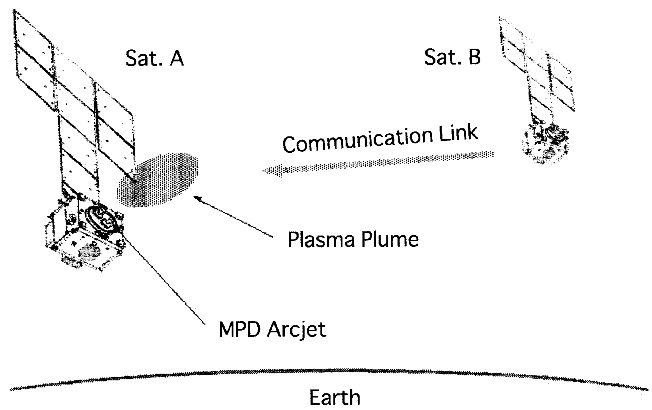

Figure 9 - Formation flight demonstration on small satellites.

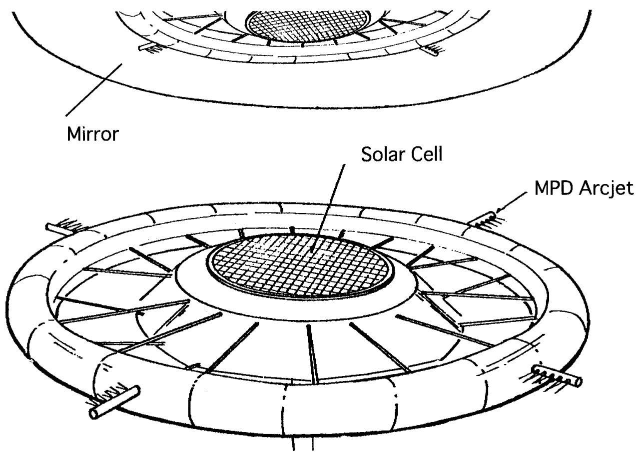

Figure 10 – 1.6 km space colony controlled by MPD arcjet thrusters.

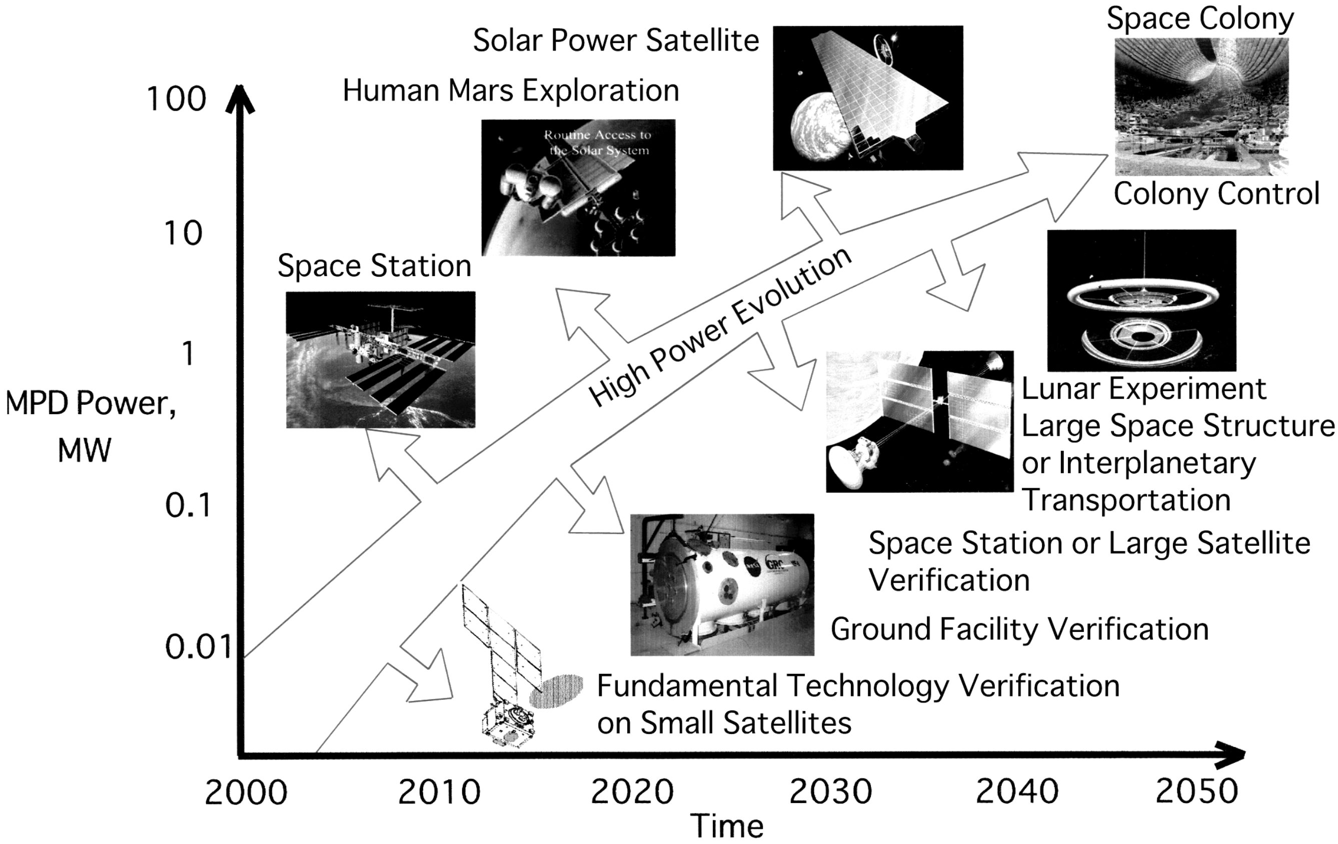

Figure 11 – A roadmap from low-power MPD arcjets toward high-power evolution in ISAS.

MPD arcjet. Since the cathode erosion is inevitable as far as the arc discharge is employed, we must supply cathode material to supplement erosion loss. In this sense, once a good idea for dispensable cathode is obtained, it will be also valid for every cathode inside the clustered configuration. And its verification is no longer the function of operating power for scaling-up. The propellant choice is still an open problem for the MPD arcjet, because hydrogenous propellant generally exhibited good thrust efficiency, especially in hydrogen, but from the viewpoint of space storability and non-toxicity, argon or water is presently the best choice. Of course Xe propellant will be ruled out, because it is too rare resource and expensive to use for massive transportation. As for the fundamental testing inside the ground facility, single low-power MPD arcjet is always advantageous compared to very high-power single/clustered MPD arcjet. After the ground tests, space tests will be required for the final validation of the electric propulsion system. Ideal vacuum environment, vast space and weightlessness are the key factors which are not available on the ground tests. We must also pay careful attention to possible interaction of exhausted plasma with spacecraft or radio communication.

Some milestones are also depicted as flight verification using a small satellites to evaluate plasma interaction with spacecraft and to demonstrate the prediction of electrode erosion and thermal analysis (Figure 9), ground tests inside vacuum chamber, flight verification on space station or large satellites, application phase of construction of solar power satellites or large space structure, lunar experiment and space colony control as the final option (Figure 10). Figure 11 exhibits a roadmap from low-power to high-power evolution of the MPD arcjet along with upcoming space events, such as the space station, human Mars exploration, solar power satellite, and eventually space colony.

Concluding Remarks

The MPD arcjet has been considered a future technology or an educational device which has never been applicable to on-going space programs, although several non-propulsive applications are vital such as plasma wind tunnel and material processing. In this very preliminary study we would like to conclude that the MPD arcjet will be a promising device for high-power transportation, because the thruster configuration is robust and very simple without any neutralizers or grids, and the propellant selection criteria of Ar, NH_3, N_2H_4, H_2, He, (H_2O) is broad for massive exhaustion. Only the task of H_2O supply remains unresolved for the reason of oxygen inclusion of which effect will be mitigated for pulsed operation or dispensable cathode configuration. As for future evolution to high-power cluster MPD arcjets, the concept is very clean to scale up by thermal analysis and electrode erosion evaluation. Both are the function of maximum thruster diameter and the operating power. These techniques of high-power plasma production and exhaust will facilitate the ultra-high-power technologies of nuclear fusion, matter/antimatter annihilation rocket and other preliminary skirmishes for the next generation propulsion system.

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