Technology and Application Aspects of Applied Field Magnetoplasmadynamic Propulsion

Gerd Krülle*
DLR, German Aerospace Center, D-74239 Lampoldshausen, Germany
Monika Auweter-Kurtz†
University of Stuttgart, D-70550 Stuttgart, Germany
and
Akihiro Sasoh‡
Tohoku University, Sendai 980-77, Japan

Currently available or realizable applied field magnetoplasmadynamic (AF–MPD) thrusters operating in the power range 5–100 kW appear to be excellently suited for orbit change and stationkeeping (drag compensation) of large satellites because of their high specific impulse, sufficient thrust, and compact geometry. They were developed to considerable maturity almost 20 years ago, but have not yet been used in space because of the lack of missions, appropriate power, and qualification. There is evidence that these engines cannot be operated realistically in the laboratory, mainly because of the high vacuum needed to exclude unknown environmental interaction with the plume, even at very low vacua. A space experiment is needed to provide proof of I_{sp} and efficiency. The International Space Station now provides the opportunity to qualify the engine in space. This paper describes the application potential, performance characteristics, and technological status of the AF–MPD thruster, remaining application issues to be resolved, and a space experiment proposed to operate and investigate the engine under space-flight conditions.

Introduction

THIS paper presents the idea and status of the applied field magnetoplasmadynamic (AF–MPD) thruster, the most powerful electric propulsion device compatible with today's spacecraft (S/C) boundary conditions. It presents arguments in favor of both qualifying the engine in principle and testing it, for example, on the International Space Station (ISS), before a decision is made as to its commercial usability.

There is, however, a widespread difference of opinion as to the effectiveness and, therefore, competitiveness of the engine in comparison to other electric propulsion devices, and there is some question as to which operational conditions will lead to optimal performance. The reason for this is that, although the principal mechanisms of propellant acceleration are fairly well known, the significance of the individual mechanisms in the system is not satisfactorily understood, and may change with operating conditions. There are several groups in the world that have worked on AF–MPDs, and their results and conclusions differ because of discrepancies in optimization hypotheses and the absence of a relevant design and operating standard. This paper takes note of this fact.

Electric propulsion (EP) in general, after more than 30 years of development, has reached a level of maturity where satellite builders are starting to make use of the high specific impulse

and fuel-saving possibilities to increase their payload margins or to improve their mission potentials. The first types of EP applied on operational satellites were resistojets [electrothermal hydrogen thrusters (EHTs), which are not plasma thrusters but use classical electric resistance as a heat source], then pulsed plasma microthrusters, Hall ion [stationary plasma thruster (SPT)] thrusters introduced by the former USSR, and arcjets, which have potential matchability in terms of fuel with auxiliary chemical propulsion. SPTs and ion thrusters are now foreseen for application on western commercial satellites for the first time.[1] A recent study of EP applications on operational and experimental satellites is given in Ref. 2.

Consequently, today, with increasing power levels available in space, the (axisymmetric) plasma thruster with added electromagnetic acceleration (AF–MPD thruster) can for the first time be considered for application, owing to its quite high thrust and remarkable specific impulse (as implied by thrust over propellant mass). Operable laboratory and prototype devices of this type do exist and have been investigated for more than 20 years, particularly in the U.S.[3–24] (Ref. 16 is a summary of previous results), Germany[25–32] (Ref. 32 is a summary of results achieved in Germany), the former USSR,[33,34] and Japan,[35–41] where theory, phenomenology, and technology have been intensively (but not conclusively) treated. There have been two main periods of activity: one in the 1960s and early 1970s, and another minor one in recent years as a result of modified boundary conditions. In addition to design and optimization problems, which still have to be studied in detail, one important open question is the interaction of AF–MPD thrusters with the environment, because electromagnetic forces act far outside of the hardware geometry (Fig. 1). The lower the backpressure, the farther out the forces act. This is relevant in laboratory tanks which, because of limited geometry and effective pumping capacity, do not provide a realistic simulation of a space environment, even with condensable propellants. Background pressure degrades thrust by interfering with the acceleration mechanism, and the background gas is entrained in the discharge to be accelerated with the propel-
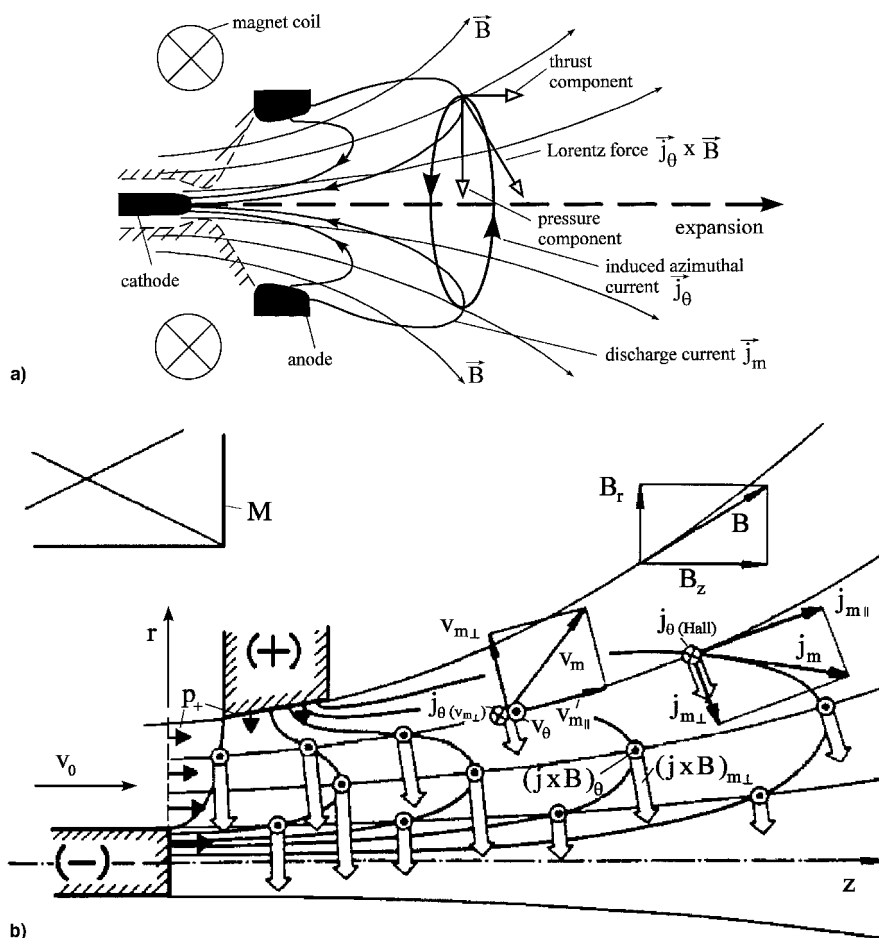
Fig. 1 a) Schematic of an MPD thruster with applied magnetic field showing current and force components, and b) distribution of currents and *j* × *B* forces in the jet.

lant.[16,32] As a consequence, in laboratory tests a certain (non-quantifiable) impact of the ambience on thrust is generally obtained, together with a considerable impact on I_{sp}, defined as the ratio of thrust over fuel mass fed through the engine. This makes laboratory data on engine performance extremely doubtful.

Moreover, contamination problems (material and electromagnetic) have to be seriously considered.

In the following, after a short discussion of AF–MPD application potential, the nominal performance characteristics of AF–MPDs, as well as their current development status, critical areas, and unresolved problems (as seen by the authors) are described. Finally, a space experiment capable of giving the required answers is presented.

AF–MPD Thruster Application Options

The installation of medium-power AF–MPD thrusters on S/C depends on the availability of sufficient power. However, future generations of satellites, like the heavy communication satellites, are planned to be provided with a source of 10 kW or more (the present preference for a large number of smaller communication satellites will not drastically change this scenario), so that power for the propulsion system, in periods when this power is not needed for the payload, is available. This opens new application fields.

Spiraling-up missions for geosynchronous Earth orbit (GEO) satellites: Spiraling-up of S/C to their destination orbit leads to large fuel savings compared with conventional positioning, which allows considerable expansion of the payload at a given overall S/C mass. These missions, however, have up to now been excluded from consideration because of the

long transfer times connected with EP. With higher power, or rather thrust, these transfer times will be reduced to an acceptable level. New studies[42] show these advantages even with the thrusters with relatively low I_{sp}.

North–south-stationkeeping: For big GEO platforms the AF–MPD is better suited than other EP thrusters such as ion engines or Hall ion thrusters (SPT). This is because of the relatively simple construction and the high-thrust densities or, in the case of arcjet thrusters, because of higher I_{sp}.

Drag compensation: For large flying space structures with sufficient power installations like space stations, AF–MPDs are ideal for drag compensation, and would substantially reduce the fuel consumption and, hence, the weight, needed to reboost.

Primary propulsion for deep space missions: And finally, the forthcoming high-power interplanetary missions, like a manned Mars mission, which are inconceivable without the assistance of high I_{sp} and high-thrust propulsion, are to be considered. Here again the AF–MPD is a well-suited candidate.

Table 1 summarizes in a simplified manner the advantages and disadvantages of the different types of EP (plasma propulsion only). For high-power missions, requiring high-velocity increments, MPD thrusters with applied magnetic field seem to be a good choice. They possess high-thrust density, good scalability to high-power levels, and a relatively simple design.

The temporary disadvantage of poor qualification and a moderate development level will be solved, based on the vast theoretical and experimental experience already accumulated in all areas of AF–MPD technology, by the time high-power installations on S/C are available.

Table 1 Electric propulsion thruster principles[a]

Thruster type	Propellant	Characteristics
Electrostatic: ion	Xenon (mercury)	High I_{sp} (20–80 km/s), high efficiency; complicated design, low-power levels <5 kW, difficult to scale up; low-thrust density; needs neutralizer
Hall ion (stationary plasma thruster, SPT)	Xenon (krypton, argon)	Medium I_{sp} (20–30 km/s); simple design Medium power levels, difficult to scale up above 5–10 kW Medium thrust density; needs neutralizer
Thermal arcjets	Hydrogen Hydrazine Ammonia	Restricted I_{sp}; 10–20 km/s for hydrogen Restricted I_{sp} 5–7 km/s for hydrazine, ammonia High-thrust density; no neutralizer needed
Self-field MPD	Noble gases (hydrogen)	Limited I_{sp}; (ca. 15 km/s); simple design Power levels >100 kW; low efficiency High-thrust density; no neutralizer needed
Applied field MPD	Noble gases Alkali metals Hydrogen N–H compounds	Medium I_{sp}; 10–40 km/s; relatively simple design Power level >5 kW, easy to scale up High-thrust density; no neutralizer needed Efficiency and lifetime to be demonstrated

[a]Steady-state operation mode.

Table 2 Operation conditions and calculated thrust components of some AF–MPD thrusters[39]

Thruster	B, T	$\dot{m}$, kg/s	I, A	F_{hall}, N	F_{swirl}, N	F_{self}, N
University of Tokyo[41]	0.10	9×10^{-7}	200	4.4×10^{-2}	1.4×10^{-2}	1×10^{-4}
Los Alamos[11]	0.19	2.5×10^{-5}	350	1.8×10^{-1}	6.9×10^{-1}	9×10^{-3}
University of Osaka[38]	0.075	2.75×10^{-3}	15,000	4.0	22.0	22.0

AF–MPD Performance Principles, Characteristics, and Technology

Theoretical Basis of Operation

Thrust Production

The design and acceleration principle of the AF–MPD thruster is demonstrated in Fig. 1. The thruster consists of a central cathode and a coaxial anode ring placed at the end of a nozzle-like (isolated) hardware extension. The configuration is surrounded by a magnetic coil or permanent magnet in such a way that the produced (applied) field forms another (magnetic) kind of nozzle diverging downstream.

The acceleration and energy production process is derived from the generalized Ohm's law (for a high degree of ionization) and the corresponding energy equation

$$j = \sigma E^* - \omega\tau(j \times B)/B \quad \text{where} \quad E^* = E + v \times B + (1/en)\nabla p_e \tag{1}$$

$$E \cdot j = j^2/\sigma + (j \times B)\cdot v - (1/en)(\nabla p_e)\cdot j \tag{2}$$

where j, σ, E, B, v, e, n, and p_e are the current density, scalar conductivity, electric field, magnetic induction $\cong$ magnetic field strength, mass velocity, electron charge, electron number density, and electron pressure, respectively ($\omega\tau$ see below).

The AF–MPD theory has been treated by a variety of authors.[3,11,22–24,30,31,39]

The following major mechanisms are currently known to be effective.

1) As the discharge current crosses the applied magnetic field, azimuthal currents are induced that yield axial and radial Lorentz ($j \times B$) forces, of which the axial component directly accelerates the plasma while the radial component confines the plasma and/or builds up a pressure hill, respectively. The magnitude of azimuthal currents (in relation to the discharge current) depends on the so-called Hall parameter, $\omega\tau$, where ω is the cyclotron frequency of electrons, being a linear function of the magnetic induction B, and τ is the collision time of electrons with heavy particles.

2) The discharge current crossing the magnetic field simultaneously results in an azimuthal force component that puts the plasma into rotation, which is considered an important source of energy addition.[11]

3) Moreover, energy is added by Joule heating.

4) The self-field (field produced by the discharge current itself) is normally negligible in the AF–MPD compared to the applied field.

All types of nondirected (rotational and thermal) energies can theoretically be converted into useful axial velocities in the mechanical and the magnetic nozzle. The latter again operates through azimuthal currents that compensate, in the ideal case, for centrifugal forces and overpressure.

Judging from single particle motions, the preceding effects can be explained by the fact that electrons cannot cross the magnetic field lines in the direction of a driving E field except through collisions. Instead, they have a drift velocity in the direction of $E \times B$ which, in our geometry, corresponds to the referenced azimuthal (electron) current.

In some studies, e.g., Ref. 39, dedicated thrust portions are attributed to the different acceleration mechanisms. All thrust production depending on azimuthal currents induced by the discharge current or electron pressure gradient is summarized under F_{hall}; thrust produced through conversion of swirl motion is called F_{swirl}; and self-magnetic thrust, if considered, is designated as F_{self}. The rest, namely thermal or aerodynamic portions not implicitly included as of yet, may be called F_{therm}; this summarizes the axial pressure components exerted on the mechanical nozzle. Formally, we can describe total thrust as

$$F_{tot} = F_{hall} + F_{self} + F_{swirl} + F_{therm} \tag{3}$$

Whether this simple algorithm is applicable depends, however, on the definition of thrust portions. Quantifying each portion as being generated by the total conversion of attributed energy added, e.g., $F_{swirl} = \int_V (j_r B_z u_\theta)\, dV)$ to useful (axial) velocity, the following dependency is obtained under simplifying assumptions[40,41]:

$$F = [(F_{hall} + F_{self})/2] + \{[(F_{hall} + F_{self})/2]^2 + F_{swirl}^2 + F_{therm}^2\}^{1/2} \tag{4}$$

Using this formula, one can estimate the order of magnitude of the maximum effect produced by each mechanism. Which mechanism prevails in thrust production depends on the selection of operating parameters.[14,41] In Table 2 a comparison is made between the electromagnetic thrust portions for different

cases of B, I, and $\dot{m}$ that proves this statement. There is evidence that Joule heating and swirl production are energetically most relevant in the AF–MPD, with a substantial portion of the conversion taking place in the magnetic nozzle.

The discharge current-equivalent mass flow $\dot{m}_{equ} = (m_i/e) \cdot I$ (single ionization), where m_i is the ion mass, is far from being arrived at in known experiments,[11,26,32,41] except in rare cases of light propellants. In the SPT, in contrast, currents are low and voltages are comparatively high, so that the $\dot{m}_{equ}$ requirement is met even with heavy propellants, whereas I_{sp} is still reasonably high at the expense of low-thrust density.

In the ideal case of energy gain and conversion under special consideration of rotational energy, voltage U (with a consequence to thrust F) should relate quadratically with the magnetic field strength B as a result of back electromotive force (EMF) produced by azimuthal velocities. This dependency is not found in the experimental results [Ref. 19, also see Eq. (5)], which is proof that those energy processes are connected with inherent losses. There are different hypotheses used to explain nonideal performance. One is that plasma viscosity plays an important role, hindering development of ideal azimuthal velocities by friction on outer (anode) walls, with velocity conversion in addition being limited by anomalous conductivity effects.[22] Plasma turbulence and anomalous diffusion have a substantial influence, which leads to very moderate effective $\omega\tau$[30,31] [see Eq. (6) later in the text].

Optimization Hypotheses

As a consequence, for AF–MPD acceleration to be effective, at least a strong magnetic field (B) of adequate shape, an optimal degree of ionization to ensure good coupling of mass to electromagnetic effects, and moderate particle density in the discharge region are required. Considering the acceleration mechanism, a lightweight propellant appears preferable for I_{sp} gain.

Applicable Propellants

In view of the need for a high degree of ionization at moderate losses, certain propellants suitable for AF–MPD engines can be considered. These are preferably easy to ionize monatomic elements: noble gases [He, Ne, Ar, (Xe)] and alkali metals[15] [Li[11,15,34] (Na, K)] (preferred materials are underscored), but H_2, N_2, and N–H combinations have also been used, e.g., Refs. 18, 19, 36, and 41, which suggests the capability of operating parallel to auxiliary chemical systems. The application of alkali metals is combined with considerable feed system problems and the danger of S/C contamination; the attainable tank pressure, however, is low in laboratory tests using condensable propellants that have a self-pumping effect.[11] Which propellant is optimal depends on system considerations; this question may still be regarded as open.

Phenomenology, Experimental Evidence

Thrust and discharge voltage generally tend to rise with the strength of the magnetic field and the discharge current[31]

$$F \text{ and } U_{tot} \sim I^{0.8\text{-}1} B_0^{0.5\text{-}1} \tag{5}$$

(see Fig. 2 for thrust). Propellant mass flow has a more complex influence, whereas thrust is hardly affected, i.e., only the aerodynamic part, voltage tends to go down as mass is increased, the effect depending on whether the mass is fed in the vicinity of the cathode or the anode (flow fractions $\dot{m}_K$, $\dot{m}_A$).[16,31,32] Thrust seems more dependent on $\dot{m}_K$, whereas voltage is more influenced by $\dot{m}_A$ as shown in Fig. 3. The role of $\dot{m}_A$ is not, or at least not primarily, to carry part of the current as an ion current, but to guarantee a certain charge carrier density in the vicinity of the anode, thus reducing anode losses and eventual strong deviation from discharge axisymmetry.[27] Figure 4 gives anode losses as a function of mass distribution.[29]

An important phenomenon that characterizes the AF–MPD propulsion is the fact that a substantial part of the accelera-
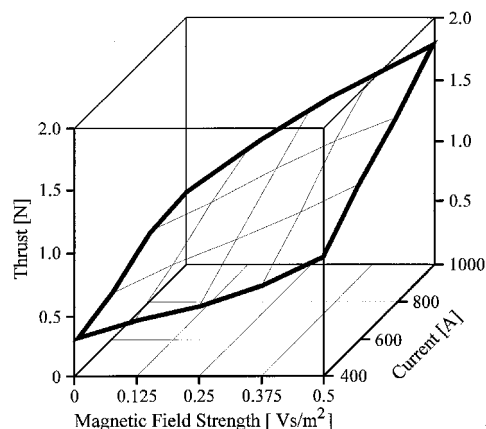

Fig. 2 Thrust as a function of discharge current and magnetic field strength (elevated power laboratory type ×9, 100 mg/s argon, p_a = 3.0 Pa).
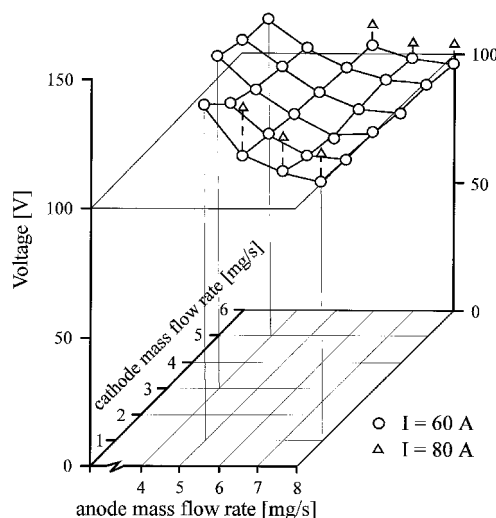

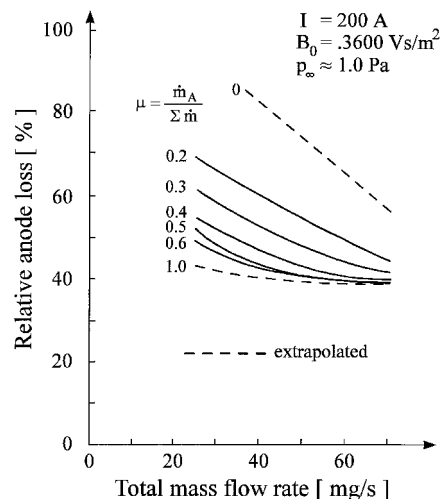**Fig. 3 Voltage as a function of anode and cathode mass fractions (×16, argon[32]).**

Fig. 4 Relative anode loss as a function of distribution of supplied mass,[29] thruster ×13.[32]

tion processes takes place outside of the hardware geometry. The discharge current, whose distribution is a function of $\omega\tau$ (=$\sigma B/en$), bulges out far downstream as B/n increases. This fact has been experimentally[11,12,16,28] and computationally[30,31,35] verified. Figure 5 shows measured current distributions at different magnetic field strengths. According to the preceding
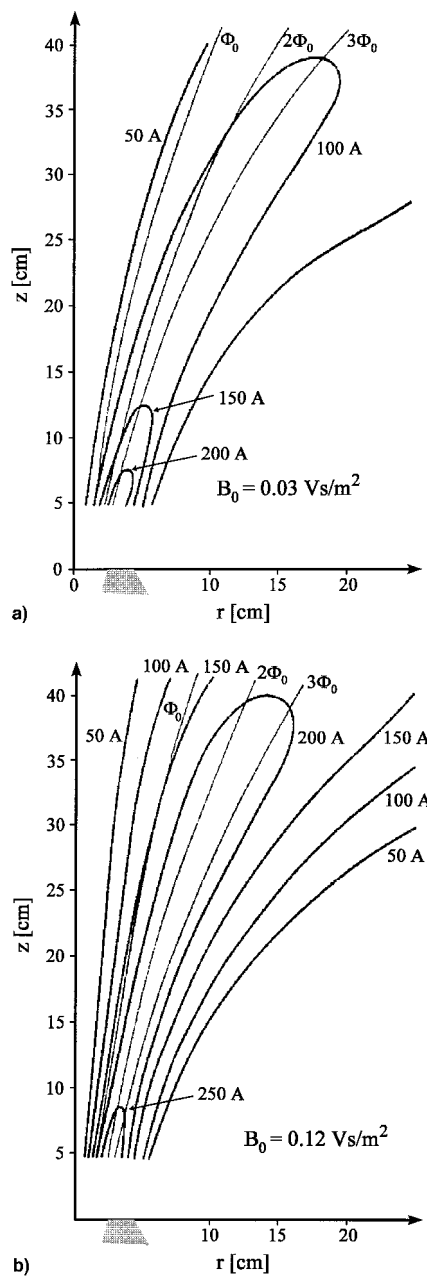
Fig. 5   Distributions of discharge current ($\times 9$, 500 A, 100 mg/s argon, $p_a = 2.0$ Pa)[28] at different magnetic field strengths. B_0 = a) 0.03 and b) 0.12 Vs/m².
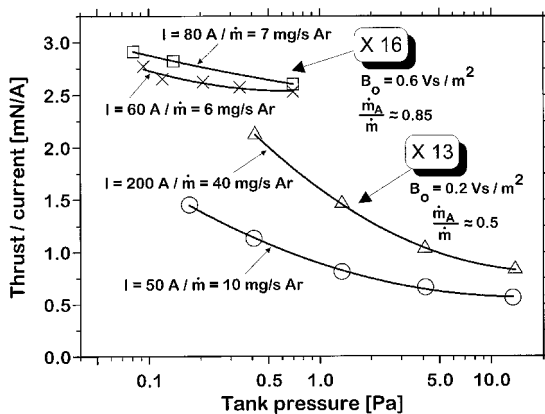

Fig. 6   Thrust per current as function of the tank pressure[30] for experimental thruster $\times 13$ and preflight model $\times 16$.[32]

dependency, the same applies when density decreases. This suggests the important influence of ambient pressure as demonstrated in Fig. 6, where specific thrust (F/I) is shown to increase as the tank pressure and, therefore, the gas density, is reduced.[12] At higher values of the critical parameter, saturation may occur. Still, environmental influence on the overall process (participation of ambient gas) is given, leading to an uncertainty of thrust and particularly I_{sp} determination. Even with condensable propellants this effect cannot be avoided reliably because of the wide extension of the plume and the normally moderate dimensions of the vacuum facility.

In contrast, measurements have also shown[10,28] that azimuthal currents are not as high as expected from $\omega\tau$, which are in the magnitude of 10–1000. Effectively,

$$j_\theta / j_{\text{disch},\perp B} \approx \omega\tau_{\text{effective}} \approx 3(-8) \qquad (6)$$

which is explained by the anomalous diffusion of electrons across the magnetic field.[6] This effect must be seriously taken into account in an assessment of AF–MPD capabilities. (This is, after all, also true for the SPT.) There are a number of consequences. For example, the magnetic nozzle is not ideally effective (cf. Ref. 22), so that the plume mass is not fully contained within boundaries given by the anode magnet lines, that is, applied field lines passing through the anode at its widest diameter.

AF–MPD thrust depends on plasma parameters and their distributions, which are a priori unknown, in contrast to electromagnetic thrust of the self-magnetic MPD thruster, which is a function of independent parameters. Consequently, computations are difficult, as a number of far-reaching assumptions have to be made.[22–24,30,31,35,39] On the other hand, as stated earlier, the discharge current crossing the applied magnetic field produces a torque that is (ideally) computable from independent parameters: $T = I_{\text{disch}}B_0 (r_{A\text{eff}}^2 - r_{C\text{eff}}^2)/2$. As mentioned previously, it can only be partially transferred into useful thrust but has to be taken into account as a disturbance in system considerations.

The typical average data for laboratory devices run at different locations are discharge current (I) = 100–200 (–1500) A; applied field (maximum) (B_0) = 0.05–0.6 Vs/m²; propellant mass flow ($\dot{m}$) = 5–50 mg/s Ar, Li (He, Kr, Xe, H₂, N₂, NH₃); ambient pressure (p_a) = 10–0.05 (–10^{-4}) Pa; discharge voltage (U) = (50–) 100–150 V; thrust (F) = 200–2000 mN; specific impulse (I_{sp}) = $F/\dot{m}_{\text{prop}}$ = 15–>35 km/s; and thrust efficiency (η_F) = $F/(2\dot{m}_{\text{prop}}U \cdot I)$ = <20–40%. Efficiencies are reported as tending to be low for gaseous propellants, in particular argon (which has been used for the majority of tests), in contrast to alkali propellants, especially lithium.[16,19] References 37 and 41, however, report excellent results using H₂ and He. The propellant's atomic mass seems to play an important role, and so does the magnetic field strength that must exceed a certain limit to effectively support performance.[30,41] As stated previously, it is the overall operating conditions that determine performance, and consequently, efficiency.

Data imply that a power range of 10–100 kW is possible, with operational voltage at an unproblematic level. The devices work in a stationary mode. There are, however, voltage oscillations (on the order of ± 5–10%) because of destabilizing effects typical for plasma accelerators. This noise has to be considered with respect to its potential system impact.

Hardware Design and Development Status

Laboratory Models

AF–MPD thruster models have been built and investigated mainly in the U.S., Germany, the former USSR, and Japan.[43]

One outstanding former U.S. hardware concept[11] is presented in Fig. 7. It shows a 25-kW hollow cathode lithium vapor AF–MPD with a free anode. The hollow cathode appears as a way to guarantee less consumptive cathode opera-
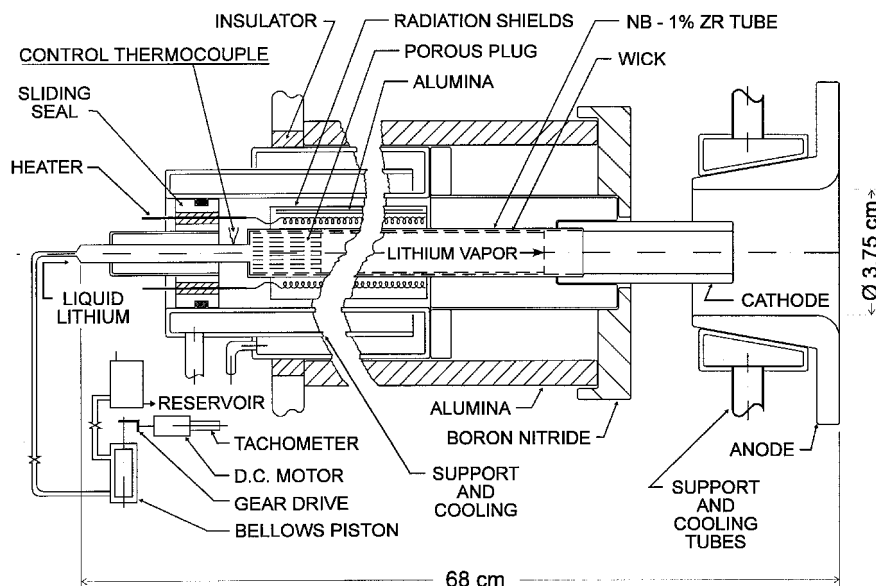
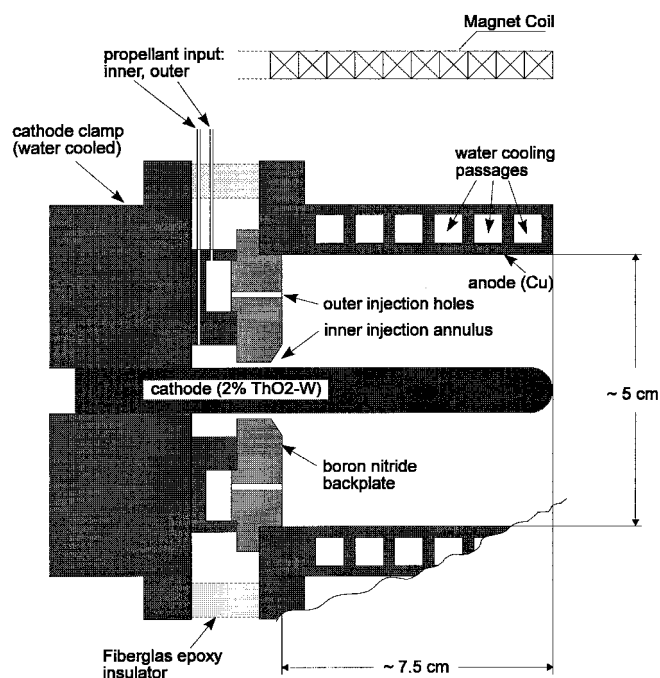Fig. 7   Schematic of hollow cathode arc and lithium feed system.[11]

Fig. 8   Applied field NASA Lewis Research Center's MPD thruster geometry used for tests[19] and comparative calculations.[22,23]

Fig. 9   Schematic of Russian high-power AF–MPD thruster operated with Li propellant.[34]

tion and has been doubled in various devices since then. The thruster operated at a current of 350 A, but at a comparatively low voltage on the order of 50 V, which may be characteristic for alkali propellants.

A classic example of thruster geometry for gaseous propellants (H_2, Ar) is the NASA LeRC thruster model shown in Fig. 8. It was used for tests[19] and for comparative simulations,[22,23] some results of which have been discussed under theoretical considerations earlier in the text. The geometry is used for benchmarking and for studying and verifying the principles of AF–MPD performance. The applied magnetic field is comparatively low (0.03–0.09 T). Efficiencies obtained under these conditions are moderate ($\leq 20\%$).

A more recent example of laboratory hardware representing the result of a joint Russian–U.S. effort to demonstrate high-power AF–MPD capacity[34] is shown in Fig. 9. In this case,
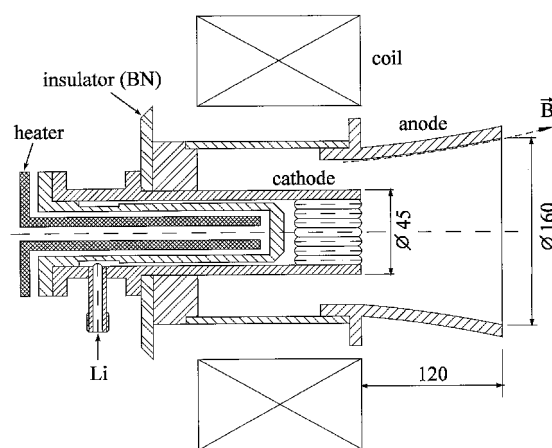
again, lithium was used as a fuel. It was liquefied, evaporated, and fed through the cathode provided with capillary holes. The solenoid was for use only in the laboratory. The operational parameters were discharge current 1000–1500 A, mass flow 50–60 mg/s, magnetic induction 0.05–0.1 T. Under optimal circumstances, an I_{sp} of 35 km/s at an efficiency of 35% is anticipated.

The following two examples represent Japanese activities. A previous concept,[36,37] shown in Fig. 10, was provided with a permanent magnet to study the influence of complex (non-classical) field shapes on the current distribution and the thrust-producing mechanisms. The concept shown in Fig. 11 (Ref. 41) is a classical hardware nozzle type AF–MPD running at approximately 10 kW. It is equipped with a flexible coil configuration permitting variation and optimization of the (slender) magnetic field shape. The device was operated safely with H_2, He, N_2, and Ar at a discharge current of 200 A. Thrust efficiencies of more than 20% were achieved. Table 2 compares thrust portions, as used in Eq. (3), of this thruster, the former U.S. lithium type, and a high current thruster described in Ref. 38.

Figure 12 shows, as another example, one of the most advanced thrusters of the medium (10–20 kW) power class built by DLR (formerly DFVLR) in Stuttgart.[32] In this preflight type called X16, the propellant (a noble gas—Ar, Kr, or Xe) is fed
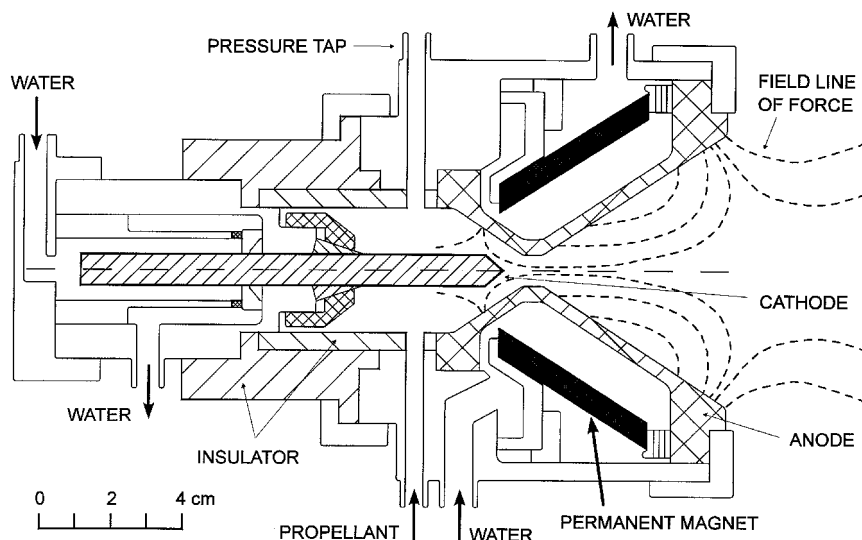
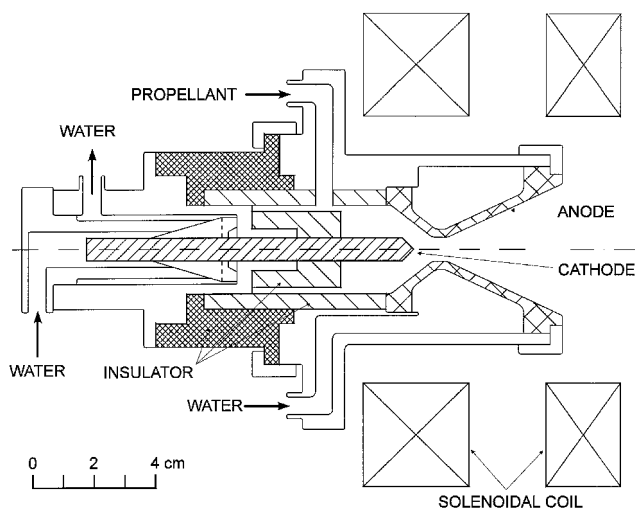Fig. 10 Steady-state AF–MPD thruster with permanent magnet.[37]

Fig. 11 Ten-kW AF–MPD thruster with two solenoidal coils.[41]

through the hollow cathode ($\dot{m}_K$) and through a circular slit along the anode ($\dot{m}_A$), which in this case consists of a radiation-cooled cylindrical tungsten body thermally isolated against the surrounding coil. The solenoid used in these experiments consisted of a nonflight type water-cooled copper tube winding operated at high currents; magnet power is not included in the data given next. The use of the secondary anode gas was to prevent serious destabilization through anode starvation as explained earlier, i.e., lack of current conducting matter at the anode surface as a consequence of the radial pressure gradient. The device reached a thrust of 250 mN (measured with an estimated accuracy of ±5%) at a mass flow of 7 mg/s (±5%) of argon, which, neglecting the probable influence of environmental gas, yields an $F/\dot{m}$ of 36 km/s (±10%) and a thrust efficiency of nearly 40% with approximately 12-kW electric power input. The other operational parameters at this point were discharge current 80 A, voltage 145 V, maximum magnetic induction 0.6 T, and ambient pressure 0.05 Pa. Figures 13a, 13b, and 14 show the operable thruster model (solenoid omitted), the thruster electrode space, and the thruster in action in the test chamber, respectively. The device has accumulated over 100 h of (cycle) operation without functional degradation.

Even if the functioning and optimization of the AF–MPD have not yet been completely clarified, the preflight model hardware has already been developed to a considerably high degree.

Components

Critical components are clearly the electrodes, whose lifetime has been the subject of numerous recent investigations.[20,21,23,33] A hollow cathode seems preferable to a solid one. As to the anode, it appears advantageous to keep it at a high temperature (radiation-cooled) to alleviate anode current transfer and reduce energy losses and material consumption. In any case, experiments have shown that lifetimes of hundreds of hours are readily achievable.

The electrodes must be perfectly isolated from each other so that the discharge current is safely prevented from crossing the magnetic field through solid material.

It appears that one of the principal hardware problems in AF–MPD design is the magnet. With regard to overall efficiency, it is necessary to consider the use of a permanent magnet where, however, the maximum field strength is limited (possibly <0.2 T). Some solutions have been offered in this area.[7,14,37] For space qualification, a dedicated engineering effort is needed for a conclusive answer.

Open Technological Areas

For space applications, the following areas need particular consideration.

1) Discharge (onset) control in combination with choice of materials and appropriate thermal design to minimize electrode erosion (as in all high-power plasma devices).

2) A strong enough magnet in combination with an optimum shape of the magnetic field and nozzle.

3) High-power electronics capable of controlling instabilities and providing safe ignition (under probable presence of the magnetic field).

4) A reliable fuel feed system (particularly in the case of nongaseous propellants).

Aspects of Space Applications— The MATEX Space Experiment

Environmental and Spacecraft Interactions

An attempt has been made to show that considerable interactions exist between the AF–MPD thruster and its environment.

1) On the one hand, the ambient pressure or gas density has a decisive impact on thruster performance.

2) On the other hand, there is the danger of contamination of the AF–MPD environment—the carrying S/C—by thruster material (propellant or eroded material).

The following questions result from this context with regard to space performance.
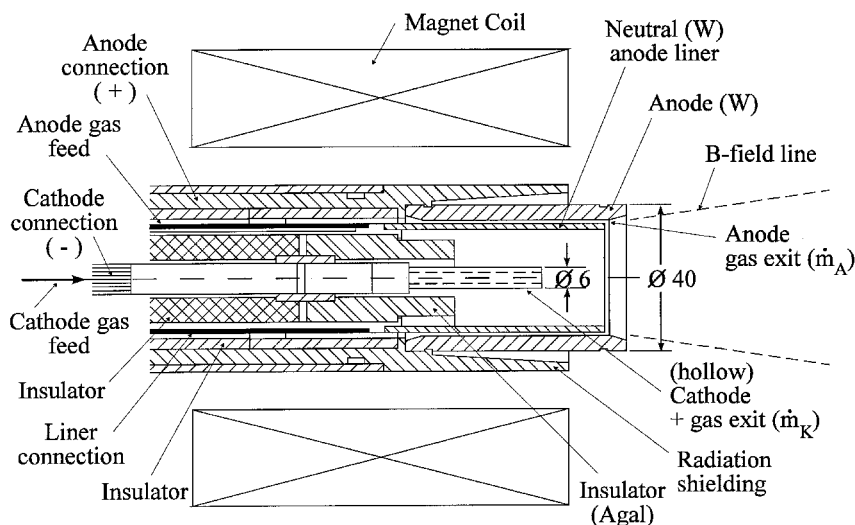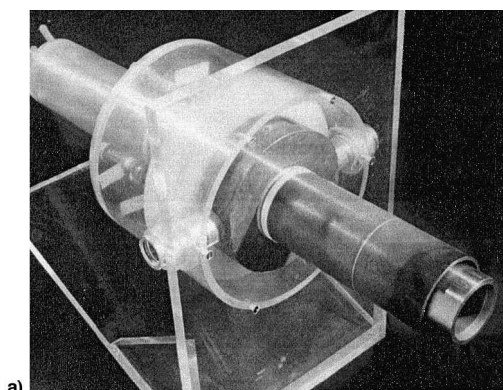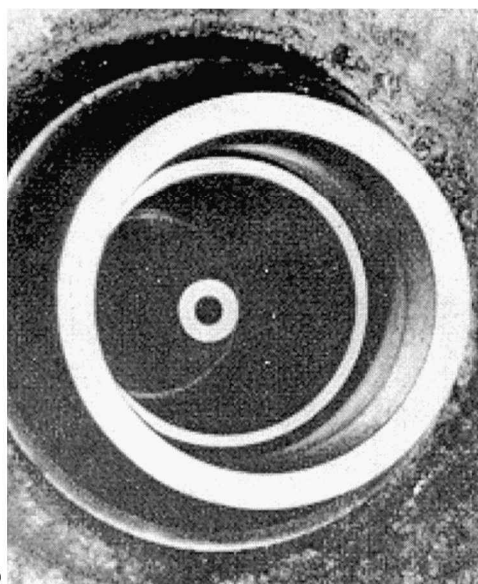
Fig. 12   Twelve-kW radiation-cooled MPD thruster ×16.[32]

Fig. 13   a) Radiation-cooled thruster ×16 displayed in holder, magnet coil omitted, and b) view of ×16 electrode space.
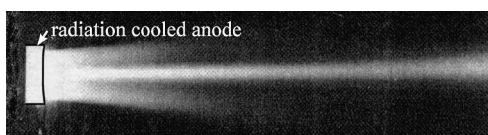

Fig. 14   Radiation-cooled MPD thruster in operation.[32]

1) How long will thrust increase with ambient evacuation? Will it reach a saturation level? Will destabilization occur when the ambient pressure goes lower and lower? Eventually, what will the I_{sp} and efficiency in space turn out to be?

2) At very low pressures, how will the thruster plume appear under the influence of the magnetic field? How far will charged particles follow the field lines (a problem addressed, e.g., 30 years ago in Ref. 9)? Will, in the extreme case, some of them turn back to the thruster and/or S/C, thereby affecting the balance of thrust and the hardware?

To begin with, an effort can and must be made to answer these questions through advanced experiments as well as by theoretical treatment [computational fluid dynamics (CFD+)]. This computational treatment is, however, different from normal CFD. It must include a comparatively large spatial area outside of the engine because of the far-reaching interaction of the aerodynamic field with electromagnetic effects that prevail and modify the aerodynamics. Computer codes exist that can be adapted to this task.[22,44,45]

The final validation, however, must be provided by operation in space. This is why a space experiment is urgently needed; it is proposed as follows.

Magnetoplasmadynamic Thruster Experiment

Experimental Concept

A test of an applied field MPD thruster in space will demonstrate the ultimate limits of the acceleration mechanism and will help resolve doubts about the environmental effects of the thruster exhaust interacting with the magnetic field far away from the thruster. Eventually, it will reliably verify AF–MPD's potential in I_{sp} and efficiency.

To solve these questions, an experimental platform attached to the ISS, the magnetoplasmadynamic thruster experiment (MATEX) is proposed. The thruster to be tested will be an improved model designed on the basis of model X16 (Fig. 12), but provided with a permanent magnet or a combination of solenoid and permanent magnet. During a period of three years, the hope is to prequalify this engine for operations in space, such that reliable and representative answers can be given to critical questions. Because the power level of the experiment exceeds the possibilities of the experimental interfaces of the ISS, a dedicated battery package will provide the thruster power, with MATEX requiring only the power for recharging the battery and some additional power for the maintenance of experiments, like a power conditioning unit (PCU) and the diagnostic package. Cyclic operations of 15 min each are foreseen, with a total number of up to 250, with a noble gas propellant and a nominal mass flow of 5–10 mg/s. The

propellant will be carried in gas bottles as part of the experiment. Eventually, additional power will be requested for the magnet coil if an electromagnet is used instead of or parallel to a permanent magnet. This will be decided after appropriate ground tests.

The following masses, size, and volume are estimated according to previous space flights of other thruster experiments, such as the ion thruster experiment RITA on EURECA,[46] and ESEX, a high-power arcjet thruster experiment on a U.S. Air Force technology satellite.[47]

Preliminary Mass Breakdown

Battery package = 120, PCU = 50, propellant gas (noble gas) = 3, pressure tank with propellant feed system = 15, diagnostic package = 25, thruster including magnet = 10, and experiment control unit = 3; this totals 231 kg.

MATEX will be mounted on a pallet as attached payload; the pallet size is estimated at 1×1.5 m^2 with probe arms jutting out 1 m, the height of the packed platform being about 0.5 m (diagnostic arms not unfolded).

Diagnostic Package

The thruster experiment will be accompanied by a variety of diagnostics instrumentation. Currently, the following are being considered.

1) The thrust is measured by a torsion thrust balance. The deflection of this balance is a measure of the thrust. It will be calibrated in space by supplying a known magnetic force to the balance.

2) The propellant mass flow will be determined by mass flow controllers.

3) The plasma plume of the discharge will be investigated for luminescence with a video camera, for electron temperatures and densities with electrostatic probes (mounted on probe arms), and the total radiation of the plume will be measured with a radiometer.

4) The thermal mapping and control of the thruster itself will be performed by a charge coupled device (CCD) camera and thermocouples.

5) The electromagnetic noise of the thruster electromagnetic interference (EMI) will be checked with EMI antennas.

6) The magnetic field in the plume and, hence, the current distribution will be monitored by magnetic field probes mounted on probe arms.

7) Possible solar cell contamination will be checked by thermoelectric quartz crystal monitor (TQCM) probes (at different positions) and sample solar cells.

Interfaces with the ISS

Power. The thruster power is supplied by a battery package; for the recharging operation, there are no constraints in duration. The necessary additional power during the experiment (for PCU, diagnostic package, etc.) is estimated at ~100 W; the power requirement for the magnetic coil has yet to be defined.

Data. During the operation of MATEX, the operational parameters plus diagnostic data are registered autonomously by the thruster-experiment-control-unit; data have to be transmitted to the ground station from time to time. During dormant times the status of batteries, propellant tank pressures, and the status of valves and control switches have to be monitored. The experiment will be started from the ISS control center at times compatible with ISS operation.

Assistance needed by the ISS crew. During the experiment, no tools are required and the on-orbit time is not restricted, and so the experiment can be included in any experimental slot. The gas used is part of the experiment. No crew assistance is required after the start of the experiment, but after experiment termination, retrieval of the MATEX platform is desired for refurbishment and checking.

Conclusions

An attempt has been made here to show that electromagnetic thrusters with applied field (AF–MPD thrusters), as an EP concept for the next generation, have a satisfactory predevelopment status and can be considered for preparation for application. With regard to their operating parameters, they appear fully suitable for future auxiliary and primary missions of large spacecraft. Development for flight readiness and prequalification can be achieved through advanced laboratory tests and computational verification, anticipating some of the most relevant features of space performance; space qualification, however, can be attained only by a space experiment. Correspondingly, the proposal has been made to fly the experimental platform MATEX on the ISS.

It is the authors' opinion that AF–MPD final development, in view of the worldwide experience in plasma techniques and technology, can be achieved in due time in a joint international effort. At the start of this renewed development of alternative space propulsion, and trusting that anticipated advantages will be verified, it is hoped that future applications will be adequately supported by both the propulsion and spacecraft/space station communities.

Acknowledgments

References

[1]Randolph, T., and Burton, R., ''Electric Propulsion,'' *Aerospace America*, Dec. 1997, p. 49.

[2]Pollard, J. E., Marvin, D. C., Janson, S. W., Jackson, D. E., and Jenkin, A. B., ''Electric Propulsion Flight Experience and Technology Readiness,'' AIAA Paper 93-2221, July 1993.

[3]Jahn, R. G., *Physics of Electric Propulsion*, McGraw–Hill, New York, 1968.

[4]Powers, W. E., and Patrick, R. M., ''Magnetic Annular Arc,'' *Physics of Fluids*, Vol. 5, 1962, pp. 1196–1206.

[5]Ducati, A. C., Giannini, G. M., and Muehlberger, E., ''Experimental Results in High Specific Impulse Thermo-Ionic Acceleration,'' *AIAA Journal*, Vol. 2, No. 8, 1964, pp. 1452–1454.

[6]Janes, G. S., and Lowder, A. S., ''Anomalous Electron Diffusion and Ion Acceleration in a Low Density Plasma,'' *Physics of Fluids*, Vol. 9, No. 6, 1966, pp. 1115–1123.

[7]Johansen, A. E., Bowditch, D. N., and Burkhart, J. A., ''Experimental Performance of a Low-Power MPD Arc Thruster,'' AIAA Paper 67-50, Jan. 1967.

[8]Cann, G. L., Harder, R. L., and Nelson, S. T., ''Experimental Performance of the Alpha Thrustor,'' AIAA Paper 67-687, Sept. 1967.

[9]Harder, R. L., ''Electromagnetic Acceleration of Ions in Axially Symmetric Fields,'' AIAA Paper 69-111, Jan. 1969.

[10]Henry, R. P., and Scott, D. S., ''Maximum Hall-to-Electrode Current Ratio in a Coaxial Plasma Accelerator, '' AIAA Paper 69-280, March 1969.

[11]Fradkin, D. B., Blackstock, A. W., Roehling, D., Stratton, T., Williams, M., and Liewer, K., ''Experiments Using a 25-kW Hollow Cathode Lithium Vapor MPD Arcjet,'' *AIAA Journal*, Vol. 8, No. 5, 1970, pp. 886–894.

[12]Connolly, D. J., and Sovie, R. J., ''Effect on Background Pressure on Magnetoplasmadynamic Thruster Operation,'' *Journal of Spacecraft and Rockets*, Vol. 7, No. 3, 1970, pp. 255–258.

[13]Seikel, G. R., Connolly, D. J., Michels, C. J., Richley, E. A., Smith, J. M., and Sovie, R. J., ''Plasma Physics of Electric Rockets in Plasmas and Magnetic Fields in Propulsion and Power Research,'' NASA SP-226, 1969, pp. 1–64.

[14]Bishop, A. R., Connolly, D. J., and Seikel, G.R., ''Test of Permanent Magnet and Superconducting Magnet MPD Thrusters,'' AIAA Paper 71-696, Sept. 1971.

[15]Fradkin, D. B., and Roehling, D. J., ''Thrust Stand Performance Measurements of a Lithium Fueled Applied Field MPD Thruster,'' *Proceedings of the 13th Symposium on Engineering Aspects of Mag-*

netohydrodynamics, Stanford, CA, March 1973.

[16]Sovey, J. S., and Mantenieks, M. A., "Performance and Lifetime Assessment of Magnetoplasmadynamic Arc Thruster Technology," *Journal of Propulsion and Power*, Vol. 7, No. 1, 1991, pp. 71–83.

[17]Polk, J. E., and Pivirotto, T. J., "Alkali Metal Propellants for MPD Thrusters," AIAA Paper 91-3572, Sept. 1991.

[18]Polk, J. E., and Goodfellow, K. D., "Ammonia Arcjet Behavior in a Cyclic Endurance Test at 10 kW," International Astronautical Federation, Paper 92-0612, Oct. 1992.

[19]Myers, R. M., "Applied Field MPD Thruster Performance with Hydrogen and Argon Propellants," *Journal of Propulsion and Power*, Vol. 9, No. 5, 1993, pp. 781–784.

[20]Mantenieks, M. A., and Myers, R. M., "100 kW Class Applied Field Thruster Component Wear," *Proceedings of the 10th Symposium on Nuclear Power and Propulsion*, American Inst. of Physics, 1993, pp. 1317–1325.

[21]Polk, J. E., Kelly, A. J., Jahn, R. G., Kurtz, H., Auweter-Kurtz, M., and Schrade, H. O., "Mechanism of Hot Cathode Erosion in MPD Thrusters," International Electric Propulsion Conf., IECP Paper 90-2673, July 1990.

[22]Mikellides, P. G., Turchi, P. J., and Roderick, N. F., "Theoretical Model for Applied Field MPD Thrusters," AIAA Paper 95-2676, July 1995.

[23]Turchi, P. J., "The Effect of Magnetic Nozzle Configurations on Plasma Thrusters," NASA CR 202341, May 1997.

[24]Thomas, H., "A Numerical Simulation of Axisymmetric, Steady Plasma Flow with Self-Induced and Applied Magnetic Fields," Ph.D. Dissertation, Univ. of Tennessee, Tullahoma, TN, Aug. 1991.

[25]Peters, T., "Erzeugung von Plasmastrahlen hoher Temperaturen und Geschwindigkeiten," (Generation of Plasma Jets of High Temperatures and Velocities), *Acta Astronautica*, Vol. 7, No. 2, 1961, pp. 150–170.

[26]Kruelle, G., "Characteristics and Local Analysis of MPD Thruster Operation," AIAA Paper 67-672, Sept. 1967.

[27]Maisenhälder, F., Ungerer, E., and Kruelle, G., "Some Experiments on the 'Spoke' Phenomenon in MPD Operation," *AIAA Journal*, Vol. 7, No. 2, 1969, pp. 348–350.

[28]Schock, W., "Diagnostics and Interpretation of the Electric Current Distribution in an MPD Thruster," AIAA Paper 72-498, April 1972.

[29]Schall, W., "Influence of Magnetic Fields on Anode Losses in MPD Arcs," AIAA Paper 72-502, April 1972.

[30]Kruelle, G., "Theoretical Treatment of Current, Mass Flow, and Related Distributions in MPD Plumes," AIAA Paper 72-501, April 1972.

[31]Kruelle, G., "On the Dynamics of the Axisymmetric Magnetoplasmadynamic Accelerator (MPD Thruster) with Applied Magnetic Field," Ph.D. Dissertation, Technical Univ. of Munich, DLR FB-74-56, DFVLR, Munich, Germany, May 1974.

[32]Kruelle, G., and Zeyfang, E., "Preliminary Conclusions of Continuous Applied Field Electromagnetic Thruster Research at DFVLR,"

AIAA Paper 75-417, March 1975.

[33]Semenikhin, S. A., and Tikhonov, V. B., "The Influence of Cathode Design on the Performance and Characteristics of MPD Thrusters with Applied Magnetic Field," *Proceedings of the 3rd Russian-German Conference on Electric Propulsion*, Univ. of Stuttgart, Stuttgart, Germany, 1994, pp. 27–37.

[34]Tikhonov, V., Semenikhin, S., Brophy, J. R., and Polk, J. E., "The Experimental Performances of the 100 kW Li MPD Thruster with External Magnetic Field," International Electric Propulsion Conf., IEPC Paper 95-105, Sept. 1995.

[35]Tanaka, M., and Kimura, I., "Current Distribution and Plasma Acceleration in MPD Arcjets with Applied Magnetic Fields," *Journal of Propulsion and Power*, Vol. 4, No. 5, 1988, pp. 428–436.

[36]Sasoh, A., Solem, A., and Arakawa, Y., "10 kW Steady-State MPD Thruster," *Journal of the Faculty of Engineering*, Univ. of Tokyo (B), Vol. XXXIX, No. 3, 1988, pp. 275–296.

[37]Arakawa, Y., and Sasoh, A., "Steady State Permanent Magnet Magnetoplasmadynamic Thruster," *Journal of Propulsion and Power*, Vol. 5, No. 3, 1989, pp. 301–304.

[38]Tahara, H., Kagaya, Y., and Yoshikawa, T. "Quasisteady Magnetoplasmadynamic Thruster with Applied Magnetic Fields for Near-Earth Missions," *Journal of Propulsion and Power*, Vol. 5, No, 6, 1989, pp. 713–717.

[39]Sasoh, A., and Arakawa, Y., "Thrust Formula for an Applied-Field MPD Thruster Derived from Energy Conservation Equation," International Electric Propulsion Conf., IEPC Paper 91-062, Sept. 1991.

[40]Sasoh, A. "Simple Formulation of Magnetoplasmadynamic Acceleration," *Physics of Plasma*, Vol. 1, 1994, pp. 464–469.

[41]Arakawa, Y., and Sasoh, A., "Electromagnetic Effects in an Applied Field Magnetoplasmadynamic Thruster," *Journal of Propulsion and Power*, Vol. 8, No. 1, 1992, pp. 98–102.

[42]Schwer, A., "Bestimmung der Einsatzbedingungen und Verwendungsvorteile elektrothermischer Raketenantriebe für Transfermissionen von Satelliten," Ph.D. Dissertation, Univ. of Stuttgart, Stuttgart, Germany, 1997.

[43]Auweter-Kurtz, M., *Lichtbogenantriebe für Weltraumaufgaben*, Teubner, Stuttgart, Germany, 1992.

[44]Boie, C., Auweter-Kurtz, M., Kaeppeler, H. J., and Sleziona, P. C., "Numerical Investigation of MPD Thrusters with Unstructured Mesh Methods," International Electric Propulsion Conf., IEPC Paper 95-168, Sept. 1995.

[45]Kruelle, G., Gavriliouk, V., Schley, C. A., and Sobatchkin, A., "Numerical Simulation Technology of Aerodynamic Processes and its Application in Rocket Engine Problems," International Astronautical Federation, Paper 94-S2414, Oct. 1994.

[46]Bassner, H., Berg, H-P., Bartoli, C., and Trippi, A., "Status of the RITA-Experiment on EURECA," Deutsche Gesellschaft für Luft- und Raumfahrt, Bericht 88-02, Bonn, Germany, 1988, pp. 180–185.

[47]Kriebel, M. M., and Stevens, N. J., "30 kW Class Arcjet Advanced Technology Transition Demonstration (ATTD) Flight Experiment Diagnostic Package," AIAA Paper 92-3561, July 1992.