DESIGN OF AN MPD ARCJET FOR OPERATION AT GIGAWATT POWER LEVELS

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ABSTRACT

For advanced space exploration missions involving human passengers, it is necessary to seek ways to minimize the duration of the voyage, and maximize the opportunity for completing return trajectories to earth. It is useful, therefore, to consider electric propulsion at much higher powers than are usually contemplated, i.e., 100 - 1000 Mw to 0.1 - 10 Mw. While such high power levels are not presently available in space, very similar values have already been demonstrated two decades ago in prototypes for space propulsion systems namely, nuclear rocket engines (1000 - 5000 Mw(th)). The possibility of using similar technology for electric propulsion purposes is a challenging task in terms of heat rejection and power conversion at very high power levels. Perhaps equally challenging, however, is the development of electric thrusters capable of operating with gigawatt powers. The present paper discusses design considerations for MPD arcjets at very high power levels. It is suggested that benefits accrue to very high power operation because of increased mass flow rates and particle densities at desired values of specific impulse. These benefits include the feasibility of mass addition at electrode surfaces (particularly the anode), and reduction of tendencies to develop microturbulence within the plasma discharge. It is also suggested that improved performance would be achieved by reversing the electrode polarity, with respect to the tradition of central cathodes. Research tasks and the development of a gigawatt, quasi-steady pulseline are also described.

I. INTRODUCTION

Over the last few years, interest has rekindled in human exploration of space. While there has been a very successful program of robotic flights to almost all the planets in the solar system, the intense drama represented by human flight into space is recognized at the highest levels of government as a principal driving force in a high technology-based civilization. Indeed, apart from significant product improvements associated with micro-gravity, or Earth-system analysis using space-based sensors, the main economic return of space flight may derive from enhanced interest in science and mathematics by young people attracted to the human adventure of space exploration. (It is this human adventure that can encourage students to accept the challenges of education in science and mathematics, and thereby provide a work force that is technologically-astute, even if not directly engaged in space exploration.)

To foster a human presence on voyages to other planets is a daunting problem primarily in terms of a single parameter: trip time. Although there has been considerable information accumulated about human performance during long missions in the vicinity of the earth (within a light-second, or so), no data exists on humans separated in a substantial way from their home planet. (Multi-year ocean voyages, while certainly perilous, generally involved periodic landfalls, and interactions with non-nautical objects, such as trees and natives. Associated with the ability to achieve such visitation was the local control of the ship’s course and maneuvering, which may be another important psychological factor.)

Presently, the baseline missions discussed in the US Space Exploration Initiative, whether powered by chemical, nuclear-thermal or nuclear-electric thrusters, share a common range of (round) trip times, all exceeding a year. In the case of chemical and solid-core nuclear rockets, the trip time is energy-based, with the transit time determined by exhaust speeds, which in turn are limited by bond-strengths of matter (either for chemical energy release or structural integrity at high temperatures). For electric rockets, the trajectory is (specific) power-limited, involving thrust-to-weight ratios that are much less than unity (-10^3). Missions to Mars with any of the baseline thrusters suffer further from the limited opportunities to intercept the earth along minimum energy trajectories returning from reasonable initial visits (< months).

Advanced concepts have, of course, been proposed involving power sources not yet demonstrated (or perhaps even properly conceived). These concepts include gas- or plasma-core nuclear fission rockets at specific impulse values - 5000 sec, and various controlled nuclear energy schemes, ranging from micro-explosion versions of Project Orion (i.e., repetitive nuclear bombs) to electro-magnetically-confined plasmas and anti-matter beams. If the technological promises of such concepts are accepted, then mission performance is greatly enhanced, especially in regard to trip times. (For example, a voyage to Mars would take about a month.) There are two main ingredients in this promised enhancement: high specific impulse, and high thrust-to-weight (relative to conventional nuclear-electric propulsion systems, at least). The latter quantity derives from the high specific power of the assumed energy source (and generally benefits from an open thermodynamic cycle). The successful development of any of these advanced concepts would be quite remarkable, particularly in the case of controlled fusion, for which the terrestrial impact could far exceed the (initial) importance of enhanced space travel. At the moment, however, the most likely program for achieving very high powers in space appears to be the redevelopment of nuclear-thermal rocket (NERVA) technology.
Before cancellation in the early 1970s, the NERVA program had succeeded in demonstrating operation of compact nuclear reactors driving hydrogen gas in the open thermodynamic process of a high thrust rocket engine. Reactor power levels up to 5000 Mw(th) were achieved, and performance as a rocket engine included powers of 1000 Mw, continuous operation in excess of ten hours, and over twenty start/stop repetitions. Successful deployment of NERVA-derived technology in space, initially in the form of nuclear-thermal rockets, could give impetus to the development of high temperature gas-cooled reactors for closed-cycle, burst-mode power generation. The opportunity would then exist for very high power electric propulsion, especially if MHD power conversion (as in present rocket-driven, burst-mode generators) is used to match the power input requirements of the thruster (thereby avoiding many of the limitations of conventional electronic power conditioning). The possibility of achieving high specific impulse, using established electric propulsion mechanisms, at relatively high thrust-to-weight ratios (>10²) depends on overcoming several system challenges, including trade-offs between closed-cycle system weights (e.g., recuperator vs heat radiator), and mission design factors (e.g., number of multiple perigee burns vs start/stop reliability). Among these challenges, there is, of course, the design of an electric thruster capable of operation at gigawatt power levels.

II. BASIC DESIGN OF A GIGAMATT NPD ARCJET

It is reasonable to claim on the basis of simplicity of construction and operation that the MHD arcjet represents a proper a priori candidate for an electric thruster operating at gigawatt power levels. In this section, sample values for such a thruster are provided, in advance of more detailed discussions. For initial consideration, suppose that an input power of 10⁹ watts is converted with a total efficiency of 50% into jet power, Pj, with an exhaust speed of 50 km/sec. The thrust is then F = 20 kN, and the operating current J (for a simple self-field MHD arcjet) is given by:

\[ F = \frac{\mu J^2}{4\pi g} \]  

(1)

where g is a geometrical factor based on the ratio of current attachment radii at the coaxial electrode surfaces. For a radius ratio r₂/r₁ = 3.5, and a uniform current density distribution on the end of the central electrode, g = 2. The necessary current in the present example is then J = 320 kA. The associated voltage across the thruster at one gigawatt is \( V = 3.1 \) kV. Note that, if voltage drops needed for current conduction near the electrodes remain modest (< 100 V) as the total arcjet power is scaled to high values, then operation at very high powers offers immediate benefits in terms of electrode losses and heat transfer relative to total thrust power. Conditions near the electrodes will be primary factors in determining the absolute size of the thruster, but should not dominate performance to the same extent as in present lower power devices. Thruster efficiency will then depend largely on energy balances within the main discharge flow, and on the uniformity of the exit velocity field.

Additional differences in thruster performance derive from the higher flow density available at very high power. For the assumed conditions, the total mass flow rate is 0.4 kg/sec. This corresponds to an equivalent current for a fully-ionized hydrogen flow of \( J_{eq} = 40 \) MA, which is much higher than the discharge current; for a heavier candidate propellant, such as singly-ionized lithium, \( J_{eq} = 6 \) MA. This suggests that a small portion of the total mass flow can be used to improve discharge conditions near the electrodes, without significantly diminishing thruster performance. Also, if the channel dimensions for mass flow are reasonably in proportion with the dimensions for current flow, there should be sufficient density of charge carriers to mitigate problems due to microturbulence and anode starvation.

The ratio of equivalent current to total discharge current increases with total current, since the mass flow rate scales as \( J^2 \) for fixed exhaust speed, u:

\[ \frac{J_{eq}}{J} = \frac{\dot{m}}{J} \frac{Ze}{J} = \frac{\mu (Ze)}{m} \frac{J}{g} \]  

(2)

The jet power for a particular equivalent current ratio is then:

\[ P_j = 2\pi \frac{m^2}{\mu} \left( \frac{Ze}{J} \right)^2 \frac{J}{g} \]  

(3)

where \( m \) is the molecular mass, and \( Z \) is the ionic charge number. The interesting case of mass addition at the anode surface to provide an ion current equal to the discharge current requires an equivalent current ratio much larger than unity, since a very nonuniform exhaust flow would otherwise occur. (If the mass flow rate through the anode surface matches a uniform current density distribution, \( j \), with field \( B = jx \), where \( x \) is the original position of a portion of the mass flow relative to the downstream edge of the discharge, then the net magnetic pressure accelerating different portions of the flow would vary as \( B^2 - x^2 \).) Suppose, therefore, that the emission of mass through the anode is limited to 10% of the total mass flow, so the equivalent current ratio is at least 10. For \( u = 50 \) km/sec, and \( g = 2 \), the necessary jet power is then 3.2 Mw, for fully-ionized hydrogen, and 156 Mw for singly-ionized lithium. This power level is readily accessible for gigawatt operation, and may even be available for more near term systems using hydrogen as the main propellant.

The choice of propellant depends on many factors in the mission design, but, for MHD arcjets, favors low molecular weight in order to
achieve high specific impulse. This is related (in self-field arcjets, at least) to possible limitations on practical exhaust speed involving the ability of the flow to handle resistive dissipation, commensurate with electromagnetic acceleration. Briefly, the thickness of the current conduction regions of the flow will scale as the density distribution can be made more uniform, with acceleration dissipation commensurate with electromagnetic between electrodes is decreased in the region the ability of the flow to handle resistive Sanchez self-field arcjets, at least) to possible ment achieve high specific impulse. This is related (in does indeed permit potential performance improve-

vacuum facility cost using condensation techniques.

storability become critical); lithium also may that, to the extent that microturbulent scattering clear candidate to obtain an exhaust speed of (especially if issues such as tankage weight and storable becomes a clearer contender). Lithium also may offer advantages as an additive at electrodes, and in a program development sense, in terms of reduced vacuum facility cost using condensation techniques.

As a final comment on the basic design, it should be noted that the resistance estimate based on the inverse of the flow magnetic Reynolds number does indeed permit potential performance improvement by varying the thrust channel geometry. In particular, continuing the suggestion of Martinez-Sanchez, if the length of the conduction path between electrodes is decreased in the region between the channel entrance and exit, the current density distribution can be made more uniform, with a consequent reduction in resistive dissipation. Proper two-dimensional expansion of the magnetized plasma flow at the exit of the thruster can also spread the current distribution in order to reduce the current density, thereby lowering resistive electric fields, and ameliorating detrimental processes (particularly at electrodes) that scale as $j$ or $j^2$.

III. THRUSTER SIZE BASED ON PLASMA CURRENT DENSITIES

In the preceding section, the thruster geometry entered only through radius ratios or other shape factors. The actual size of the device is determined by comparing a total extensive quantity of operation (e.g., current) with an intensive quantity based on local physical processes needed for operation (e.g., current density). Within the MPD arcjet, there are three regions that provide current density concerns: anode, cathode, and the plasma discharge itself. The last region has recently received considerable attention by E. Choueiri, et al, in terms of the growth of microinstabilities within the MPD discharge. There are also other instability processes related to current density that are manifested by nonuniformities in physical space (e.g., spoking) that can result in loss of thruster performance.

Without pursuing here the details of the large number of candidate micro-instability processes available in a low density, high current plasma, it is useful to note that the general behavior involves a growth of local, fluctuating electromagnetic fields that scatter particles whose trajectories might otherwise have maintained an ordered and concentrated flow at speeds in excess of local thermal speeds. The result of this scattering is to broaden the flow (in phase space), thereby reducing its directed speed relative to thermal speeds (that may be increased by the scattering process itself). A characteristic result is that the effective resistivity of the plasma is increased, providing enhanced dissipation, but also reduced current density (at least in some regions of the discharge). This enhanced dissipation can result in greater heat transfer to thruster surfaces, increased frozen-flow loss, and other problems associated with the presence of populations of higher energy particles. It is interesting to note that, to the extent that microturbulent scattering can be expressed as an enhanced resistivity, the resistance estimate of equation (5) continues to be independent of the actual value of the resistivity. This presumes, of course, that the current conduction area based on enhanced resistivity is not larger than the available attachment area, a condition that may fail, for example, if the
magnetized plasma flow exits the thruster too abruptly.

The importance of current-driven microinstabilities in a self-field MPD arcjet may be estimated by comparing the electron drift speed, \( j/\eta c_{te} \), to an appropriate kinetic speed such as the ion thermal speed or the electron thermal speed based on the electron temperature, \( T_e \), using the mass flow rate to calculate the electron density, \( n_e \), and the inverse magnetic Reynolds number to scale the current conduction thickness, as before:

\[
\frac{j}{\eta c_{te}} = \frac{2\pi y}{\eta c_{le}} \left( \frac{m}{e} \right) u^3
\]  
(7)

where the mass flow rate is again based on the electromagnetic thrust divided by the exhaust speed, and the resistivity is given its classical value. The ratio of the channel area for mass flow to the mean circumsference of the current conduction path is \( y \). For the conditions assumed in Section II, and an electron temperature of \( 1 \text{ eV} \) (\( \eta = 5.2 \times 10^4 \text{ ohm}^{-1} \text{ cm}^{-1} \), \( c_{te} = 15.6 \text{ km/sec} \) for \( A = 1 \)), the necessary effective channel height to limit the drift speed to the ion thermal speed is \( y < 63.3 \text{ cm} \). (This value presumes that the exit flow is shaped so that only half the total current travels in a narrow region near the channel entrance.) For lithium, with \( A = 1 \), the maximum channel height is reduced by \( A^{1/2} = 18.5 \), a result that may eliminate lithium (and higher mass elements) from consideration as the primary propellant, if microturbulence is a major difficulty in MPD arcjet operation.

If the coaxial geometry of the thruster is addressed explicitly in algebra along the preceding lines, the electrode radii may be determined. In order to do this in a consistent fashion, however, it is necessary to specify the distribution of mass density with respect to radial position in the discharge. For example, it is reasonable to attempt to achieve a uniform profile of axial velocity by matching the input mass density distribution to the pressure variation of the (azimuthal) magnetic field, \( B = B_0 (1/r^2) \). (This technique has been used successfully in very high power coaxial plasma guns.

The electron drift speed will then increase linearly with \( r \), so the worst situation for microinstabilities would occur at the outer electrode \( (r = r_2) \). For \( j/\eta c_{te} \leq 1 \), the outer electrode radius must be less than a value that depends on the current and desired exhaust speed:

\[
r_2 < \frac{\eta c_{le} (e/j)}{2\pi (m/u)^3}
\]  
(8)

This condition satisfies the need for sufficient particle density by forcing the mass flow rate through a smaller area. It works, however, in opposition to the need for sufficient electrode area to provide the necessary current at limited electrode density.

### IV Thruster Size Based on Electrode Current Densities

For high magnetic Reynolds number plasma accelerations, the problem of matching the current distributions in the freestream and on the electrode surfaces must be addressed. In particular, it is possible for the relatively narrow discharge, with thickness scaled by the inverse magnetic Reynolds number, to attach in a similarly narrow region on the electrode, ignoring the available expanses of electrode surface provided, and thereby locally overwhelming electrical and thermal conduction processes. Varying the interelectrode gap can certainly help by increasing the effective discharge thickness in the freestream flow. It may also be reasonable to reduce the flow speed near the electrode surface by mass addition, so that resistive diffusion can predominate over convection, and the effective discharge thickness can be locally increased to match the available electrode surface.

As an approximation to the substantially two-dimensional flow, suppose that a region of extent \( \Delta \) along the electrode surface is supplied with mass flow at a rate \( \dot{m}_s \) such that the local plasma speed is \( u \). This speed develops under the influence of self-magnetic forces acting in a thickness \( \delta \) normal to the electrode surface, (chosen in order to match the thickness of the freestream discharge, and thereby attempt a reasonable transition for current flow between the surface plasma and the freestream). For a thin, annular region of area \( 2\pi r_2 \delta \), the surface flow speed and mass flow rate are proportional to values for the main flow:

\[
\frac{u_s}{u} = \left( \frac{\delta/r_2}{g} \right)
\]  
(9)

\[
\frac{\dot{m}_s}{\dot{m}} = \frac{\delta}{f_gr_2}
\]  
(10)

where \( f_g = m_s/\dot{m} \) is the surface mass flow relative to the main mass flow. If discharge thickness values are again scaled inversely with their respective magnetic Reynolds numbers, then the necessary values of \( f_g \) to obtain a discharge thickness \( \Delta = \eta/\mu_S \) near the surface is \( f_g = \Delta/2g \), (assuming that resistivity values are the same for both the surface and freestream plasma flows.) The value of \( \Delta \) is based on the required current (say half the total current for this portion of the discharge at the outer electrode) divided by the allowable current density \( j_s \), i.e., \( 2\pi r_2 j_s = J/2 \Delta \), so

\[
\frac{J}{2\pi r_2^2 2g} = j_s
\]  
(11)

From the condition in the freestream discharge, which may have to support the full current at
positions approaching \( r = r_2 \), the outer radius limit of equation (9) can be substituted to obtain:

\[
j_s = \frac{\pi}{g_s f_i} \left( \frac{1}{m} \right)^{1/2} \left( \frac{u}{e} \right) J
\]

(12)

which displays a formidable dependence on exhaust speed. For values as before, and \( f_i = 0.10 \), \( j_s = 127 \) \( \text{A/cm}^2 \), using hydrogen as the main propellant; (note that the molecular weight of the surface plasma does not enter directly, so the additive may be selected for other useful properties, e.g., work function or ionization control.) Since the computed current density is not unreasonable for MPD arcjet cathodes, thruster dimensions (Table I) based on the preceding approximate calculations may be adequate for initial design choices.

V. OUTER CONDUCTOR EXIT REGION

It has been presumed that about half the current flow is associated with the entrance of plasma and magnetic flux into the discharge, while the remainder occurs as the magnetized plasma flow exits the thruster into a field-free, low density region. In the strict limit of a very high magnetic Reynolds number, highly magnetized plasma (kinetic pressure \(<\) magnetic pressure), a natural break point between the entrance and exit regions is the condition of local flow speed \( u_0 \) equal to Alfven sound speed \( v_A \), natural condition; thus, only a third of the total current is carried by the upstream plasma discharge. The remaining current is distributed in the downstream, supersonic flow as the plasma and its magnetic flux expand in the exhaust. Finite values of resistivity and relative kinetic pressure alter this idealized picture, so for purposes here, the total current is simply split equally between the entrance and exit regions.

If the notion is retained, however, of a magnetized, supersonic plasma flow expanding as \( \gamma = 2 \), and \( q_0 = u_0/v_A = 1 \) corresponds to a field at the sonic point \( B = 2 B_0 \), where \( B_0 \) is the initial field value; thus, only a third of the total current is carried by the upstream plasma discharge. The remaining current is distributed in the downstream, supersonic flow as the plasma and its magnetic flux expand in the exhaust. Finite values of resistivity and relative kinetic pressure alter this idealized picture, so for purposes here, the total current is simply split equally between the entrance and exit regions.

By symmetry, each expansion fan contributes equally to the total expansion of the field from \( B = B_0/2 \) to zero. Locally then, treating the flow field as approximately constant-radius near the electrode, the flow deflection may be calculated from the Prandtl-Meyer function, with \( \gamma = 2 \) and \( B/p = \text{constant} \):

\[
\Delta \theta = \frac{1}{\gamma - 1} \left[ \sqrt{\frac{\gamma + 1}{\gamma - 1}} \tan^{-1} \sqrt{\frac{\gamma + 1}{\gamma - 1} \left( \frac{M^2 - 1}{M^2 - 1} \right)} - \tan^{-1} \right]
\]

(13)

TABLE I

VALUES FOR A GIGAWATT SELF-FIELD MPD ARCJET

<table>
<thead>
<tr>
<th>Assumed Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input power, ( P = 10^9 ) W</td>
</tr>
<tr>
<td>Exhaust speed, ( u = 50 ) km/sec</td>
</tr>
<tr>
<td>Electron temperature, ( T_e = 1 ) eV</td>
</tr>
<tr>
<td>Radius ratio, ( r_2/r_1 = 3.5 )</td>
</tr>
<tr>
<td>Propellant, hydrogen</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Derived Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total current, ( J = 320 ) kA</td>
</tr>
<tr>
<td>Total voltage, ( V = 3.1 ) kV</td>
</tr>
<tr>
<td>Outer conductor radius, ( r_2 = 32 ) cm</td>
</tr>
<tr>
<td>Inner conductor radius, ( r_1 = 9.1 ) cm</td>
</tr>
<tr>
<td>Main discharge thickness, ( \delta = 8.3 ) mm</td>
</tr>
<tr>
<td>Exit lip radius, ( r_e = 33.4 ) cm</td>
</tr>
<tr>
<td>Outer conductor attachment ( j_s = 127 ) A/cm²</td>
</tr>
<tr>
<td>Surface current density ( j_s = 127 ) A/cm²</td>
</tr>
<tr>
<td>Exit lip current density, ( j_e = 60 ) A/cm²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Particle densities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner radius, ( n_1 = 7.2 \times 10^{16} ) cm³</td>
</tr>
<tr>
<td>Outer radius, ( n_2 = ) 5.9 \times 10^{16} cm³</td>
</tr>
<tr>
<td>Surface Plasma, ( n_p = 2.3 \times 10^{17} ) cm³</td>
</tr>
</tbody>
</table>

The total current may be examined in order to focus some attention on design of the exit region. In particular, current concentration at the exit lip of the outer conductor is a concern. It is possible to cast the expansion process in the traditional form of a minimum-length, diverging nozzle for supersonic flow. Although the flow field for such a problem is considered to be "nonsimple" because of the interaction of expansion fans emanating from opposite sides of the throat, and has additional complexity in the present case of cylindrical flow around the inner conductor, it is possible to estimate the radius of curvature at the exit lip in terms of the allowable current density.
Expansion of the frozen magnetic flux to the condition $B = 0$ requires a total flow deflection $\Delta \theta = 65$ degrees. This is a result of an outward deflection by one fan, followed by a deflection due to the opposing fan that returns the flow to its original direction. The initial turn is thus through 32.5 degrees. The corresponding magnetic field value is $B/B_{0} = 0.245$. The current flow in the initial fan (with $B = B_{0}/2$) is then $(1 - 0.245) J/2 = 0.377 \ J$; (for the strictly high magnetic Reynolds number flow, with $B_{0}/B_{0} = 2/3$, the result is 0.503 J).

With a limited current density condition, $j \leq j_{E}$ at the exit lip, the minimum area of the lip region is specified, and the radius of curvature can be estimated. For a constant radius of curvature, $r_{c}$, starting with the surface at $r_{2}$ parallel to the thruster axis, and deflecting the flow through $(\Delta \theta / 2)$, the area of the exit lip is:

$$A/2\pi r_{2}^{2} = \frac{r_{c}}{r_{2}} \left(1 + \frac{r_{c}}{r_{2}}\right) \frac{\Delta \theta}{2}$$

$$= \frac{r_{c}^{2}}{r_{2}^{2}} \sin \frac{\Delta \theta}{2}$$

$$= 0.377 J/2\pi r_{2}^{2} j_{E}$$

(15)

If $j_{E} = 30 A/cm^{2}$, and other values are as before, $r_{c} = 33.4 \ \text{cm}$. The maximum radial excursion is $r_{c}(1 - \cos (\Delta \theta / 2)) = 5.2 \ \text{cm}$, so the neglect of cylindrical flow corrections may be adequate. Since $r_{c}$ is not small compared to $r_{2}$, however, the effects of other expansions of the flow should be experienced on the surface, so the current density is probably higher than specified by a factor of about two ($\sim 60 A/cm^{2}$). If the maximum, initial radial excursion is simply doubled, the final diameter of the nozzle would be on the order of 85 cm.

### VI. ELECTRODE POLARITY

In the preceding sections, it has been implicit that the outer conductor is the cathode, (thereby setting the anode at the center). This is counter to the traditional polarity of MPD arcjets, and many coaxial plasma guns. Indeed, experiments with quasi-steady, megawatt-level MPD arcjets in which the direction of driving current alternated through several flat-topped pulses displayed grossly different luminosity patterns depending on electrode polarity. With the center conductor negative, the expected axisymmetric "trumpet" pattern was observed; while for the outer conductor negative, the discharge appeared as an irregular spoke. These experiments utilized an initially cold, thoriated-tungsten center conductor and an aluminum outer conductor. It is likely that the aluminum outer conductor could not operate as an axisymmetric, diffuse arc cathode because of its relatively large area, and poor emissive properties. The thoriated-tungsten center conductor, however, was observed, when negative, to support a rapid transition from individual spots to an (apparently) diffuse arc.

For very high current, steady-state operation, with proper material selection, it is reasonable to expect that sufficiently high temperatures can be achieved with high current densities even though the outer conductor has a large surface area. Calculations in previous sections have sought to limit the current density at the outer conductor to values less than 150 $A/cm^{2}$, but there may be some advantage in attempting higher current density operation ($\sim 400 A/cm^{2}$) in order to allow cooling by electron emission to dominate the surface power balance. (In the present calculations, this can be achieved simply by reducing the surface mass flow fraction $f_{s}$ to a few percent.) The opportunity to invoke multiple hollow cathode techniques, along with mass injection through the outer conductor, also presents an interesting possibility, especially at the lower particle densities available with the uniform-velocity profile, tailored mass density distribution. Basically, by setting the cathode at the outer conductor, it has a better opportunity to operate in a diffuse arc mode.

At the same time, the centrally-placed anode operates at higher density, and is, in fact, pumped by electromagnetic forces, rather than starved as in high $J/m$ regimes with the traditional polarity. In the present study of gigawatt power levels, the use of lithium for mass addition is possible at the anode with minor effect on the overall thruster performance, since the necessary mass flow rate to match the discharge current is only 5-6 % of the total mass flow. This mass addition is not based on slowing the local plasma flow in order to allow resistive diffusion to dominate, and occurs automatically because of stagnation off the end of the center conductor. Instead, the central location can result in a constricted-arc type flow in a hollow anode for which the lithium may provide transpiration cooling. The high pressure due to the "pumping" component ($\mu_{j}^{2}/8\pi$) of the electromagnetic force contains a relatively high density plasma ($\sim 10^{18} \ \text{cm}^{-3}$) that can readily supply charge-carriers to support the discharge current.
VII. SCALING DOWN TO LOWER POWERS

While it may be interesting to contemplate the operation of MPD arcjets with potentially available gigawatt power sources, it can also be useful to employ considerations of very high power devices in the improvement of more modest MPD arcjet technology. Suppose, therefore, that the available input power is reduced to 100 MW. At fixed exhaust speed, \( J = P \), so the current decreases by \((10)^{1/2}\) to 101 kA. This requires the outer conductor radius to decrease in order to maintain the necessary particle density at reduced mass flow rate, so \( r_2 \) becomes 10.3 cm. The surface current density at the outer conductor, however, increases by \((10)^{1/2}\) to 400 A/cm\(^2\), which may be higher than desired. The exit lip current density will also increase by the same factor.

To maintain the surface current densities at the previous levels, a slightly higher exhaust speed could be accepted at lower powers. Thus, since \( P - U^2 J \), and \( J - U^2/J \), for fixed current density, \( J = P^{3/13} \). The exhaust speed is then a very weak function of power, \( u - P^{1/3} \). Values for MPD arcjets at scaled-down powers, but constant proportions and current densities, are displayed in Table II. Particle densities drop by about a factor of two for each decade of power reduction.

| TABLE II |
|-----------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| VALUES FOR SCALED-DOWN MPD ARCJETS | (\( g = 2, T_a = 1 \text{ eV}, J_a = 127 \text{ A/cm}^2 \)) | | | | | | |
| POWER LEVEL [MW] | 100 | 10 |
| Total current [kA] | 110 | 38.2 |
| Total voltage [V] | 904 | 262 |
| Exhaust speed [km/s] | 42 | 35 |
| Outer conductor radius [cm] | 19.2 | 11.3 |
| Inner conductor radius [cm] | 5.5 | 3.2 |

It is interesting to note that the values for \( P = 10 \text{ MW} \) match reasonably to multi-megawatt (quasi-steady) operation. A particular concern, of course, in reducing the total power (for self-field arcjets) is the decrease in total voltage to levels for which electrode drops become significant, with the associated loss of efficiency (and increased system difficulty).

Electrode erosion often scales with the total charge passed \( \Delta \text{m} = Q = J \Delta t \), where \( \Delta t \) is the thruster operating time to perform its mission. But \( \Delta \text{m} \sim 1/m \cdot 1/P \), so that \( \Delta \text{m} \sim P^{-1/3} \), and the actual mass eroded decreases with higher power. For some steady-state processes, the mass loss is simply due to evaporation at a particular current density, the total mass loss (at fixed \( J \)) then scales as \( \Delta \text{m} \sim P^{1/3} \), so again higher power operation is favored.

VIII. RESEARCH TASKS

The design of a gigawatt MPD arcjet can serve as a starting point for various elements of potentially useful technology. In particular, present modest power devices would benefit considerably from better control of processes near electrodes, including the generation of charge-carriers in a manner that is more independent of the free stream plasma. (Often electrodes are simply machined in shapes that have some intuitive basis, out of materials for which there is some favorable experience, and are then inserted into a complicated plasma environment with the hope that a reasonable match will occur between conditions for emission and charge-collection, and conditions for thrust performance.) Along these lines, two items of possible interest discussed in the present paper are: 1) large-scale, multiple hollow cathodes with mass addition for the outer conductor, and 2) a hollow anode, also with mass addition, for the inner conductor.

A separate endeavor that has been followed here is the need to scale the geometry and flow properties to avoid problems associated with high current density. This has included specification of conductor sizes as a function of current and desired exhaust speed, and the development of proper shapes to accommodate the expansion of magnetized plasma flows without causing current concentrations. The algebraic estimates utilized in the present paper merely point the way for more detailed calculational techniques. In particular, computational tools exist for MPD arcjet-type flows (such as the MACH2 code\(^5\)), and can be applied to basic problems of current and mass flow distributions.

Experimentally, it will be useful to place benchmarks at the higher power levels, (where in some sense the complexity of electrode problems can be separated from the main plasma acceleration process). In this regard, a gigawatt pulseline\(^6\) is being assembled at the Ohio State University. It consists of 2100 capacitors (43 \( \mu \)F each, rated at 12 kV, when new). The system, known locally as Godzilla, has been arranged in three racks, each of which comprises a ten-section, LC-ladder pulseline. The connections between racks are designed to allow several variations of output current and pulsetime. These include 333 kA for 1.63 msec, 111 kA for 4.9 msec, and a 17 msec pulse at 15.9 kA; (this last variation is possible because there are actually seven separate lines in each rack). The initial charging voltage in all cases is 6 kV, and the current values are quoted for matched impedances. The first case corresponds to the gigawatt MPD arcjet design, while the other variations can power scaled-down devices.

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REFERENCES


9. Ibid., P.134.


