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DESIGN
CHARACTERISTICS OF
THE VARIABLE $I_{sp}$
PLASMA ROCKET

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ABSTRACT
Light on the fundamental operational characteristics of this engine.

Research on the Variable $I_{sp}$ Plasma Rocket has continued for a number of years. These studies are beginning to yield a large quantity of data which is being used to formulate design options and criteria for future NEP thrusters utilizing this technology. This paper focuses on some of the salient design features of a flight system utilizing this propulsion technology, and discusses the fundamental experimental and theoretical findings on which they are based.

CONCEPT DESCRIPTION

As described earlier, this ICRF heated device is capable of continuous exhaust modulation at constant power. This particular feature enables it to be optimally "tuned" throughout the flight by a preselected thrust/$I_{sp}$ schedule (i.e., to maintain a constant acceleration.) Additionally, the absence of electrodes virtually eliminates materials constraints on the plasma temperature.

The basic system, shown in Fig. 1, consists of a three-stage process of plasma injection, heating and controlled exhaust in a compact magnetic tandem mirror configuration. The device also features a novel two-stage nozzle arrangement, consisting of a magnetic first stage which merges into an expanding material section. This latter portion utilizes a uniform array of hypersonic annular jets to insulate and detach the hot plasma from the field.

Radial plasma containment and control are accomplished in an asymmetric tandem mirror configuration which provides for an MHD stable plasma column over a wide range of plasma temperatures and densities. The tandem mirror also provides variable magnetic and electrostatic "gates" at the end-cells for plasma exhaust control over a wide operational envelope. Expected system operating parameters for a power level of...
10 MW at 60% efficiency are shown in Fig.2.

ICRF SUBSYSTEM

Referring to Fig 1., Neutral gaseous fuel, typically Hydrogen, or others, as appropriate (see Alternate Fuels Section) is injected and ionized by Electron Cyclotron Resonance Heating (ECRH) at the Forward End Cell. This initial cold plasma is subsequently heated to the desired temperature by Ion Cyclotron Resonance (ICRH) while flowing in the much larger central cell of the tandem mirror. After heating, the plasma is allowed to escape into the magnetic nozzle at the aft end cell where it is exhausted to provide thrust.

The main ICRF subsystem consists of two half-loop antennae located at each end of the central cell, near the inboard side of the mirrors, as well as their associated transmitters. This system provides the main heating power (4 MW. each), at operating frequencies ranging between 500 KHz and 10 MHz. This particular configuration has been chosen after extensive experimental and theoretical work which demonstrates greater RF absorption than that obtained using the conventional geometry of fusion concepts (1). Two smaller (ICRH) antennae at the end-cells (not shown) are being considered to provide 1 MW each of ambipolar control and additional heating of the flowing plasma.

The above design choices have been prompted by experimental and theoretical results being reported by our research group (2). For example, the overall damping of RF waves and hence the RF absorption efficiency, is enhanced when the waves are launched near the mirror throats and away from the midplane of the device. In these cases, the waves travel radially inwards and axially towards the center where resonance occurs. This behavior, called "Beach" heating and shown in Fig 3, is expected to account for RF coupling efficiencies in excess of the 55% predicted by previous models (3). However, no upper bound on the coupling efficiency has been obtained as of this writing.
Additionally, numerical simulations of the absorption dynamics show two other simple but important effects: 1) the maximum damping rate, as expected, does occur at the center, where the field is nearly uniform and at resonance and 2) the total power delivered is proportional to the central cell volume. These results, shown in Figs. 4 and 5, imply that the optimum configuration favors a long central cell with a nearly uniform magnetic field over most of its length. This condition, in turn implies that the system “alpha” tends to improve with machine length.

In order to extrapolate the current experimental device and estimate a value for the specific weight or “alpha” of such a system in a multimegawatt-class flight unit, we have examined the actual weights of present-day, off-the-shelf hardware in our laboratory. These simple estimates for the main components of the ICRH subsystem at 1 MW are shown in Table 1. They lead to overall “alpha” values of 4 Kg/KW.

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>OFF THE SHELF COMPONENT WEIGHTS AND “ALPHA” VALUE FOR THE ICRH SUBSYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRANSMITTER (1 MW)</td>
<td>1250 LB</td>
</tr>
<tr>
<td>SWITCHING GEAR</td>
<td>1000</td>
</tr>
<tr>
<td>HVDC CAPACITOR</td>
<td>2000</td>
</tr>
<tr>
<td>FINAL PWR AMPLIFIER</td>
<td>1100</td>
</tr>
<tr>
<td>FPA FIL.PWR SUPPLIES</td>
<td>3500</td>
</tr>
<tr>
<td>DRIVER, IPA CONTROL</td>
<td></td>
</tr>
<tr>
<td>TOTAL MASS</td>
<td>8850 LB</td>
</tr>
<tr>
<td>SPECIFIC WEIGHT</td>
<td>4 (KG/KW)</td>
</tr>
</tbody>
</table>

MAGNET SUBSYSTEM

The magnet subsystem consists of a long central cell and two end-cells operating at magnetic fields of 1-5 Tesla. The field is axially asymmetric and it is trimmed at the
injection and exhaust ends to match the configuration of the neutral gas injector and ionization cell at the forward end, and the magnetic nozzle at the exhaust end. The arrangement of windings also provides Thrust Vector Control (TVC) at the exit.

The main approach in the superconducting coil design has been compactness and simplicity. However, this, being a critical sub-system of the rocket, requires a significant amount of failure-tolerance. Accordingly, the system is being designed with a certain degree of initial redundancy.

Two coil designs are being explored: A conventional liquid Helium system with individually controlled coils, and an advanced liquid Helium design with an integrated redundant coil. Fig.6 illustrates some of the design aspects of this subsystem. A new high temperature superconducting system being developed by L. Bromberg, et. al.\(^{(4)}\) of the MIT Plasma Fusion Center opens up new operational capabilities at liquid hydrogen temperatures. In either case, the design of a fully regenerative superconducting arrangement is being sought.

GAS INJECTION SUBSYSTEM

At the exhaust, the system consists of a two-stage nozzle arrangement featuring an inner magnetic nozzle to guide the plasma out of the mirror, followed by a material nozzle section which is also insulated from the hot plasma through a coaxial hypersonic neutral boundary layer. This layer is injected through the nozzle walls by an array of uniformly distributed small jets at a preselected "pitch angle" with respect to the main flow. The presence of this layer also induces sufficient collisionality to effectively detach the plasma from the magnetic field. The two stage nozzle utilizes liquid fuel in a similar regenerative approach, much like that employed in conventional rocket nozzles. This phase change also produces the gas charge necessary to drive the boundary layer near the plasma.

While it is important to minimize the presence of neutral gas near the hot plasma in the central cell, as it would lead to excessive charge exchange losses during the heating process. The presence of neutrals at the exhaust and within the nozzle region may, in fact be beneficial, as they will provide a magnetically unconstrained component to the overall Isp of the device. Nevertheless, the contribution of hot neutrals to the overall performance of the device has not been evaluated.

Numerical research using a 3-D, multi-fluid, fully magnetized time-dependent code has given an initial understanding of the dynamics affecting the separation of the plasma from the magnetic field at the rocket nozzle. Four "snapshots" at 3.75 microseconds are shown in Fig 7, illustrating the flow dynamics for different cases involving: 1) free expanding flow with no gas, 2) expanding plasma within a fully developed, axially flowing gas blanket, 3) expanding plasma in the presence of a thin radial jet and 4) the same as 3) for a wider jet.
It is evident from Fig.7 that the plasma, in the absence of any gas, tends to follow the lines of induction. Moreover, the purely axial blanket is an artificial case since even at hypersonic velocity, its motion would be negligible when compared to that of the hot plasma. The plasma will ultimately erode it away. However, Cases 3) and 4) are of interest, as they show a substantial limiting effect on the plasma radial motion. The optimum design is expected to lie at some intermediate injection “pitch” angle. This effect is currently under investigation.

GENERAL DESIGN ISSUES

Alternate Fuels:

The thrust and Isp combination at a given power level can be greatly affected by the atomic mass of the propellant. For certain applications, such as the Mars mission, the maximum Isp requirements are not as high as for the more energetic missions. Under these circumstances, it becomes more advantageous to use a heavier fuel, at the expense of Isp to gain on thrust. The use of fuels other than Hydrogen (i.e., Helium, Deuterium, etc.) can boost the maximum thrust density to levels comparable to those of nuclear thermal rockets at the same power. In those cases, the minimum Isp of the system can still be in excess of 2000 sec. Moreover, the higher atomic mass fuels reduce the required ionization power. However, while these are all beneficial effects, heavier fuels may also increase the radiation losses of the system and hence reduce the overall efficiency. These design tradeoffs have not been fully examined and are undergoing further scrutiny.

High voltage / low current operation:

One of the main advantages of this technology lies in the utilization of high power at high voltage. This reduces the required weight of the power handling equipment. Typical operating voltages for these systems are in excess of 10.KV. The present 10 MW system will make use of a Nuclear Rankine power conversion cycle with a specific weight of 4 Kg/KW providing 10KV input power to the system.
CONCLUDING REMARKS

Much remains to be done theoretically and experimentally in understanding the operating characteristics of this system; however, certain design features are becoming clear. Future research goals and plans call for continued methodical attention to the basic physics of the device in order to illuminate some of the design options that lie ahead.

Mission analyses using variable Isp have not been carried out exhaustively; however, some initial calculations have been made (5). These initial numbers need to be subject to optimization techniques which take into account a large array of variables such as trip time, fuel vs. payload mass, maximum velocity at arrival, the use of aerobrake techniques. These efforts are ongoing.

REFERENCES


5 J.Gilland, NASA/ LeRC. Private Communication


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