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Second Magnetoplasmadynamic Thruster Workshop

Proceedings of a workshop held at
NASA Lewis Research Center
Cleveland, Ohio
May 19, 1992

NASA

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I. Summary

The 2nd Magnetoplasmadynamic (MPD) Thruster Workshop was held at the National Aeronautics and Space Administration (NASA) Lewis Research Center on May 19, 1992. There were 32 participants, including experts from NASA, the Department of Energy (DOE), the Department of Defense (DOD), and academia. Six government laboratories and six universities were represented at the workshop, the purpose of which was to review technical progress made since the last meeting held at NASA Headquarters in 1991 and discuss plans for future work. Specifically, the meeting focussed on progress made in establishing:

- performance and lifetime expectations of MPD Thrusters as functions of power, propellant, and design,
- models for the plasma flow and electrode components,
- viability and transportability of quasi-steady thruster testing,
- engineering requirements for high power, long life thrusters, and
- facilities and their requirements for performance and life testing.

A two hour discussion period followed programmatic presentations by representatives of NASA Headquarters and reviews of technical progress by the research organizations working on MPD thrusters. During this period the workshop participants **established lists of Key Technical Issues in five areas: Anode, Cathode, Flow, Modeling, and Diagnostics. Committees were then formed for each of these areas to prioritize and establish approaches for resolving the highest priority items.** Following the workshop, the committee chairmen contacted all the committee members to solicit inputs. Final reports for each area were prepared which are presented in subsequent sections.

The overriding theme that emerged from the workshop was the need to improve the coordination among the various groups working on MPD thruster technology. This is true for both experimental and theoretical efforts. At present it is impossible to compare the various efforts due to the large differences in the approaches and devices studied. Specific recommendations were established by the committees to foster a more unified approach, and an effort should be made to ensure continued communication between the various research groups.

The purposes of these Proceedings are to **disseminate the workshop results and document the status of MPD thruster technology such that progress can be quantified**. It is critical that we show **measureable progress toward realistic goals**. Following a list of action items established by the committees and the committee reports, a brief summary of the presentations and key discussions is provided. Descriptions of the technical efforts underway at each organization are given in this section. Copies of the presentation graphics are presented in the Appendices.

II. Action Items

The following action items were established at the workshop and by the various committees. Please provide the following inputs to Roger Myers (LeRC) by December 15, 1992:

- Respond on feasibility of running MPD thruster codes on geometries and operating condition matrix established by modeling committee. Provide results if possible.

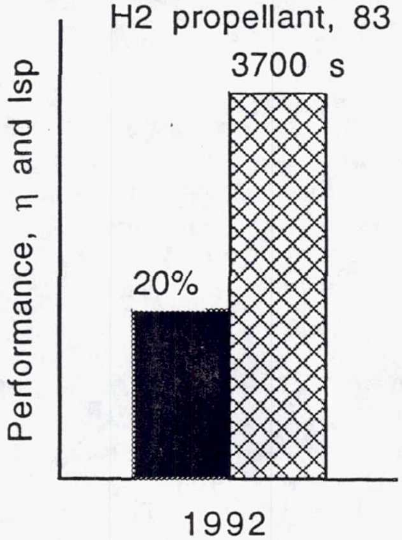
- Respond on suggestions for standardized experimental configuration(s).

- Provide list of observed failure/gross erosion mechanisms for all thruster components (eg. gross melting of anode, localized pitting, thermal stress, etc.)

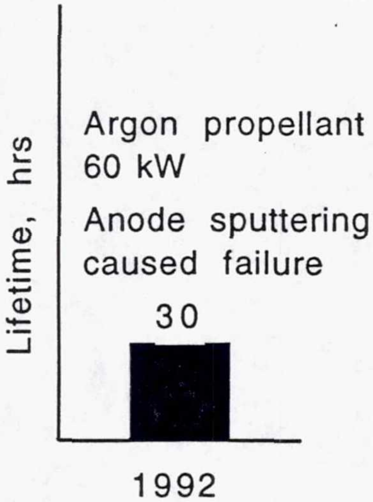
- Provide responses to issues raised in Anode, Cathode, Flow, and Modeling Committee Reports. Specifically, there were many issues concerning the applicability of particular models and experimental approaches **which must be addressed to demonstrate that the community is moving forward.**

Inputs will be included in a newsletter to be sent out in January of 1993.

In addition to these, Dave Byers of LeRC requested that the community **prepare two charts which summarize progress made each year**. The first is a **plot of efficiency and specific impulse vs. year**. This would show performance improvements in a given year, and would represent the best measured performance and/or best estimates from the latest models. The second chart would show **thruster lifetime vs. year**, and would again show the maximum demonstrated and/or best estimate for thruster lifetime based on experiments and models. These charts will be updated at each MPD thruster workshop, and should represent a consensus of the MPD thruster community. To initiate this process the following is proposed for 1992 based on applied-field thruster results obtained at LeRC:



Performance



Lifetime

Please provide input for an update to be distributed in January.

III. Committee Reports

III. A. Anode Committee

Chairman: Roger Myers
Anode Committee inputs were received from K. Diamant , A. Gallimore, R. Gerwin, M. Martinez-Sanchez, E. Niewood, J. Polk, D. Tilley, and P.Turchi.

General Comments:

In general, all committee members had difficulty with separating the key technical issues, feeling strongly that the various aspects of anode power deposition were strongly coupled. As a result, the following write-up does not exactly follow the listing of Key Technical Issues which was established at the workshop. Several committee members pointed out that there are sufficient uncertainties in our understanding of the dominant physics (especially for the wide range of devices the community is studying) that we **must not focus too narrowly on a particular aspect of anode power deposition** (such as voltage drops) for fear that we will miss a major contributor to the anode power loss. This emphasizes the importance of **direct measurements of the anode power loss.**

All committee members felt that a purely experimental approach runs the risk of missing the solution to the anode problem. All emphasized the requirement for **local plasma property measurements in the anode region**, and **the strong coupling of the flow and anode physics**. All were concerned about establishing the appropriate model/experiment balance.

Almost all modeling is currently done on self-field devices. Applied-field devices have clearly shown higher steady-state performance at power levels of interest. This is a potential problem in that the **self-field plasma boundary conditions are probably completely different than they are in applied-field devices** (Gerwin). This most fact that the applied-field lines intersect the electrode surface.

Issue Prioritization and specific comments:

<u>1. Anode Fall</u> (uniformly picked as the key issue)

Experimental Approaches:
Major emphasis should be placed on identifying causes of anode fall voltage and ways to reduce it. The same techniques for reducing anode loss were advocated by all who commented. These were:

Anode gas injection to reduce Hall parameter
Modify magnetic field/anode shape to permit parallel electron current to the anode
Reduce magnetic field strength at anode surface.

While most work must be done on actual thrusters, fundamental studies can likely be done in small benchtop experiments (Myers, Gallimore, Tilley). In the role of fundamental physics studies, these experiments need not be faithful simulations of the thruster environment (Polk), however, care must be exercised when extrapolating the results to thruster anodes. For the latter, extreme care is likely required to ensure that the test conditions, including current and plasma density, temperature, magnetic field, etc., are close to those observed in actual thrusters. It will probably be difficult to match plasma velocities. To ensure use of appropriate test conditions, local diagnostics of the anode plasma in thrusters and bench-top experiments are required.

In addition, appropriate engineering judgement should be used to ensure that all studies are done for realistic conditions. This is particularly an issue with quasi-steady testing, where thrusters can easily be operated at surface power densities where there is no expectation of building a practical device. For example, reasonable anode power and current density limits can be established based on lifetime and heat transfer considerations. Given our relatively poor understanding of anode physics, it is doubtful that data taken under conditions very different from those for which actual thrusters can be built will be transportable to relevant operating conditions.

2. Modelling:

There currently appear to be **two dominant theories for anode power deposition**, one relying on classical transport and anode plasma depletion (currently investigated at MIT), the other relying on anomalous transport (currently investigated at Princeton). It is clearly necessary to use the models and associated experiments to establish which of these mechanisms is dominant.

Issues with current models:

Absence of sheath models (Gallimore, Myers)
Use of continuum model (fluid) near wall (Martinez-Sanchez, Gerwin),
Neglect of several heat transfer terms (Gerwin)[1]
Wall effects on electron gyrations (Martinez-Sanchez),
Use of homogeneous plasma approximation for microturbulence near wall (Martinez-Sanchez),
Coupling of flow-field/boundary layer (Martinez-Sanchez, Gerwin, Turchi)
Impact of magnetic field and electrode geometry on anode fall/flow field (Gerwin, Myers)
Need to include ionization/recombination phenomena in anode models (Myers)

Given the diversity of approaches and boundary conditions, it is quite difficult to establish regions of model validity. It appears to be very important to establish a few standard geometries and operating conditions with which to compare WHICH ALL MODELS CAN RUN (Gerwin, Myers). This would permit valid comparisons of the results of the various modeling approaches.

3. Diagnostics:

A detailed listing of suggested diagnostics, advantages and disadvantages of each, and a list of contacts and references is provided in the Diagnostics Committee report. However, several issues specific to anode studies were raised by the committee which are discussed below.

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[1] Gerwin has indicated that a more careful consideration of the heat flux to the anode (following Braginskii, S.I., in Reviews of Plasma Physics, Vol. 1, Consultants Bureau, M. A. Leontovich, ed., 1965) reveals that several terms usually neglected in the analysis of anode power deposition become substantially larger under certain conditions.

Direct measurements of anode power deposition must be correlated with detailed maps of all plasma parameters which control it. This is the only way to properly identify mechanisms of power loss. Required measurements definitely include the plasma potential, electron temperature and density, current density, magnetic field strength, and radiated flux (predominantly from hot cathode), and may include the ion velocity, and ion temperature. Diagnostics are also needed to evaluate the role of microturbulence (Tilley). Suggested resolution ranged from 1 mm to 0.01 mm, and property maps must address both radial and axial variations (Niewood). Note that the only thruster geometry for which both detailed power deposition and plasma parameter maps exist is the Princeton benchmark thruster (and two slight variations of it), a geometry for which the anode power density was found to be far above that acceptable for viable devices and which is extremely difficult to model (Gerwin, Myers, Turchi). Studies are clearly required using other geometries which eliminate these issues.

Probe diagnostics in the near anode region may highly perturb the anode fall region. In addition, the distribution function near the anode is expected be non-Maxwellian due to the absorbing nature of the surface, which will likely complicate the data reduction. While work at Princeton is not detecting any significant problems with probes within 0.1 mm of the anode (Diamant, see Appendix C), there is clearly a need to develop non-invasive diagnostics for the near-anode plasma.

Specific experimental suggestions:

Gallimore:

Use of Langmuir probes to map the near anode region (to within 0.5 mm) in thrusters and benchtop experiments, and the use of benchtop experiments to establish fundamental correlations between plasma conditions, geometry, and magnetic field configuration.

Need to establish differences, if any, between quasi-steady and steady-state thruster anode phenomena. Could be done with a benchtop experiment.

Design experiment where anode is shielded from hot cathode to assess impact of cathode radiation.

4. Facility effects:

This is important only insofar as the community is careful to ensure **all testing is done under conditions for which the tank pressure does not affect anode power deposition**. This value is usually placed at 5 x 10^{-4} torr. As long as this requirement is met, facility effects are not an issue.

5. Others

Lower priority items which should be addressed after the above include stability, symmetry, and fluid turbulence. In addition, until the performance of thrusters improves and we can identify specific geometries which satisfy mission performance requirements, it is premature to study mechanisms of anode heat rejection and select anode materials.

III. B. Cathode Committee

Chairman: Jay Polk

Inputs were received K. Goodfellow, M. Mantenieks, R. Moses, R. Myers, P. Turchi, and W. Stirling.

General Comments

All respondents agreed that the **primary issue with the cathode is its lifetime.** Although the heat transfer to the cathode represents a thermal loss, its impact on performance is relatively low. Cathode failure will likely be defined as the point at which cathode damage leads to unacceptably low performance or an inability to start the engine. Cathode damage may also precipitate failure of other components. A number of failure modes were identified, but **the most troublesome are likely to be evaporation and possibly sputtering.** There was no consensus on the proper methodology to use in establishing cathode reliability. Modeling of cathode processes was felt by all respondents to be important. The emphasis should be on modeling cathode thermal behavior and erosion processes. **The most important physical processes identified by the committee were work function, magnetic field and propellant effects, and the detailed erosion and mass transport processes.** To identify failure modes, validate models and provide input informantion for models a number of measurements were suggested. **The highest priorities were measuring cathode temperature, erosion rates, and work function.** Most respondents felt that **hollow cathodes had the highest potential for long life, and that the best materials were likely to be barium compounds in tungsten or lanthanum oxide in molybdenum.**

Cathode Failure

Definitions

Failure may be defined as the point at which cathode wear results in intolerable degradation in engine performance. Testing and modeling will be required to determine what effect wear will have on performance (Polk), but one likely result is an increase in voltage with a corresponding decrease in efficiency (Myers). Stirling suggests that a decrease in restart reliability will be the first indication of failure, based on his experience with quasi-hollow cathodes for ion sources. In addition, cathode wear has been observed to cause anode or insulator failures at ORNL, and Stirling recommends in particular that **insulators be shielded from the discharge.**

Failure Modes

Arcing due to transients has been observed in the quasi-hollow cathode at ORNL and melting may occur as a result of aging (Stirling). Insulator failure can also occur as a result of exposure to the plasma or cathode start-up erosion products (Stirling). **Thermal runaway** caused by loss of low work function impregnates or increased Joule heating due to diameter changes is the most common failure mode observed in steady-state applied-field thruster testing at LeRC (Myers). **Internal melting** leading to cavity formation and cathode rupture has occurred in high-current steady-state thruster testing at Stuttgart. **Oxidizing impurities in the propellant** were also found to dramatically increase cathode erosion at Stuttgart, and to modify the erosion pattern at LeRC (Mantenieks, Myers). Significant **tip melting** was observed in cathodes with conical tips in steady-state applied-field thrusters at JPL, but this problem was solved with the use of hemispherical-tipped cathodes (Polk). **Cathode fracture** has also occurred occasionally at LeRC and Princeton. However, a number of these failures probably represent immature designs. A mature cathode design is probably going to be subject to wear primarily by evaporation or sputtering, with transport of the erosion products through the ambient gas playing a significant role in determining loss rates.

Establishing Reliability

There was considerable spread in opinions on this issue. Stirling replied that there is no substitute for testing, and Myers argued that the testing conditions must be appropriate. The cathode behavior in engines must be understood before any methodology can be applied. Goodfellow emphasized that the **coupling between performance and lifetime must be understood**. In addition, Polk and Goodfellow commented that testing alone is insufficient to establish lifetime in a statistically significant manner, and that a probabilistic treatment of the available analytical and experimental results is the best approach to quantitatively assessing reliability.

Cathode Modeling

Model Regions

The responses were also somewhat scattered in this area. Stirling, although confessing less knowledge of this area, replied that he thought modeling was very important and that the focus should be on the sheath, boundary layers and the core plasma flow. Polk responded that the solid, surface, sheath, ionization zone and core flow are the highest priority model areas, with the boundary layers (momentum, thermal and concentration) and pre-sheath being less important. Moses emphasized that the sheath region, particularly current transport, must be understood. Myers, based on observations of applied-field thrusters at LeRC, chose the ionization zone, particularly the effect of non-maxwellian emitted electrons, as the highest priority, with the solid, surface, sheath and pre-sheath as secondary issues which have been modeled previously for cathodes in other discharges. Goodfellow ranked the regions in terms of modeling priority by progressing out from the surface. The solid, surface, sheath and pre-sheath should be addressed first, then the boundary layers, and finally the core plasma flow. Turchi's reply emphasized the importance of matching the flow to the nonlinearities encountered near the wall, and suggested the potential for decoupling the cathode plasma from the main plasma flow with the use of a hollow cathode. While groups from other fields have modeled the cathode sheath and presheath region, there hasn't been a successful attempt to couple these models to the cathode thermal characteristics and the plasma flow field (Myers).

Cathode Phenomena

Cathode work function was identified as one of the most important phenomena in cathode modeling (Polk, Goodfellow) **as well as the effect of the magnetic field** (Myers, Mantenieks, Polk, Stirling), particularly in light of observations at LeRC. The propellant gas can also have a significant effect (Myers), particularly for alkali metal propellants which may alter the work function (Polk). Thermal-field emission was chosen as the most important emission mechanism to study. Moses emphasized the importance of understanding the components of current transport, and Polk ranked the distinction between microspot and diffuse attachment as a high priority for quasi-steady operation. The impact of anomalous transport in the cathode region was generally ranked as a low priority, except by Stirling. The erosion mechanisms were rated one of the highest priority phenomena to study by Polk because erosion is the primary concern, but Myers rated erosion mechanisms as the last priority, arguing that the other phenomena must be addressed first. Because chemistry plays an integral role in the determination of the work function and in chemical attack on the cathode, it must be addressed in assessing alternate materials and testing requirements (Myers, Polk). The role of eroded product transport through the ambient gas was rated as a high priority by Polk. The only transient effects identified by the respondents as important were transient arcs (Stirling) and activator depletion (Goodfellow).

Experimental Requirements for Model Inputs/Verification

Measurement of erosion rates and temperature distributions were identified by all respondents as the highest priority because these are the most important model predictions. Stirling also ranked the measurement of potential distributions high. Moses felt that the detailed profiles of electron and ion temperature, density and current, as well as magnetic and electric fields in the near-cathode region should be measured, although achieving adequate spatial resolution in the sheath region may be difficult. Cathode work function (Goodfellow, Polk) and the extent of the attachment zone (Polk) were also identified.

Cathode Testing and Design

Facility Effects

Ambient pressure was identified as the most important facility parameter, and Mantenieks pointed out that the species present in the ambient gas can be important. A good example is the partial pressure of pump oil in the facility. The purity of the propellant itself was also listed as an important consideration. The effect of the flow field, power supply interactions and plume interactions were considered to be less important in cathode studies. The only comment on the importance of power level scaling was that we should concentrate on 100 kWe class steady-state engines and megawatt class quasi-steady thrusters (Myers).

Cathode Concepts

Conventional rod-shaped cathodes have little potential, but might provide adequate lifetime if they are constructed as dispenser or reservoir cathodes (Myers, Mantenieks, Polk) or continuously fed into the engine (Stirling). **Hollow cathodes were identified by all as a technology with high potential** for meeting MPD thruster cathode requirements. Turchi's response outlined a number of particular advantages to the use of hollow cathodes, including more **control over the cathode plasma, greater retention of the energy radiated from the emitting surface, a higher vapor pressure, which reduces the evaporation rate, and decoupling of the cathode plasma from the main discharge plasma**. Stirling suggested the use of a quasi-hollow cathode similar to that used in ion sources at ORNL. They have demonstrated operation at up to 1000 A, but have not attempted operation beyond several hours. Externally heated cathodes were identified as important only for quasi-steady operation (Myers). Moses suggested that appropriate shaping of the magnetic field near the cathode might minimize the thermal and momentum losses to the cathode.

Cathode Materials

The consensus was that **low work function, high melting temperature, low resistivity and mechanical integrity are the most important material properties for MPD thruster cathodes**. From a list of candidate cathode materials, barium compounds in a tungsten matrix (Myers, Mantenieks, Polk), thoriated tungsten (Goodfellow) and lanthanum oxide in a molybdenum matrix (Stirling) were identified as the ones with most potential. Mantenieks responded that lanthanum hexaboride is too brittle, and Stirling indicated that lanthanum oxide in molybdenum has similar emission capabilities, but is less brittle. Pure tungsten was thought by all to be of little or no use.

Cathode Thermal Management

This area did not appear to be a high priority, because cathode heat fluxes are relatively low. Regenerative cooling was generally identified as the best approach, with heat pipes and radiators listed as less important technologies.

Cathode Design Impact on Performance

The **current capability and geometry were generally considered to be the cathode parameters with the greatest impact on thruster performance**. The power loss associated with heat transfer to the cathode was listed by Stirling and Turchi, although Mantenieks suggested that it is fairly small. Of the other suggested effects, the cathode's impact on current contours was listed as a somewhat higher effect than its effect on voltage and its role as a source of impurities.

Participating Organizations Interests and Activities

A number of cathode phenomena are being studied both experimentally and theoretically at the government and university laboratories that participated in the questionnaire. JPL has developed a cathode thermal code using boundary conditions supplied by a model of the cathode sheath, pre-sheath and ionization zone. Models which predict the cathode work function for thoriated tungsten cathodes and cathodes immersed in alkali metal vapors have been developed and are being incorporated into the thermal model. The temperature distributions given by the thermal code can be used with a set of existing models which describe the dominant erosion mechanisms to predict mass loss rates. A dedicated high-current cathode test facility is being established which will be used to obtain model input parameters and validate model predictions, as well as develop new cathode concepts and perform long duration cathode tests. Another large facility is being established to test lithium MPD thrusters. A component of that program will be to determine the effect of lithium on cathode lifetime. The ultimate goal is to develop the analytical tools to calculate prior distributions of cathode failure probability and update these distributions with information from endurance tests in a Bayesian framework to yield quantitative estimates of cathode lifetime that incorporate all available information. Specific milestones for the next year include the development of a two-dimensional thermal model, collection of a database of measurements to test the model predictions, and identification of a cathode design for a 2000 hour endurance test at 2500 A.

LANL is involved in the development of large scale MPD thrusters and the testing of a geometry with a magnetic field generated by a solenoid located inside the cathode. While they are not actively studying the cathode phenomena, they are using a variety of diagnostics to establish current and electric potential distributions and measure cathode power deposition.

The major focus of LeRC is on testing of rod and hollow cathode geometries made from both 2% thoriated tungsten and barium impregnated tungsten in applied-field MPD thrusters. The testing is devoted to measuring performance and lifetime, such that the fundamental coupling between the two can be established. The MPD thruster cathode studies currently include surface temperature, weight-loss and surface morphology measurements as a function of thruster operating conditions and cathode geometry. There is considerable work being done to establish the impact of propellant impurities and feed system contamination on cathode life. While most of the work is experimental, there is an ongoing hollow cathode modelling effort underway in collaboration with Ohio State University. An experimental program of internal hollow cathode diagnostics has also been initiated to validate the model. The potential for high efficiency, high power pulsed MPD thruster systems led to the initiation of an effort to establish the feasibility and practicality of long-life pulsed cathodes using internal heaters. Assuming successful demonstration of a low erosion, 10 kA pulsed cathode, a thruster will be built and sent to Princeton University for testing.

ORNL has developed "quasi-hollow cathodes" for ion beam acceleration and neutralization. These cathodes are the evolutionary result of development starting with a duoplasmatron version. The cathodes are characterized by low temperature emitters (lanthanum oxide-molybdenum) operating in a magnetic field free, high density gas discharge with the main arc voltage appearing across a double sheath at the cathode exit, which is in a region of magnetic field constriction. The voltage drop at the surface is between 20 and 30 volts. Thus, emitter erosion is minimal and the emission temperature is maintained by resistive heating. The highest current cathode to date is 1000 A, limited by ion source requirements. This application requires test pulses no longer than 30 seconds in duration. However, this cathode was run for an accumulated time of 3.3 hours at 30% duty cycle over a two day period with no obvious signs of wear.

As mentioned above, Ohio State is concentrating on the development of a first principles model of hollow cathode behavior. Generation of data to validate the model is presently underway by an OSU student at NASA LeRC. The MACH2 MHD code is also being applied by another student in order to model the overall MPD thruster flow field.

Princeton University is developing a porous tungsten cathode fed from a lithium reservoir. This geometry should be capable of maintaining a layer of lithium on the cathode surface to reduce the work function and will also serve to seed the main discharge with lithium vapor. Princeton may also participate with LeRC in the testing of an externally heated cathode for pulsed thruster operation.

III. C. Flow Committee

Chairman: Roger Myers

Flow Committee inputs were received from E. Choueiri, B. Hooper, M. LaPointe, R. Mayo, N. Roderick, D. Tilley, and P. Turchi.

General Comments

In all the contributions, there was an emphasis on the need for numerical simulations. All pointed out that codes can offer insight into problems at considerably lower expense than experimental work. **However, the codes must be reliable predictors of at least some of the experimentally observed parameters before the program can rely on them for guidance.** In fact, it has only been in the past couple of years, in work by Martinez-Sanchez and LaPointe, that the codes have been used to show the benefits of modifying the thruster geometry (Myers). A relevant MHD code, MACH2, has been successfully used in extremely complex simulations of plasma flow switches, where complex geometries and both self-induced and applied magnetic field effects must be included (Turchi). In addition, it is **extremely important that a standard set of geometries** and operating conditions be chosen for code development which will permit valid comparisons to be made between the codes (LaPointe, Myers). **The need to match simulation with experiment led to a loud call for improved in-chamber diagnostics** (Roderick, Tilley, Mayo, LaPointe).

Otherwise, there was some disagreement in the flow committee about what the immediate emphases should be. Two "camps" could be discerned. The first advocated a primary emphasis on establishing the effects of microinstabilities, including ionization and transport phenomena. The second advocated a primary emphasis on studies of acceleration mechanisms (principally in applied-field thrusters), the effects of magnetic field and electrode geometry, plasma/field separation, etc., followed by work on anomalous transport phenomena. It is likely, however, that successful modeling will involve the simultaneous study of both of these arenas, as they are strongly coupled (Turchi, Hooper). **It is critical that information flow freely and frequently** among various groups to ensure rapid progress. The following summarizes the two views.

Microinstability effects

A large part of the discrepancy between predicted and measured terminal voltage is likely the result of anomalous resistivity (Choueiri). We need to establish operating conditions where instabilities affect thruster performance significantly (Tilley, Choueiri). This can be done by using newly developed anomalous resistivity equations to properly evaluate the impact in MHD codes. This work must be expanded to solve for the electron distribution function which can be coupled to a collisional radiative model for ionization (Choueiri). Once these numerical techniques have been developed they can be coupled to MHD codes for thruster optimization.

On the experimental side, Langmuir probe techniques should be used to establish the spatial distributions of the various instability modes and to directly measure the electron distribution function (Tilley, Choueiri). In addition, measurements of plasma resistivity, like those of Lovberg and Gallimore, would greatly assist in verification of non-linear microinstability models (Tilley).

An unexplored avenue to mitigating the instability is **active wave damping.** This should be attempted and may provide a way to independently control the effects of instabilities without forced modifications of geometry and operating condition (Choueiri). However, the **increased complexity of the associated power supplies** runs counter to a principal advantage of MPD thrusters – that of their simplicity (Turchi).

Issues to be resolved -

Effect of propellant species, ionization energy, mass, etc. (Choueiri, Turchi, Myers),
Influence of applied field on microturbulence (Choueiri, Myers).
Lack of particle simulations of MPD thruster plasmas (Choueiri, Turchi).
Difficulty of model/experiment comparisons until electrode boundaries are included in models (Myers).

There are clearly several ways to address these issues, including use of models and experimental measurements. Specifically, the Princeton MHD model should be used to evaluate the effect of propellant species on microinstabilities, and power spectra and wavelength measurements should be made throughout the chamber of an MPD thruster to establish the spatial dependence of the phenomena (Tilley).

Classical Approach:

The emphasis in this group was on establishing the parametric dependence of acceleration mechanisms, performance, and plasma properties on electrode and magnetic field geometry. Plasma/magnetic field detachment was also raised as a principal concern for applied-field thrusters (Mayo).

In general, the consensus was that a hierarchy of models needs to be worked on (Turchi, Choueiri, LaPointe):

1. continuum 2-D axisymmetric geometry, single temperature, with an ideal gas law
    a. include applied magnetic fields
2. Two temperature continuum with equilibrium ionization/dissociation
3. include non-LTE ionization/dissociation, but only classical transport
4. introduce anomalous transport and kinetics
5. add electrode models

There are currently several groups with models past part (1), though only Ohio State includes applied-fields. With simplified geometries, including insulators at the exit plane, MIT and Princeton have advanced to stage (3), though there are some differences in the approaches, including neglect of viscosity in the Princeton model. The LeRC and OSU models are the only ones which include a full plume expansion and the cathode tip region, both of which have been found to result in some numerical problems (LaPointe). Princeton and OSU are the only groups now including anomalous resistivity, and Princeton has developed an improved model for the anomalous resistivity. There is a more complete discussion of model status in the Modelling Committee report.

Experimental

The combined overall performance and electrode loss measurements indicate that the efficiency with which plasma power is converted to thrust power is generally not high (Myers), though it exceeds 60% in some cases. This clearly dictates the need for continued direct performance measurements, and the establishment of good velocity and ionization state measurement techniques. It is extremely important that diagnostics be developed to accurately establish the scaling of flow losses, so that we can decouple them from electrode losses.

Several other points were raised in the context of better isolating the flow phenomena from wall effects. These include the need to:

- Make the measurements using a thruster geometry which everybody can model (see the Modeling Committee report).
- Measure anode and cathode fall voltages directly to isolate plasma voltage drop. This should take precedence over more demanding measurements of streamline shape, Te and Ne distributions, etc. (Martinez-Sanchez).
- Obtain maps of plasma properties in the chamber and plume for thruster geometries which are being modeled (LaPointe).
- Directly measure the ion temperature and velocity (Tilley).
- External heating of the cathode to eliminate spot-mode emission as a variable. This may have a substantial effect on the cathode fall voltage (Martinez-Sanchez, Myers).
- Increase the precision of current density maps. This is especially needed near the anode surface.

Specific techniques for these measurements are discussed in the Diagnostics Committee report.

Lower priority issues

Plasma radiation, divergence, and profile losses were felt to be minor issues by most, though the decrease in flow efficiency with increasing thruster size reported for applied field thrusters has yet to be explained and they may play a role. Additionally, the way in which "lossy" plasma/magnetic field detachment manifests itself is unclear, and may result in increased divergence losses.

III. D. Modeling Committee

Charmain: Mike LaPointe

Committee input was provided by E. Choueiri, R. Gerwin, K. Goodfellow, M. Martinez-Sanchez, R. Myers, E. Niewood, N. Roderick, E. Sheppard, and P. Turchi.

General Summary

The MPD thruster modeling committee was formed to review the status of current MPD thruster models and to propose directions for the development of more advanced simulations. An overview of current MPD thruster modeling efforts is presented below, followed by a prioritized list of the key physics issues which must be addressed as the modeling efforts evolve. In general, the committee agreed that the basic acceleration processes (electrothermal and electromagnetic) are sufficiently well understood for self-field MPD thrusters, although they are not well understood for applied-field thrusters. There was **a strong consensus that electrode models capable of predicting fall voltages and electrode power deposition must be developed** and incorporated into the existing flow models to accurately predict MPD thruster performance. There was **unanimous agreement on the need to compare the numerical models with one another and with experimental results, using a set of standard thruster geometries and operating conditions. A matrix of geometries was established and is included in this report.** Committee members were generally not receptive to the idea of establishing a common code at this time. The preferred method was to seek a consensus on the relevant physics that each code should incorporate, and to continually cross-check the models as they are developed and refined. In addition, there may be a need to develop particle simulations to model thruster regions where non-continuum effects might be important, such as the plume region and plasma/electrode interfaces. Particle simulations would also provide insight into the evolution and saturation mechanisms of observed plasma microinstabilities, propellant ionization processes, and a host of additional effects which would complement the continuum flow models.

Review of MPD Thruster Simulations

A brief review of the status of MPD thruster models was deemed necessary to provide a benchmark against which progress can be reported. This review is limited to work by members of the modeling committee, and does not represent the numerous modeling efforts, both national and international, which are devoted to understanding the complex dynamics of the MPD thruster. An overview of the various modeling activities can be found in the review paper by Myers et al. [1].

Choueiri et al. [2] have developed a detailed analytical model describing the occurrence of current-driven plasma microinstabilities in MPD thrusters. The model predicts that the generalized lower hybrid drift instability plays a dominant role in turbulent dissipation and the concurrent degradation of plasma thruster efficiency. Analytic forms for the associated anomalous transport coefficients were obtained, and incorporated into a numerical flow model developed by Caldo et al. [3]. The numerical model is a fully two-dimensional (2D), two-fluid, time-dependent simulation which employs a modified finite-difference MacCormack scheme to solve the two-fluid conservation equations, and a modified Jacobi method to solve the electromagnetic equations for a self-field MPD thruster. A real gas equation of state is used, and Hall effects are included. The model is being modified to incorporate a nonequilibrium ionization model developed by Randolph

[4]. Plume regions are not modeled at present, and viscous effects are neglected. Both classical and anomalous transport coefficients can be modeled to determine the effects of anomalous transport on thruster performance. Preliminary results [3] indicate enhanced turbulent dissipation near the cathode root and tip, and along the anode tip, leading to decreased thruster efficiencies.

Gerwin et al. [5] have modeled the flow of ideal MHD plasmas through magnetic nozzles for a wide range of plasma densities and temperatures, and provide detailed discussions of issues related to ideal plasma acceleration and detachment from magnetic field lines. Recent modeling efforts have focused on adapting the Los Alamos National Laboratory FLX code to simulate MPD thruster plasma flows. The FLX code is a single-fluid, time-dependent Eulerian MHD code, available in 2D and 3D versions, incorporating resistivity, viscosity, and Hall effects. The simulation utilizes an unconditionally stable, semi-implicit time advance method, and has been extensively used by the LANL plasma theory group for a variety of applications. The FLX simulations are part of an integrated experimental and theoretical effort undertaken at LANL to address the performance and scaling properties of megawatt-class magnetohydrodynamic thrusters.

A truly predictive MPD thruster model must incorporate electrode effects, and Goodfellow et al. [6] are developing a cathode model which may be used in conjunction with MPD thruster flow models. The model consists of a thermal model of the cathode and a near-cathode plasma model, which connects the properties of the main plasma flow with the cathode. A preliminary 1-D, self-field version of the cathode model has been completed, and good agreement has been obtained between predicted cathode temperature distributions and experimental measurements performed at the University of Stuttgart [6]. Work is now progressing on a more extensive, computationally faster model, and efforts are underway to develop a similar model to describe anode processes.

Martinez-Sanchez [7] has analyzed self-field accelerated flows in MPD thrusters using a quasi-1D approximation, assuming zero axial current and neglecting Hall effects. Analytic calculations of thrust vs. current for the Princeton University half-scale flared anode thruster agreed very well with experimental data, and a variety of features relevant to self-field acceleration processes were identified. Niewood and Martinez-Sanchez [8] have developed a numerical 2D, axisymmetric flow model which incorporates separate time dependent equations for ion and neutral density, ion and neutral momentum, and electron and heavy species temperatures for self-field MPD thrusters. The code includes separate ion and neutral viscosity models, electron and heavy species heat conduction, ion-neutral, ion-electron, and electron-neutral elastic collisions, and the Hall effect. The model has not yet been used to simulate complex geometries or the plume region. The code is fully debugged, and simulations have been performed for a geometry with an anode radius of 0.072 m, a cathode radius of 0.052 m, and a mass flow rate of 4 g/s for discharge currents below 30 kA. The model incorporates classical plasma transport coefficients. A previous one-dimensional version of the code was used to investigate the presence of electrothermal instabilities and to evaluate the effects of anomalous transport induced by modified two-stream instabilities [9]. The present two-dimensional model equations include terms for rate controlled ionization and recombination using a nonequilibrium model developed by Sheppard [10]. In related work, Sheppard [11] is using a 1D flow model to analyze the initiation of propellant ionization ("ignition") at the inlet region of self-field MPD thrusters. Both back diffusion of ion/electron pairs and photoexcitation/photoionization are considered as candidate mechanisms for ignition. The multi-level plasma model employs a two-temperature, two-speed (electron/ion slip speed and a single neutral slip speed) approximation. Preliminary models incorporating constant speed approximations are completed, and the full accelerating model is currently under development.

LaPointe [12] has developed a steady state self-field MPD thruster model based on the

2-1/2D, two-temperature, single-fluid MHD equations. The simulation incorporates classical transport coefficients and Hall effects, but currently assumes full propellant ionization. The coupled equations are solved using a generalized Newton-Raphson iteration scheme on a fixed computational grid (50 radial x 100 axial grid points). The plume region is included in the simulation. Good agreement has been obtained between predicted and experimental thrust values for straight cylindrical and flared anode geometries. As with other flow models, the magnitude of the discharge voltage is underpredicted, but voltage-current trends are reproduced. Electrode models must be incorporated into the flow simulations to obtain accurate predictions of discharge voltages and thruster efficiencies. Results of the MHD simulation have been used to develop a criteria for stable self-field thruster operation over a limited range of cylindrical thruster geometries and operating conditions. Efforts are underway to include nonequilibrium ionization and dissociation processes in the model. An applied-field version of the code is under development.

An existing MHD code with the capability to simulate both self-field and applied magnetic field effects is being adapted by Turchi, Roderick, and Mikellides for the study of MPD thrusters [13]. The MACH2 code was initially developed to support experimental efforts in the Air Force SHIVA radiation source program, and has since been used with great success on a wide variety of plasma problems. MACH2 is a 2-1/2D, single fluid, multi-temperature, nonideal radiation MHD code which can be run for either planar or cylindrical geometries. The single fluid MHD equations include the continuity equation, the momentum equation in three component vector form, a set of energy equations (depending on the choice of single or multi-temperature), and the magnetic field transport equation. Hall effects, plasma radiation effects (including an option for flux-limited nonequilibrium radiation diffusion), and plume expansion regions are included. MACH2 allows for multiple materials and includes models to handle material strength, if required. The equation of state and transport coefficients, electron and ion thermal conductivity, electrical resistivity, opacities, etc., can be either analytic or tabular, with tabular functions provided by the SESAME equation of state library maintained by LANL. MACH2 also provides several microturbulence models for collision frequency calculations, for use in determining anomalous transport coefficients. The MACH2 code is a time dependent, finite volume spatial differenced ALE (Arbitrary Lagrangian-Eulerian) code. The Lagrangian hydrodynamic time advance, and the thermal, radiation, and magnetic field diffusion are done with implicit time differencing. Implicit solutions are carried out with an SOR (Successive Over Relaxation) algorithm, supplemented with a multigrid algorithm to accelerate convergence of the diffusion solvers. Recent efforts have been devoted to incorporate time-dependent applied magnetic field boundary conditions into the model, and preliminary results have been obtained for relevant MPD thruster geometries. Comparisons between model predictions and the extensive applied-field MPD thruster data base provided by Myers [14] are underway.

Abbreviated List of Modeling Priorities

There was general agreement between the committee members on the overall approach required for successful MPD thruster model development: flow processes, electrode models, nonequilibrium ionization models, and instability models, followed by systems studies to evaluate thruster performance as a function of geometry, operating conditions, propellant species, etc. Opinions varied on the order and importance of the fundamental physics contained in each of these areas, but the general pattern which emerged is outlined below. It is expected that this list will be subject to review and revision as the models continue to evolve.

(1). Plasma Flow Models
  - electrothermal and electromagnetic processes

- self-field and/or applied-field models

  Model evolution:
  - (a) 2-D continuum flow, axisymmetric geometries, ideal gas, classical transport coefficients, Hall effect
  - (b) incorporate two temperatures (electron and heavy species), equilibrium ionization and dissociation
  - (c) incorporate electrode models
  - (d) include nonequilibrium ionization/dissociation models, retain classical transport coefficients
  - (e) introduce microturbulence, anomalous transport
  - (f) other non-local effects (chemical species, etc..)
  - (g) develop and integrate non-continuum models

(2). Electrode Models
- derive fundamental physical models
- expand to include variations in geometry, mass flow, etc.
- incorporate as boundary conditions in flow models
  - (a) anode models
    - voltage drops, power deposition
  - (b) cathode models
    - voltage drop for thermionic cathodes
    - heating rates, erosion estimates
  - (c) develop and integrate non-continuum models

(3). Nonequilibrium Ionization Models
- establish effects of collisions, radiation, instabilities

(4). Instabilities
- continue developing both numerical and analytical models
  - (a) onset mechanisms
  - (b) microturbulence, anomalous transport effects
  - (c) develop and integrate non-continuum models

(5). Systems Studies
- variations in thruster geometry
- injector placement, injector physics
- propellant species effects
- heat transfer in materials
- facility effects

The successful development of any MPD thruster model requires the frequent validation of such codes with other models and with experimental results. Though not specifically listed, fostering and maintaining a dialogue between members of the MPD thruster modeling community and our experimental colleagues is recognized as a continuing priority.

Standard Thruster Geometries and Operating Conditions for Code Comparisons

As noted previously, there was unanimous agreement between the committee members on the need to compare the existing numerical models with one another and with experimental results, using a set of standard thruster geometries and operating conditions. Members felt that both

cylindrical and flared geometries should be modeled over a wide range of operating conditions in order to better evaluate the range of validity for each model. Balancing this was the need to be as unobtrusive as possible with existing research schedules. After discussion, the following set of geometries and operating conditions were agreed upon:

Self-Field Thrusters:

(1). Princeton University extended anode thruster (Fig.1) [15]
Ra = 3.2 cm, Rc = 0.95 cm, La = 21.6 cm, Lc = 20.0 cm
Argon propellant, 50:50 backplate injection
(a) $\dot{m}$ = 6 g/s, J = 10,000 A ($J^2/\dot{m}$ = 16.7 kA -s/g)
(b) $\dot{m}$ = 6 g/s, J = 20,000 A ($J^2/\dot{m}$ = 66.7 kA -s/g)

(2). Princeton U. half-scale flared anode thruster (Fig. 2) [16]
Argon propellant, 50:50 backplate injection
(a) $\dot{m}$ = 3 g/s, J = 7,900 A ($J^2/\dot{m}$ = 20.8 kA -s/g)
(b) $\dot{m}$ = 3 g/s, J = 17,800 A ($J^2/\dot{m}$ = 105.6 kA -s/g)

This set of self-field geometries and operating conditions provides for both a simple cylindrical geometry (set 1) and a fairly simple flared geometry (set 2), with both geometries evaluated over a range of specific impulse values. Further details of the geometries, operating conditions, and experimental measurements may be found in the referenced papers.

Applied Field Thrusters:

(1). NASA LeRC 2" diameter cylindrical thruster [17]
Ra = 2.5 cm, Rc = 0.64 cm, La = 7.6 cm, Lc = 7.6 cm
(a) $\dot{m}$ = 0.025 g/s (Ar), J = 750 A, B = 0.05 T (cathode tip)
(b) $\dot{m}$ = 0.025 g/s (H_2), J = 750 A, B = 0.05 T (cathode tip)

(2). NASA LeRC 4" diameter cylindrical thruster [17]
Ra = 5.1 cm, Rc = 1.27 cm, La = 7.6 cm, Lc = 7.6 cm
(a) $\dot{m}$ = 0.1 g/s (Ar), J = 1,000 A, B = 0.05 T (cathode tip)
(b) $\dot{m}$ = 0.1 g/s (Ar), J = 1,000 A, B = 0.10 T (cathode tip)

The first set of applied-field simulations allows a comparison using different propellants under similar operating conditions, while the second set allows a prediction of the effect of changing the magnetic field strength for otherwise similar discharge parameters. The magnetic field value is given at the cathode tip in each case. For those interested in performing the applied-field simulations, a simple numerical routine which predicts the field components for the solenoid magnets used in the NASA LeRC tests is available (contact Myers or LaPointe).

Results of the modeling efforts will be presented at the 3rd MPD Thruster Workshop at LeRC, at a date to be determined.

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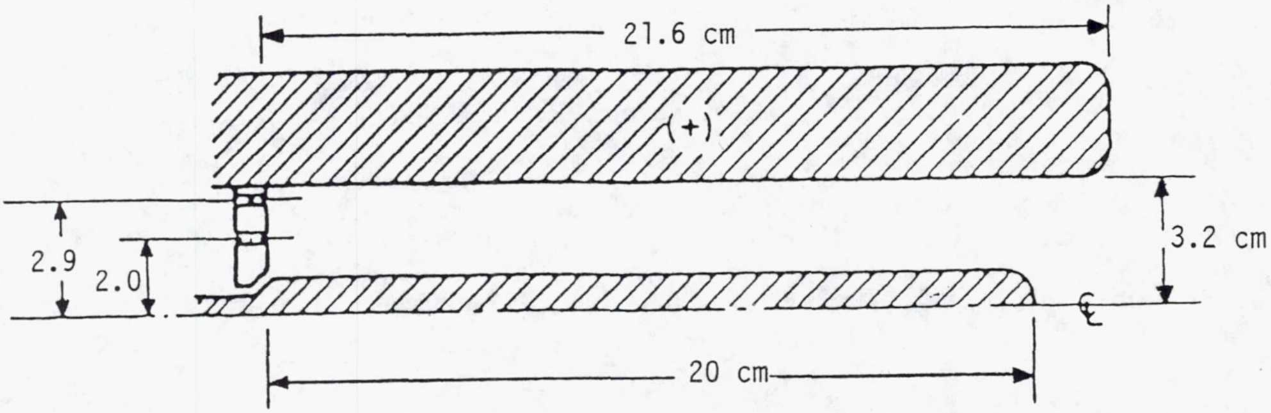

Fig. 1. Princeton University Extended Anode Thruster [15]

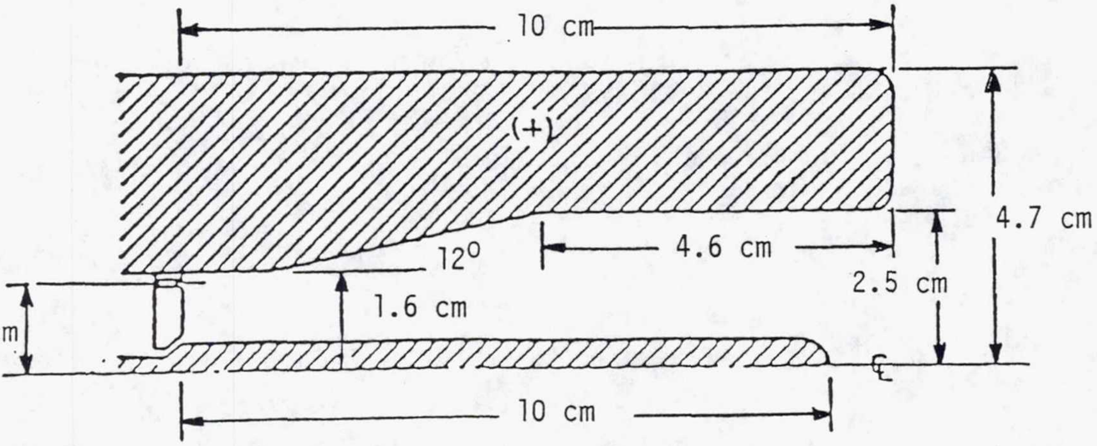

Fig. 2. Princeton University Half-Scale Flared Anode Thruster [16]

III. E. Diagnostics Committee

Chairman: Dennis Tilley

Members/Contributors:

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There was concensus among diagnostics committee members that **the diagnostics committee should act as a support group for the other committees** (anode, cathode, flow, and modeling). In particular, the diagnostics committee will identify experimental approaches for the measurement of those quantities identified by the other committees. In this report the list of important quantities to be measured (measurement objectives) and approaches for their measurement are listed in a table format.

The list of measurement objectives was split into the five tables listed below:

Table 1: Performance Measurements
Table 2: Cathode Phenomenon
Table 3: Anode Phenomenon
Table 4: Microturbulence Phenomenon
Table 5: Flow Phenomenon

For each measurement objective, various diagnostic techniques are tabulated. The list of techniques is not meant to be exhaustive, but is limited to those used or proposed for use in MPD thrusters. In addition, for each measurement technique, **the following are tabulated: the advantages and disadvantages of the technique, measurement issues, a point of contact, and references. Addresses and phone numbers of the contact points are given below**. The advantages and disadvantages of the technique are listed to allow for comparison of different techniques used to measure a particular quantity (as applied to the MPD thruster). Measurement issues include matters that the experimenter must consider when applying the technique to the MPD thruster, although issues that have yet to be satisfactorily resolved are also listed. In general, those issues which have yet to be resolved loom over all experimental results obtained using the diagnostic technique. **The point of contact is a person whom has previously applied the diagnostic technique to a MPD thruster**. Although there are many experts in Japan, Europe, and the former Soviet Union who have applied the diagnostic techniques listed below to the MPD thruster, the list is limited only to those researchers in the United States. The references provide information on past experience in applying a diagnostic technique to the unique MPD thruster environment. References 1 - 5 are general plasma diagnostics references. They are not included in the tables. Finally, many boxes in the tables are blank due to lack of information. This is mainly due to the fact that the diagnostic has yet to be applied to the MPD thruster.

It is hoped that these tables will serve as a guide to experimentalists by identifying those quantities of interest to modelers, by accelerating the identification of new diagnostics for use in the MPD thruster, and thus lead to further the improvement of diagnostic techniques commonly used in the MPD thruster.

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Table 1: Performance Measurements

Measurement Objective	Measurement Technique	Advantages/Disadvant.	Measurement Issues	For More Information
Thrust (Steady State)	*Thrust Stand	A: Measures thrust directly	*Magnetic tares, thermal tares, vacuum tank pressure, tank deformation during pumpdown, calibration	Tom Haag, Roger Myers References: 6
Thrust (Quasi-Steady)	*Impulse Thrust Stand w/Accelerometer	A: Fast time response D: Sensitive to thruster/thrust stand structural resonances	*Magnetic tares, vacuum tank pressure, tank deformation during pumpdown, calibration, repeatability, thruster/thrust stand structural resonances	Arnold Kelly References: 7, 8
	*Impulse Thrust Stand w/position transducer	A: Straight forward to implement D: Measures total impulse only	*Magnetic tares, vacuum tank pressure, tank deformation during pumpdown, calibration, repeatability	Rod Burton Edgar Choueiri Arnold Kelly References: 9, 10, 11
Mass Flow Rate (SS)	*Flow Meter/Controller	A: Straight forward implementation	*Must be calibrated in situ	Roger Myers
	*Calibrated Orifice	A: Straight forward implementation	*Must be calibrated in situ	Roger Myers
Mass Flow Rate (QS)	*Calibrated Orifice	A: Straight forward implementation	*Must be calibrated in situ	Arnold Kelly References: 10

Table 2: Cathode Phenomena

Measurement Objective	Measurement Technique	Advantages/Disadvant.	Measurement Issues	For More Information
Erosion Rates	*SLA Technique	A: Temporally and spatially resolved, high sensitivity, non-intrusive D: Complicated, uses radioactive material	*Redeposition of eroded tracer material, signal attenuation in thruster body, unequal evap. rates of tracer and cathode material, diffusion of tracer in cathode material, radiation damage to the cathode during bombardment, uniformity of activated material, tracer depth profile curves	Jay Polk References: 12, 13, 14
	*Precision Weight Measurements	A: Straight forward implementation D: Temporally and spatially integrated, requires engine disassembly	*Can be biased by deposition of material or cathode damage during disassembly; balance sensitivity, range, and stability *Both techniques must be supplemented with detailed profilometry, photography, and SEM work	Roger Myers, Jay Polk References: 14, 15
Surface Temperature	*Optical Pyrometry	A: Non-intrusive D: Expensive	*Must be calibrated in situ, uncertainty in emissivity, angle of view, optics contamination, temperature resolution, stray radiation from plasma and reflections, noise and drift in the detector; transmittance of windows, optics, and filters	Roger Myers, Maris Mantenieks, Jay Polk References: 14, 15
Cathode Work Function				

Table 2: Cathode Phenomena cont.

Measurement Objective	Measurement Technique	Advantages/Disadvant.	Measurement Issues	For More Information
Plasma Potential Near The Cathode, Cathode Fall Voltage	*Langmuir Probe	*See Anode Phenomenon table	*See Anode Phenomenon table	References: 17 See Anode Phenomenon table
	*Emissive Probe	*See Anode Phenomenon table	*See Anode Phenomenon table	Roger Myers Never applied to the cathode region
	*Emission Spectroscopy of Forbidden Transitions[16]			Never applied to the MPD thruster
Current Density/Magnetic Field	*Induction Probe	*See Anode Phenomenon table	*See Anode Phenomenon table	References: 17 See Anode Phenomenon table
	*Hall Effect Probe	*See Anode Phenomenon table	*See Anode Phenomenon table	Never applied to the cathode region, see Anode Phenomenon table
Near-Cathode Plasma Properties: T_e, N_e	*Langmuir Probe	*See Anode Phenomenon table	*See Anode Phenomenon table	References: 17 See Anode Phenomenon table
	*Relative Line intensities	*See Anode Phenomenon table	*See Anode Phenomenon table	Never applied to the cathode region, see Anode Phenomenon table
	*Stark Broadening	*See Anode Phenomenon table	*See Anode Phenomenon table	Never applied to the cathode region, see Anode Phenomenon table
	*Microwave Interferometry	*See Anode Phenomenon table	*See Anode Phenomenon table	Never applied to the cathode region, see Anode Phenomenon table

Table 3: Anode Phenomena

Measurement Objective	Measurement Technique	Advantages/Disadvant.	Measurement Issues	For More Information
Heat Flux To The Anode	*Calorimetry (SS)	A: Straight forward implementation, non-intrusive D: Non-local measurement, difficult for radiation-cooled anodes, slow time response	*Calibration	Alec Gallimore Roger Myers References: 18, 19
	*Thermocouples (QS)	A: Non-intrusive	*Accurate thermal model is required, thermocouples must be in good contact with wall	Alec Gallimore References: 20, 21
	*Pyrometry (QS)	A: Good temporal and spatial resolution, non-intrusive D: Thruster geometry can obscure view	*Modelling is required, calibration, sensitive to the uncertainty in emissivity	Jay Scheuer References: 22
Plasma Potential Near The Anode, Anode Fall Voltage	*Langmuir Probe (Single, Button, Triple)	A: Straight forward implementation, inexpensive D: Intrusive	*Probe perturbations (e.g. shocks, shadowing of the anode, ablation of the probe support), contamination of the probe surface, the effect of the magnetic field on electron current collection	Kevin Diamant, Alec Gallimore, Roger Myers, Dennis Tilley References: 19-21, 23-25
	*Emissive Probe	A: Straight forward implementation, inexpensive D: Intrusive	*Probe perturbations	Roger Myers References: 26 Never applied to the anode region
	*Emission Spectroscopy of Forbidden Transitions[16]			Never applied to the MPD thruster

Table 3: Anode Phenomena cont.

Measurement Objective	Measurement Technique	Advantages/Disadvant.	Measurement Issues	For More Information
Current Density/ Magnetic Field	*Induction Probe	A: Inexpensive, straight forward implementation D: Applicable only to QS thrusters, intrusive	*Probe perturbations (e.g. plasma cooling, probe ablation, current obstruction), spatial resolution, symmetry of the discharge, calibration	Alec Gallimore Andy Hoskins, References: 20, 21, 23, 24
	*Hall Effect Probe	A: Applicable to SS thrusters, straight forward implementation D: Active cooling of the probe may be required, sensitive to the noise associated with QS thrusters, intrusive	*See those listed for the induction probe	Roger Myers Dennis Tilley References: 27-29 Never applied to the anode region
	*Segmented Anode	A: Straight forward to implement D: limited resolution		Alec Gallimore References: 30-32
Near Anode Plasma Properties: T_e, N_e	*Langmuir Probe (Single,Double,Triple,Button)	A: inexpensive, straight forward to implement D: intrusive	*See Anode Fall Voltage Box, plus: accuracy depends on the ion and electron current model	Kevin Diamant, Alec Gallimore, Roger Myers, Dennis Tilley References: 19-21, 23-25
	*Relative Line intensities	A: non-intrusive D: line-of-sight integrated	*Plasma model required, line profile deconvolution, symmetry of the discharge, uncertainties in constants	Roger Myers, Peter Turchi References: 33-35 Never applied to the anode region
	*Stark Broadening	A: Non-intrusive D: A small percentage of hydrogen may significantly alter thruster operation	*Deconvolution of Stark broadening from other sources of broadening, Abel inversion technique, symmetry of the discharge	Roger Myers Peter Turchi References: 36-38 Never applied to the anode region
	*Microwave Interferometry			References: 39 Never applied to the anode region

Table 4: Microturbulence Phenomena

Measurement Objective	Measurement Technique	Advantages/Disadvant.	Measurement Issues	For More Information
Electron Dist. Function	*Single Langmuir Probe	A: Straight forward to implement, inexpensive D: intrusive	*Perturbations	Never applied to the MPD thruster
Plasma Conductivity	*Conductivity Probe[40]			Never applied to the MPD thruster
	*Inferred From Other Measurements	D: Indirect, many quantities are required to infer σ, large uncertainty	*The ion flow velocity is the most difficult measurement required	Alec Gallimore References: 24, 41
Plasma Property Fluctuations	*Langmuir Probe	A: Straight forward implementation, inexpensive D: The frequency response of the Langmuir probe is on the order of the ion plasma frequency, the minimum observable wavelength is equal to the closest distance between two electrodes	*Calibration, interpretation is often difficult	Edgar Choueiri Dennis Tilley References: 29, 42
	Microwave Scattering[43]			Never applied to the MPD thruster
	Laser Scattering[43]			Never applied to the MPD thruster

Table 5: Flow Phenomena

Measurement Objective	Measurement Technique	Advantages/Disadvant.	Measurement Issues	For More Information
Ion Flow Velocity	*Doppler Shift/ Emission Spectroscopy	A: Non-invasive D: Line-of-sight integrated	*Axial averaged, Doppler shift is often too small, Abel inversion for radial flow field requires special consideration[38]	Roger Myers Peter Turchi References: 38, 44
	*Doppler Shift/LIF	A: Good spatial resolution, non-intrusive D: Expensive		Never applied to the MPD thruster
	*Charge Exchange Neutral Spectroscopy	A: Non-intrusive D: Limited spatial resolution		Robert Mayo References: 45, 46
	*Ion Energy/Mass Spectroscopy			Robert Mayo Never applied to the MPD thruster
	*Langmuir Probes:			
	*Cross-Probe Technique	A: Straight forward, inexpensive D: Intrusive	*The accuracy depends on the ion current model, perturbations	Rod Burton, Dennis Tilley References: 47, 48
	*Injected Wave Technique	A: Straight forward, inexpensive D: complicated, intrusive	*Careful signal analysis is required, perturbations	Edgar Choueiri, Kevin Diamant References: 49
	*Time of Flight Technique	A: Straight forward, inexpensive D: Intrusive	*The group velocity of the disturbance must be much smaller than the flow velocity, perturbations	Edgar Choueiri, Kevin Diamant References: 49, 50
	*Retarding Potential Analyzer	D: Applicable to the far-field plume only		Never applied to the MPD thruster

Table 5: Flow Phenomena cont.

Measurement Objective	Measurement Technique	Advantages/Disadvant.	Measurement Issues	For More Information
Ion Temperature	Doppler Broadening	A: Non-invasive D: Line-of-sight integrated	*Deconvoluting other broadening effects (e.g. Stark, pressure, turbulence), Doppler broadening may be too small, directed flow effects	Roger Myers Peter Turchi References: 37, 44
	*Retarding Potential Analyzer	D: Applicable to the far-field plume only		Never applied to the MPD thruster
	*Charge Exchange Neutral Spectroscopy	*See Ion Flow Velocity section	*See Ion Flow Velocity section	Robert Mayo References: 45, 46
	*Ion Energy/Mass Spectroscopy			Robert Mayo Never applied to the MPD thruster
Ionization Fraction	*Relative Line Intensities (Emission Spectroscopy)	A: Non-intrusive, direct measurement D: Line-of-sight integrated	*Critically dependent on the model and the T_e measurement, Abel inversion is required, symmetry of the discharge	Tom Randolph Reference: 51
Neutral Density	*Absolute emission spectroscopy	A: Non-intrusive D: Transitions are in the UV	*Modelling is required, critically dependent on the integral over wavelength to get the intensity, calibration	Never applied to the MPD thruster
	*Charge Exchange Neutral Spectroscopy	*See Ion Flow Velocity section	*See Ion Flow Velocity section	Robert Mayo Never applied to the MPD thruster
	*Absorption Spectroscopy			Never applied to the MPD thruster
Radiation Losses	*Bolometry	A: Straight forward, inexpensive D: Sensitive to particles as well as radiation	*Calibration, sensitive to particles as well as radiation	Glen Wurden References: 22, 52

IV. Summary of Presentations, Discussions, and Program Directions

Transportation and Platforms Program Perspectives

Dr. Gary Bennett

The NASA OAST mission is to provide for future civil space missions and provide a base of research and technology capabilities to serve all national space goals. This means that **there should be a clear connection between technology development efforts and potential applications**. The NASA Flight programs Forecast includes:

5 year: Focus on Space Station Freedom (SSF) and initial SEI Architecture, evolving GEO comsats;
10 year: SSF evolution, initial SEI/lunar outpost start;
20 year: SSF - Mars evolution, Mars SEI architecture chosen, large GEO comsats

These mission forecasts imply a variety of technology requirements. For instance, the Office of Space Science and Applications (OSSA) **has placed 50-100 kW nuclear electric ion propulsion technology into its far-term high priority list**. No other office has done this for NEP. It is clear that **we must find advocates in the mission organizations if we are to maintain support for high power electric propulsion**. This can be done in the context of transportation technology or space platforms technology within OAST. It is also important to consider the space technology budget planning cycle when advocating programs. Details are provided in Appendix C.1.

Low Thrust Propulsion Program Objectives

Dr. Frank Curran

The Base Research and Technology program has been perceived as having a "sandbox" mentality in which various programs are continued for many years without rigorous review and assessment of their degree of success. The new organization at NASA HQ is attempting to address this issue by ensuring that all ongoing efforts have **an established, logical path connecting the research with its eventual application. We must show measurable progress toward realistic goals**. While this does not mean that we must produce an operational system tomorrow, we must establish a logical path by which we can quickly establish the viability of the concept on a timely basis. In addition, the scarcity of resources dictates that **the community must work together toward the development of high performance MPD thruster technology**.

"Near Term" NEP Missions and Systems

Mr. James Gilland, Sverdrup Technology, Nuclear Propulsion Office, NASA LeRC

NASA's Office of Space Science and Applications has identified NEP as first priority on its far term technology needs list to OAST. OSSA is interested in 50 - 100 kWe systems with Isp > 5000 seconds and efficiencies > 50%. The system specific mass must be less than 50 kg/kW. "Near term" means using SP-100 reactor with 7 year life and thermoelectric power conversion, with follow-on development of low temperature Brayton and Rankine cycle conversion technology. Possibility of using pulsed thrusters has not been adequately assessed from a system level given the recent advances in pulsed power technology.

NEP demonstration missions are restricted to power levels of less than 100 kWe, and include LEO-GEO transfer missions, Lunar science missions, Mars precursor missions, and interplanetary robotic missions. The presentation focused on **the LEO-GEO and interplanetary robotic missions, though most of the latter require specific impulses > 7000 seconds which may be a problem for MPD thrusters.** It is clear that near term missions push the technology toward higher efficiency and specific impulse and lower power level. Mission analyses were presented for Mars cargo missions for a two system specific masses and a wide range of thruster performance characteristics. While the assumed power level was 1500 kWe and the payload masses were over 50 metric tons, results for nearer term systems can estimated by scaling power and payload mass linearly. In other words, a 5 ton payload would require 150 kWe for the same Isp, efficiency, and trip time. The results show that **for Mars cargo missions optimal specific impulses are between 2000 and 6000 seconds.**

Jet Propulsion Laboratory

Mr. Jay Polk

The presentation focussed on engine lifetime assessment, lithium MPD thruster development and the results of some radiation cooled applied-field MPD thruster testing. There is currently considerable uncertainty in the required engine life, failure modes, and what the statistical distributions of the life-limiting parameters are. It is apparent that engine lifetime is inherently probabalistic, and ultimately this must be accounted for in all analyses. JPL is currently pursuing the first step in this process, that of establishing a theoretical model of cathode phenomena. This will eventually be used to predict cathode mass loss. Erosion models must include melting, chemical attack, evaporation, and sputtering as potential causes for cathode degradation. Comparison of the erosion model results with experimental data from Stuttgart indicates the need to more accurately account for the transport of cathode material in the boundary layer. A thermal model is currently under development, and has been coupled to a model for the near cathode plasma. Models which will predict the cathode work function are under development. Preliminary results using a constant work function and fall voltage show good agreement with measured temperature distributions from Stuttgart.

JPL has also invested in a cathode test facility which will be used to obtain material and plasma property measurements under carefully controlled discharge conditions. In addition, the facility will be used to conduct extended endurance tests.

Anode studies are focussed on the engineering tasks of modeling heat transfer in anodes and exploring methods of heat rejection. Currently developing an electrostatic sheath model and are examining the effect of anode work function on heat transfer rates. The primary goal of the modeling effort is to provide appropriate boundary conditions for the thermal models. No work is currently planned to study magnetic field effects, and there is considerable interest in collaborating with others who are.

Lithium MPD thrusters are also being studied at JPL. A lithium propellant feed system has been designed and is currently under construction. The thruster test facility design is nearing completion, and construction is expected to be complete in FY93. Initial testing will focus on 100 kWe-class radiation-cooled engines.

Results of testing with ammonia propellant were presented, including a preliminary study of the influence of a diffuser on tank pressure and thrust measurements. The diffuser was found to decrease the tank pressure, though pressure levels were still over 10 millitorr. Thrust measurements were taken on the applied-field magnet and archead independently, and it was found that the applied-field magnet thrust did not vary as a function of thruster power, whereas the archead thrust increased linearly. These phenomena are not currently understood.

Lewis Research Center

Dr. Roger Myers

The in-house LeRC MPD thruster program is currently focused on evaluating steady-state 100 kW class applied-field MPD thrusters using a combined experimental and modeling approach. The large vacuum facilities permit steady-state testing of inert gas and hydrogenic propellants at ambient pressures low enough to preclude any adverse effects on thruster performance or power distribution. Diagnostics currently include direct performance measurements, electrode power loss, plume properties, anode plasma properties, and cathode surface temperature. In addition, a small facility has been built for fundamental electrode physics studies.

In the past year a new 100 kW class MPD thruster test facility was established in LeRC's Tank 5 which is devoted to thermal and flow efficiency optimization and lifetime studies. The facility incorporates helium cryopanels which increase the argon pumping speed by a factor of 4, and will in the near future be used with liquid helium to pump hydrogen.

Performance measurements taken in Tank 6 were used to establish thruster scaling laws for cylindrical applied-field MPD thrusters. A large number of geometries were tested across a broad range of operating conditions and the influence of electrode size, propellant flow rate, applied-field strength, and discharge current were quantified. The data showed that while the anode electrode losses decreased as the thruster size was increased, the plasma losses increased, which resulted in generally similar overall efficiencies for the different thrusters. It is clear that the physics controlling anode power deposition and plasma flow losses must be isolated to permit overall thruster optimization. Studies of the anode power deposition indicate that the anode fall region is magnetized, with fall voltages increasing with both applied-field strength and anode radius and decreasing with increasing propellant flow rate.

The dominance of the anode loss has led to the adoption of several approaches to studying it and mitigating its impact. A thruster was built which permits near surface plasma property measurements. This involves both imbedding probes in the anode wall, flush with the surface, to obtain electron temperature and density measurements, and attaching pressure transducers to holes in the anode. In addition to the thruster studies, a bench-top experiment was established for fundamental studies of anode power deposition. Variables examined in this work include the arc pressure, current density, anode surface magnetic field, and anode work function. Results are similar to those obtained in thruster tests, with the anode power and fall voltage increasing with applied-field strength and decreasing with increasing arc pressure.

Significant progress has been made with the MHD modeling of the MPD thruster plasma. The LeRC code is now two-temperature, and has been used to study geometric scaling in self-field MPD thrusters. It is restricted to fully ionized argon propellant. The code predicts thrust well, but underpredicts discharge voltage due to its neglect of the fall voltages. A series of numerical experiments were performed to examine the effect of electrode length and radius on thruster performance and stability. The highest calculated performance was 1400 s specific impulse at 76% flow efficiency (not including electrode losses). Note this specific impulse is still too low to be of interest for most missions. A quantitative scaling rule for thruster stability was developed. For the cases tested, the predicted stable operating range agreed with experimental observations.

MPD thruster lifetime studies at LeRC are currently focussed on evaluating alternative cathode concepts, extensive thermal mapping of the thrusters, and measurements of the cathode surface temperatures and the internal plasma properties of hollow cathodes. The latter is being done with Ohio State Univ. Several high current hollow cathodes have been tested, and a large number of surface temperature measurements have been obtained with a variety of thrusters over a range of operating conditions. In addition, a design has been completed for an internally heated, low work function pulsed cathode which may eliminate the lifetime limitations of pulsed MPD thrusters.

A lithium test facility has been designed which will permit performance measurements of radiation-cooled, 100 kWe class, applied-field MPD thrusters. Testing should begin in 1993. The facility is large enough to permit studies of plume contamination issues.

In the next year, thruster performance studies focus on increasing the thruster power to 350 kW, studying the effect of anode and applied-field shape on anode power deposition, and evaluating the performance of 20 - 50 kWe lithium MPD thrusters. In addition, the MHD model will be improved by adding ionization effects, applied-magnetic fields, and anomalous transport. The latter will be done using the models proposed by Princeton. Lifetime studies include an extended test at 100 kWe, improvements in the cathode surface temperature diagnostic, and greatly expanding the data base of fundamental cathode surface and plasma property measurements. In addition, a joint program with Princeton will be initiated to evaluate long-life pulsed cathode technology.

Los Alamos National Laboratory

Dr. Richard Gerwin

LANL has tested a large scale cylindrical applied-field plasma thruster at power levels between 10 and 50 MW. Their emphasis has been on examining the scaling implications of the ideal MHD equations to establish regimes where dissipation does not dominate. The experimental work has been devoted to establishing an overall power balance for their plasma thruster. This has included development of an imaging technique for anode power deposition measurements, and development of models for plasma separation from the applied magnetic field. Results indicate that there is an economy of scale associated with the ideal MHD formulation, and that the ratio of the discharge current to the number of injected charges (the electrical effort) is a key parameter. The limits on values of the electrical effort can be used to establish an approach to development of a high efficiency plasma thruster.

In their experimental work, the LANL group has taken advantage of an existing experiment to diagnose the plasma acceleration processes. No attempt was made to optimize the thruster. Results showed that the plasma was accelerated to the magnetosonic velocity, that the magnetic Reynolds number was ~ 1000, and that the electrical effort was approximately 0.5. Remarkable agreement with ideal MHD flow predictions was observed over a wide range of accelerator size and power level. This latter result, which encompasses devices from 2 cm in radius to 24 cm in radius, implies that exhaust velocity scaling may not be very complex. Results of electrode power deposition studies indicate that the magnetic field geometry plays a fundamental role in the establishing the magnitude and sign of the anode fall voltages. A reversal of the fall voltage was observed during the discharge when the magnetic field transitions from directly connecting the anode and cathode to when they connect the cathode to the tank wall. The radiated power measurements indicate that plasma radiation leads to relatively small performance losses (less than

10%).

Future work includes extending the pulse length to 10 milliseconds at 10 MW with mass flow rate control. In addition, the thruster will be completely isolated from the tank, and the measurements reported here repeated.

Massachusetts Institute of Technology

Dr. Daniel Hastings

The MIT Space Power and Propulsion Laboratory has several students developing numerical simulations of various aspects of MPD thruster flows. These currently include 2-D flow models, boundary layer analysis, and a study of arc ignition in the thruster inlet region. Progress in the past year include expanding the codes to include an axisymmetric formulation, a magnified anode layer, and heavy species heat conduction. In addition new nonequilibrium ionization and viscosity models have been developed which is based on the Bates-Kingston-McWhirter formulation. The new viscosity model allows for the presence of substantial slip between the plasma and electrode wall, and leads to low ionization fractions near the electrodes. The detailed anode region study has revealed that the Hall effect can lead to substantial skewing of the current lines and density depletion in the anode region, which may be responsible for the large anode voltage drops. These phenomena may also explain the sensitivity of anode losses to tank pressure, which would modify the Hall parameter near the anode surface.

The inlet ionization model has been developed to establish the mechanisms by which an initial electron density is established near the backplate. Current emphasis is on evaluating back diffusion of electron-ion pairs and radiation from the downstream plasma. The importance of the work is derived from the potential limitations on propellant injection speed: if the particle residence time is too short, then insufficient ionization will take place and the arc will not be sustained.

Future work at MIT will focus on improving the near-anode plasma model and obtain solutions for a variety of thruster geometries. The model will be used to establish configurations in which the anode fall voltage drop is decreased. The inlet ionization work will be extended to include the role of inlet acceleration, radiation, and emission of cathode electrons.

Ohio State University

Dr. Peter J. Turchi and Dr. Tom York

MPD thruster research at The Ohio State University has focussed on using a small vacuum facility and pulsed power system to study magnetic nozzle flows, code development for hollow cathodes and applied field MPD thrusters, and the installation of an extremely high power capacitor bank. In addition, considerable effort has been devoted to developing non-invasive laser-based diagnostics for flow-field studies.

The magnetic nozzle studies are currently using emission spectroscopy to obtain chordal averages of the flow properties, including species distributions, electron temperatures and number densities. The work builds on previous studies using probes and single-point laser scattering techniques. Quantitative results have been obtained which clearly show the plasma confinement due to the applied magnetic field.

The hollow cathode studies are were initiated in an attempt to improve cathode performance in MPD thrusters by enhancing the control over the near-cathode plasma. The first-principles model includes no empirically derived scaling rules, and is cast in terms of the thruster operating parameters. The model has been compared with an existing experimental data base for ion thruster hollow cathodes and shown good agreement in its predictions of plasma density, temperature, and plasma potential. However, those measurements were given as spatial averages and did not address property distribution. For this reason, an experiment has been initiated at NASA LeRC to obtained detailed maps of plasma and cathode surface properties as a function of position inside the cathode. In addition, work has commenced on an experimental study of high current MPD thruster hollow cathodes.

The numerical simulation efforts are devoted to modifying the DOD developed MACH2 code for application to applied-field MPD thrusters. Improvements in code since last year include the availability of a two-temperature equation of state and incorporation of steady-state poloidal fields. Preliminary results indicate that the application of an external magnetic field dramatically changes the nature of the thruster flow field.

OLAC/Phillips Laboratory

Mr. Dennis Tilley

The Air Force Phillips Laboratory currently has a fully operational quasi-steady MPD thruster test facility at the Electric Propulsion Laboratory at Edwards AFB. The MPD thrusters are tested in a quasi-steady mode in a steel test chamber measuring 8 ft. in diameter by 10 ft. long. The test chamber is pumped by two 10 diffusion pumps (backed by a mechanical pump and roots blower) allowing for the chamber pressure to be in the low 10-4 torr range before thruster firing. A 20 kJ pulse forming network is capable of delivering ~10 MW of power over ~ 1 msec to the MPD thruster. The primary diagnostic techniques currently in use include Langmuir and magnetic field probes and emission spectroscopy. Advanced diagnostics utilized by the EP Lab's arcjet research program, such as LIF techniques, are also available.

The primary emphasis of the MPD thruster research program at the A.F. Phillips Laboratory is to identify methods to significantly increase the efficiency of the MPD thruster. Projects currently in progress include the investigation of ionization processes, anode losses, and the effects of microturbulence on MPD thruster performance.

In the past year a quadruple probe diagnostic technique for simultaneous density, temperature, and velocity measurements was used to study the MPD thruster exhaust. This was done in collaboration with R. Burton at U. of Illinois. The design of a hollow/porous anode MPD thruster, in collaboration with A. Gallimore of U. of Michigan, has been completed which will hopefully lead a significant decrease in the anode losses of these devices. Over the next year, collaborative efforts with MIT and Purdue University will examine ionization fronts and microturbulence inside the MPD thruster chamber. A principal strength of the Phillips Laboratory program is the close collaboration with university efforts.

Princeton University

Dr. Robert Jahn and Dr. Edgar Choueiri

Over the past year work at Princeton has been emphasized studies of anode power deposition, the effects of anomalous transport, and the potential application of lithiated cathodes to improving MPD thruster lifetime. Key results of this years efforts include establishing the scaling of anomalous resistivity Hall parameter, the impact of anomalous resistivity on the anode voltage drop, the observation of microturbulence in the anode region, and the development of a numerical MHD simulation including the effects of anomalous resistivity. In addition, the use of small permanent magnets near the anode was shown to decrease the anode fall voltage, and the performance of a thruster with these magnet was measured.

Numerical studies of anomalous transport showed that the anomalous resistivity could exceed classical values by factors between 10 and 30 for conditions expected inside MPD thrusters. Inclusion of anomalous resistivity in a 2-D, axisymmetric, 2-temperature MHD simulation revealed that regions of high resistivity were concentrated near the cathode base, cathode tip, and anode lip. Improved numerical methods are being implemented to increase computational speed and accuracy.

Following the establishment of the correlation between electron Hall parameter and the anode fall voltage, an experiment was conducted in which small permanent magnets were used to locally decrease the magnetic field. Measurements revealed a substantial decrease in the anode fall voltage for discharge current levels corresponding to approximate cancellation of the self-induced magnetic field. However, the total discharge voltage did not change significantly, and thrust measurements revealed no significant performance enhancement resulting from use of permanent magnets. However, testing still needs to be done under conditions of maximum decrease in the fall voltage. Experimental studies have also revealed that the plasma resistivity near the anode is substantially higher than classical values, and high-frequency floating potential measurements indicate the presence of micro-turbulence near the anode surface.

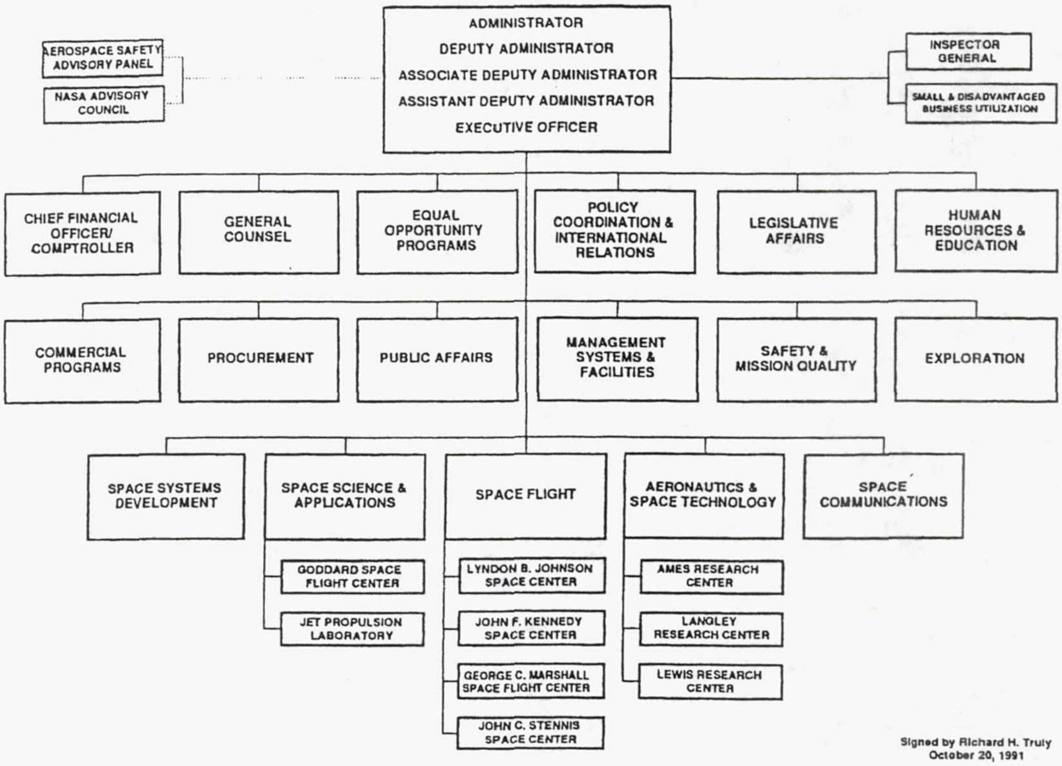
Modifications have been made to the steady-state thruster which now permit internal spectroscopic studies of the discharge plasma. Results indicate the presence of an ionization front, which is consistent with the presence of microinstabilities in the thruster. The instability studies are also being applied to orbital release experiments being conducted in cooperation with the Russian APEX experiment.

Studies of cathode lifetime are currently focussed on the use of lithium to form an electropositive layer on the cathode surface so as to reduce its work function. At present the work has resulted in an improved surface temperature measurement system.

TRANSPORTATION AND PLATFORMS PERSPECTIVE

Gary L. Bennett
National Aeronautics and Space Administration
Washington, DC

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION



Signed by Richard H. Truly
October 20, 1991

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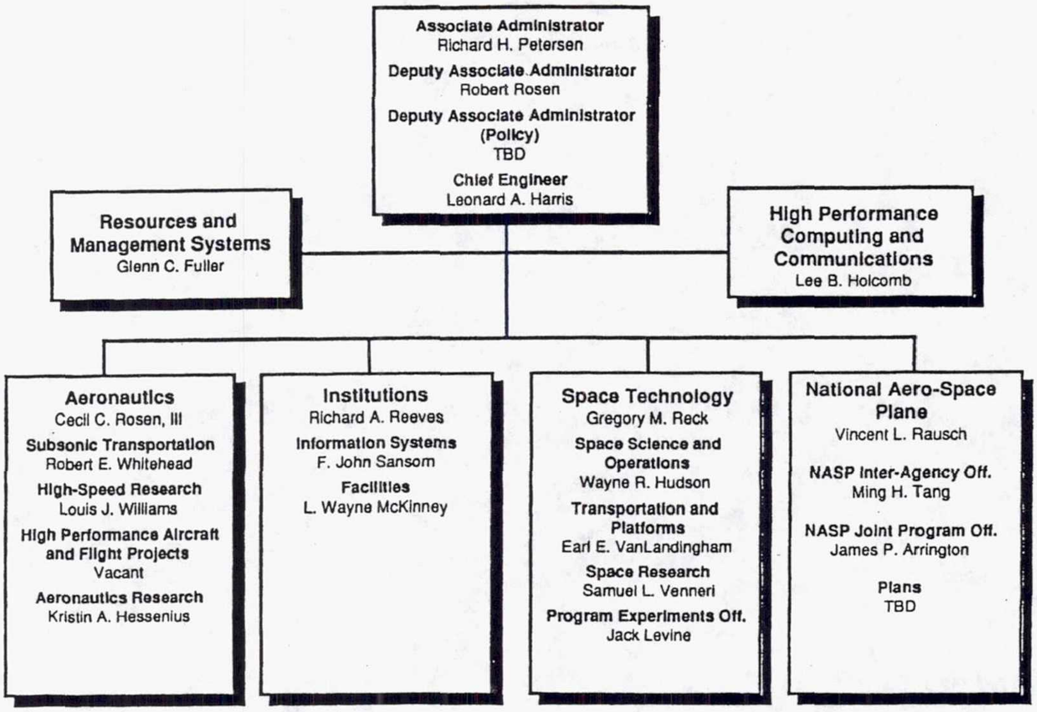
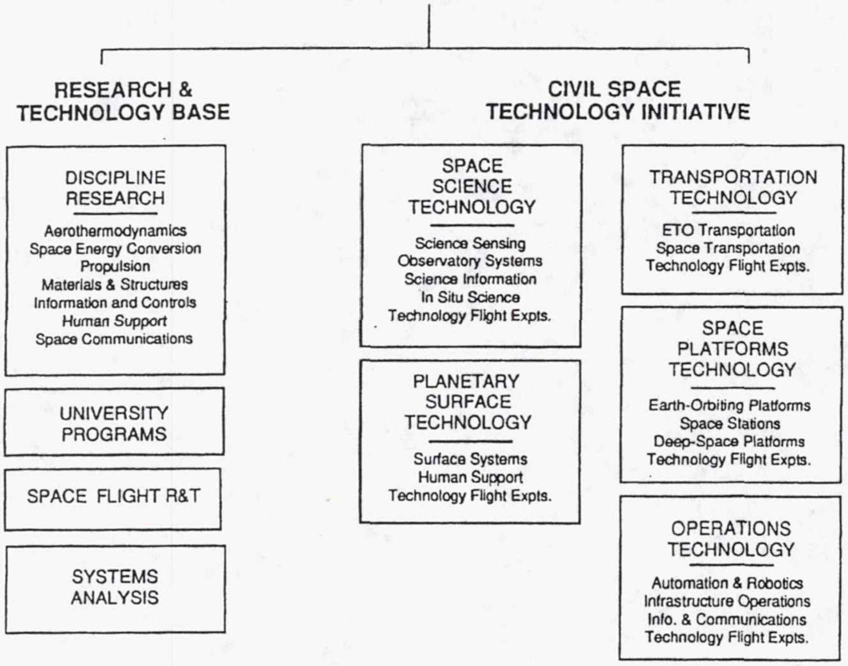


INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

SPACE RESEARCH & TECHNOLOGY



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SPACE R&T MISSION STATEMENT

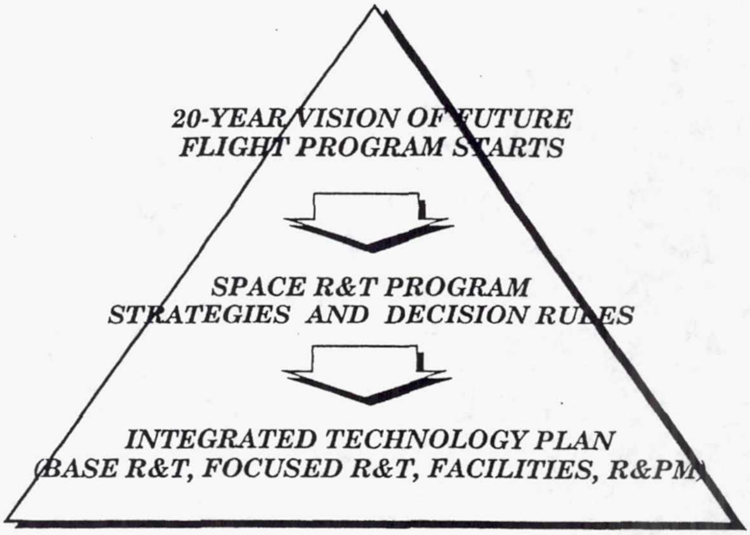
OAST SHALL PROVIDE TECHNOLOGY FOR FUTURE CIVIL SPACE MISSIONS AND PROVIDE A BASE OF RESEARCH AND TECHNOLOGY CAPABILITIES TO SERVE ALL NATIONAL SPACE GOALS

- *IDENTIFY, DEVELOP, VALIDATE AND TRANSFER TECHNOLOGY TO:*
  - INCREASE MISSION SAFETY AND RELIABILITY
  - REDUCE PROGRAM DEVELOPMENT AND OPERATIONS COST
  - ENHANCE MISSION PERFORMANCE
  - ENABLE NEW MISSIONS
- *PROVIDE THE CAPABILITY TO:*
  - ADVANCE TECHNOLOGY IN CRITICAL DISCIPLINES
  - RESPOND TO UNANTICIPATED MISSION NEEDS

LBF4194B

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

SPACE R&T PROGRAM DEVELOPMENT



20-YEAR VISION OF FUTURE FLIGHT PROGRAM STARTS

SPACE R&T PROGRAM STRATEGIES AND DECISION RULES

INTEGRATED TECHNOLOGY PLAN (BASE R&T, FOCUSED R&T, FACILITIES, R&PM)

MAY 4, 1991
JCM-7686

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

RESEARCH & TECHNOLOGY STRATEGY

FLIGHT PROGRAMS FORECAST

- **5-YEAR FORECAST INCLUDES**

'93 THRU '97: LIMITED NEW STARTS

COMPLETION OF INITIAL SSF
SOME SHUTTLE IMPROVEMENTS
INITIAL EOS & EOSDIS
SELECTED SPACE SCIENCE STARTS
NLS DEVELOPMENT
INITIAL SEI ARCHITECTURE SELECTION
EVOLVING GEO COMMERCIAL COMMSATS
MINOR UPGRADES OF COMMERCIAL ELVS

- **10-YEAR FORECAST INCLUDES**

'98 THRU '03: MULTIPLE NEW STARTS TO BE LAUNCHED IN 2003 THRU 2010

SSF EVOLUTION/INFRASTRUCTURE
FINAL SHUTTLE ENHANCEMENTS
ADVANCED LEO EOS PLATFORMS/FULL EOSDIS
MULTIPLE SPACE SCIENCE STARTS
NLS OPERATIONS/EVOLUTION
EVOLVING LAUNCH/OPERATIONS FACILITIES
INITIAL SEI/LUNAR OUTPOST START
DSN EVOLUTION (KA-BAND COMMUNICATIONS)
NEW GEO COMMERCIAL COMMSATS
NEW COMMERCIAL ELVS

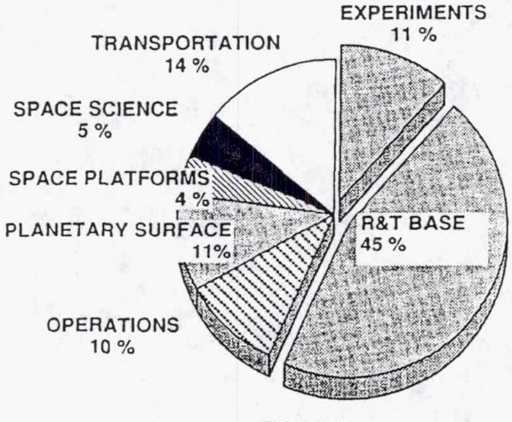
- **20-YEAR FORECAST INCLUDES**

'04 THRU '11 MULTIPLE OPTIONS FOR NEW STARTS TO BE LAUNCHED IN 2009 THRU 2020

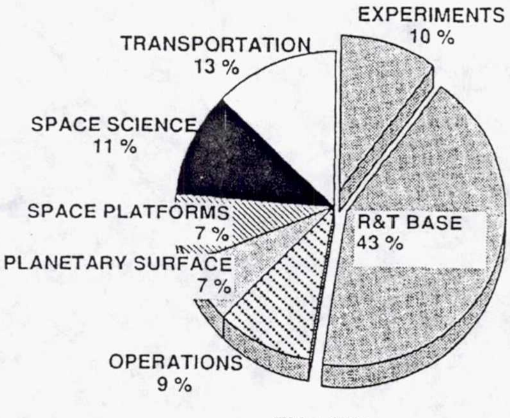
SSF-MARS EVOLUTION
BEGINNING OF AMLS/PLS DEVELOPMENT
MULTIPLE SPACE SCIENCE STARTS
DSN EVOLUTION (OPTICAL COMM)
INITIAL MARS HLLV DEVELOPMENT
EVOLVING LUNAR SYSTEMS
MARS SEI ARCHITECTURE CHOSEN
LARGE GEO COMMSATS
NEW COMMERCIAL ELVS

LBF40305
(JCM-7692)

SPACE RESEARCH & TECHNOLOGY PROGRAM



FY 1992
$309.3M



FY 1993
$332.0M

LBF 40423c

OSSA TECHNOLOGY NEEDS
Grouped According to Urgency & Commonality

REVISED:
NOVEMBER 15, 1991

	HIGHEST PRIORITY		2nd-HIGHEST PRIORITY			3rd HIGHEST PRIORITY			
Near Term	Detectors: IR Si & Ge arrays, multiplexers, CCD, optical, Xe, non-cryo IR, high purity Ge, sensor readout electronics & tunnel sensors (SE, SL, SZ, SS)	Cryogenic Systems -- Optics, coolers, shielding, electronics (SZ, SE, SL, SS)	High Frame Rate, High Resolution Video (SN, SL)	2.5 - 4m, 100K Lightweight, PSR (SZ)	Fluid Diagnostics (SN)	Real-Time Radiation Monitoring (SB)	Solar Arrays/Cells (SL, SZ, SE)	Telerobotics (SN)	High Transmission UV Filters (SZ)
	Submm & Microwave Tech: -- SIS 1.2 THz Heterodyne Rec. -- Active SAR Integrated circuits -- Passive submm 600 GHz diodes (SZ,SE)	Vibration Isolation Technology (SN, SZ, SB)	Telescience, Telepresence, & AI (SN, SL, SB)	Automated Biomedical Analysis (SB)	Rad Hard Parts & Detectors (SZ, SL)	Solid/Liquid Interface Characterization (SN)	Laser Light Scattering (SN)	High Temperature Materials For Furnaces (SN)	K-band Transponders (SZ)
	Efficient, Quiet Refrigerator/Freezer (SB)	Extreme Upper Atmosphere Instrument Platforms (SS)	Batteries -- Long life time -- High energy density (SL, SZ)	Real-Time Environmental Control & Monitoring (SB)	Space Qualified maser & ion Clocks (SZ)	Field Portable Gas Chromatographs (SB)	Advanced Furnace Technology (SN)	3-D packaging for 1 MB Solid State Chips (SZ)	Rapid Subject/ Sample Delivery & Return Capability (SB)
	Lasers: Long-life, Stable & Tunable (SE, SZ, SL, SB)	Mini/microsystems -- Instrumentation, rovers descent imager, camera, RTG ascent vehicle/lander, S/C subsystems (SL)	Low-drift Gyros, Trackers, Actuators (SZ)	Combustion Diagnostics (SN)	Plasma Wave Antennas/ Thermal (SS)	High Temperature Electronics (SL)	Non-Contact Temperature Measurement (SN)	Ultra-high Gigabit/sec Telemetry (SZ)	Microbial Decontaminatio Methods (SB)
	Data -- High Volume, High Density, High Data Rate, On-board Storage & Compression (SE, SL, SN, SZ)	Interferometer-specific Tech: -- picometer metrology -- active delay lines -- control-structures interact. (SZ, SL, SB)	Microphonics Technology, FET development (SZ)	Auto S/C Monitoring & Fault Recovery (SL)	Improved EVA Suit/PLSS (EMU) (SB)	Thermal Control System (SZ)	Special Purpose Bioreactor Simulator Syst. (SB)	Animal & Plant Reproduction Aids (SB)	
	Controlled Structures/ Large Antenna Structure Arrays/Deployable (SE, SZ, SS, SB)	Parallel Software Environment for Model & Data Assimilation, Visualization Computational Techniques (SE, SL, SZ)	X-ray Optics Tech: -- imaging system -- low cost optics -- Bragg concentrators -- coated apertures (SZ)	SETI Technologies -- Microwave & Optical/Laser Detection (SB)	Regenerative Life Support (SB)	Auto Rendezvous Auto Sample Transfer, Auto Landing (SL)	Non-Destructive Monitoring Capability (SB)	Non-Destructive Cosmic Dust Collection (SB)	
Far Term	Interspacecraft Ranging & Positioning Precision Sensing Pointing & Control (SS, SZ, SL)	Large Filled Apertures -- lightweight & stable optics -- Cryo optical ver., fab., test. -- Deformable mirrors -- 15-25m PSR (SL, SZ, SE)	Sample Acquisition, Analysis and Preservation (SB, SL)	32 Ghz TWT Optical Communication (SL, SS)	High Resolution Spectrometer (SB)	Spacecraft Thermal Protection (SL)	Partial-g/ µg Medical Care Delivery Systems (SB)	Dust Protection/ Jupiter's Rings (SL)	
	50-100Kw Ion Propulsion (NEP) (SL)		Radiation Shielding for Crews (SB)	SIS 3 Thz Heterodyne Receiver (SZ)	Human Artificial Gravity Systems (SB)	CELSS Support Technologies (SB)			

Tally:
SB: 5 SN: 2
SE: 8 SS: 5
SL: 9 SZ: 11

SB: 10 SN: 4
SE: 1 SS: 2
SL: 7 SZ: 8

SB: 10 SN: 5
SE: 0 SS: 0
SL: 5 SZ: 6

NASA

NUCLEAR ELECTRIC
PERFORMANCE CHARACTERISTICS

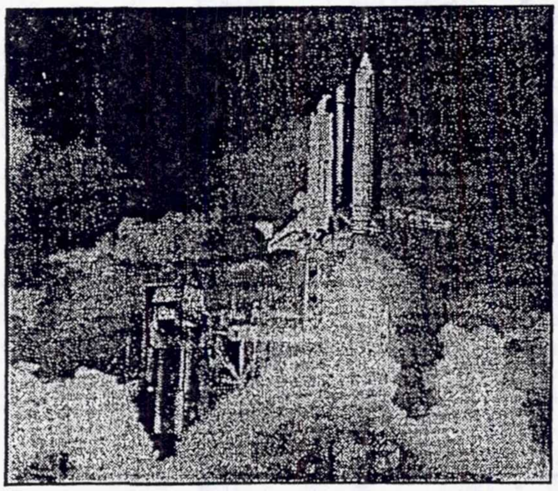
- Mission Performance Factors
  - Specific Impulse (Isp): Determines propellant mass
  - Power Level (P_e): Affects trip time
  - System Specific Mass (α): Determines trip time limits
  - Thruster Efficiency (η): Affects trip time, vehicle mass

Parameter	Desired Range	Mission Impact
Isp	High (>5000s)	Low initial mass, Resupply mass
P_e	High (MWe)	Reduced trip time
α	Low (<10 kg/kWe)	Reduced Mass, trip time
η	High (>50%)	Improved mass, trip time

Office of Exploration

TRANSPORTATION TECHNOLOGY

PROVIDE TECHNOLOGIES THAT SUBSTANTIALLY INCREASE OPERABILITY, IMPROVE RELIABILITY, PROVIDE NEW CAPABILITIES, WHILE REDUCING LIFE CYCLE COSTS



- ENHANCE SAFETY, RELIABILITY, AND SERVICEABILITY OF CURRENT SPACE SHUTTLE
- PROVIDE TECHNOLOGY OPTIONS FOR NEW MANNED SYSTEMS THAT COMPLEMENT THE SHUTTLE AND ENABLE NEXT GENERATION VEHICLES WITH RAPID TURNAROUND AND LOW OPERATIONAL COSTS
- SUPPORT DEVELOPMENT OF ROBUST, LOW-COST HEAVY LIFT LAUNCH VEHICLES
- DEVELOP AND TRANSFER LOW-COST TECHNOLOGY TO SUPPORT COMMERCIAL ELV's AND UPPER STAGES
- IDENTIFY AND DEVELOP HIGH LEVERAGE TECHNOLOGIES FOR IN-SPACE TRANSPORTATION, INCLUDING NUCLEAR PROPULSION, THAT WILL ENABLE NEW CLASSES OF SCIENCE AND EXPLORATION MISSIONS

91-8048

TRANSPORTATION TECHNOLOGY

SHUTTLE ENHANCEMENT

- SSME Improvements
- Durable Thermal Protection Systems
- Improved Health Monitoring
- Light Structural Alloys
- Lidar-Based Adaptive Guidance & Control

NEXT GENERATION MANNED TRANSPORTS

- Configuration Assessment
- High Frequency, High Voltage Power Management/Distribution Systems
- LOX/LH2 Propellant for OMS/RCS
- Maintenance-free TPS
- Advanced Reusable Propulsion
- GPS-Based Autonomous GN&C
- Composites & Advanced Lightweight Metals
- Vehicle-Level Health Management For Autonomous Operations

HEAVY-LIFT CAPABILITY

- Advanced Fabrication (Forming & Joining)
- STME Improvements
- On-Vehicle Adaptive Guidance & Control
- Systems & Components for Electric Actuators
- Health Monitoring for Safe Operations
- AL-Li Cryo Tanks

LOW-COST COMMERCIAL

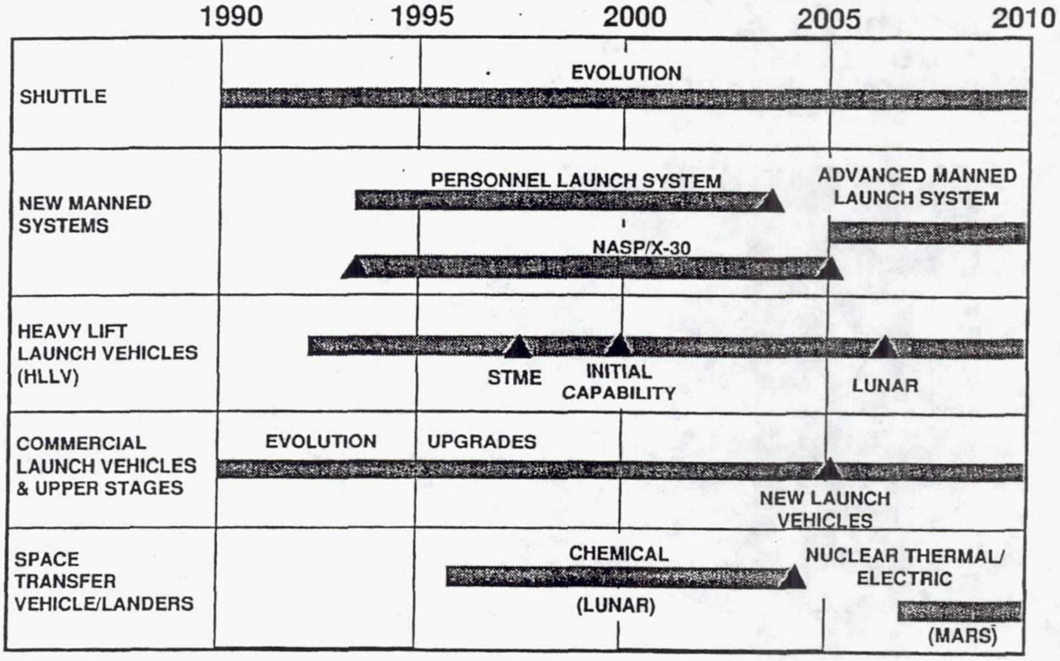
- Alternate Booster Concepts
- Advanced Cryogenic Upper Stage Engines
- Low-Cost Fab./Automated Processes/NDE
- Continuous Forging Processes for Cryogenic Tanks
- Fault-Tolerant, Redundant Avionics

IN-SPACE TRANSPORT

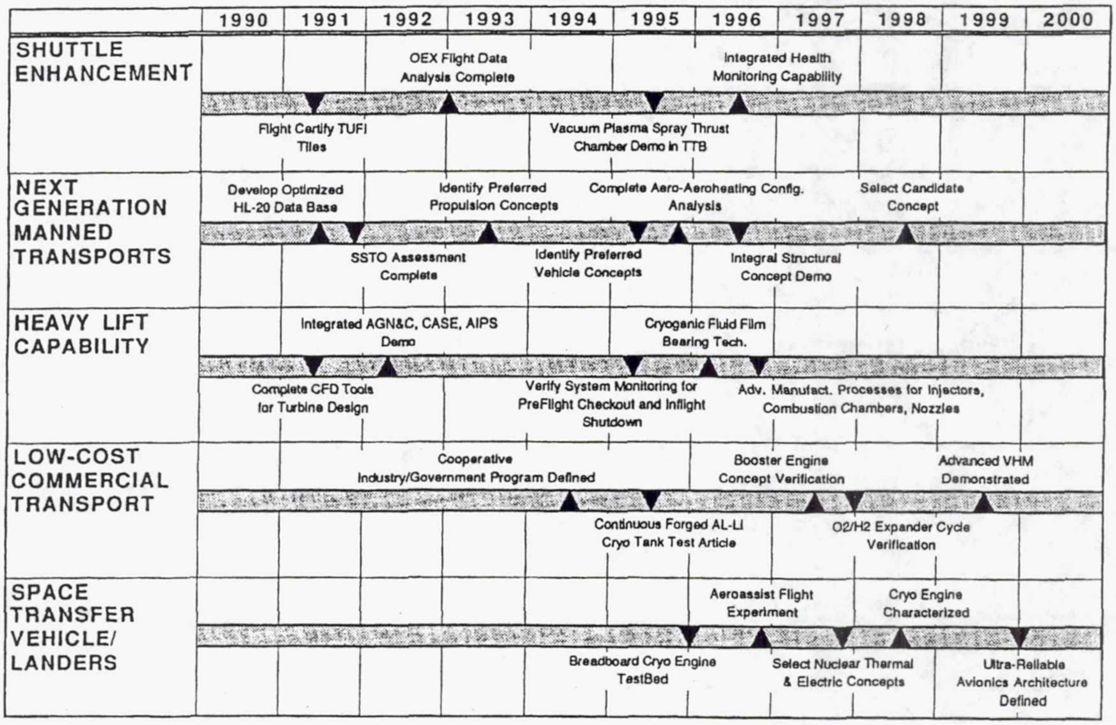
- High-Power Nuclear Thermal & Electric Propulsion
- High Performance, Multiple Use Cryogenic Chemical Engine
- Highly Reliable, Autonomous Avionics
- Low Mass, Space Durable Materials
- Long-Term, Low-Loss Management of Cryogenic Hydrogen
- Autonomous Rendezvous, Docking & Landing
- Aeroassist Technologies

91-8066

TRANSPORTATION TECHNOLOGY MISSION MODEL

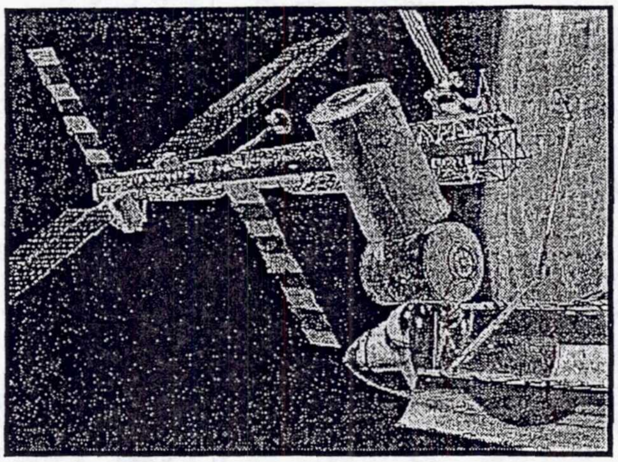


TRANSPORTATION MILESTONES



SPACE PLATFORMS TECHNOLOGY

DEVELOP TECHNOLOGIES TO INCREASE ON-ORBIT MISSION EFFICIENCY AND DECREASE LIFE CYCLE COSTS FOR FUTURE MANNED AND UNMANNED SCIENCE, EXPLORATION & COMMERCIAL MISSIONS.



- DEVELOP TECHNOLOGIES THAT WILL DECREASE LAUNCH WEIGHT AND INCREASE THE EFFICIENCY OF SPACE PLATFORM FUNCTIONAL CAPABILITIES
- DEVELOP TECHNOLOGIES THAT WILL INCREASE HUMAN PRODUCTIVITY AND SAFETY OF MANNED MISSIONS
- DEVELOP TECHNOLOGIES THAT WILL INCREASE MAINTAINABILITY AND REDUCE LOGISTICS RESUPPLY OF LONG DURATION MISSIONS
- IDENTIFY AND DEVELOP FLIGHT EXPERIMENTS IN ALL TECHNOLOGY AND THRUST AREAS THAT WILL BENEFIT FROM THE UTILIZATION OF SSF FACILITIES

91-8052

SPACE PLATFORMS TECHNOLOGY

EARTH ORBITING PLATFORMS

- Structural Dynamics
- On-Orbit Non-Destructive Evaluation Techniques
- Space Environmental Effects
- Power Systems
- Thermal Management
- Advanced Information Systems

SPACE STATIONS

- Regenerative Life Support
- Integrated Propulsion and Fluid Systems Architecture
- Extravehicular Mobility
- Telerobotics
- Artificial Intelligence

SPACE BASED LABORATORY AND TESTBED

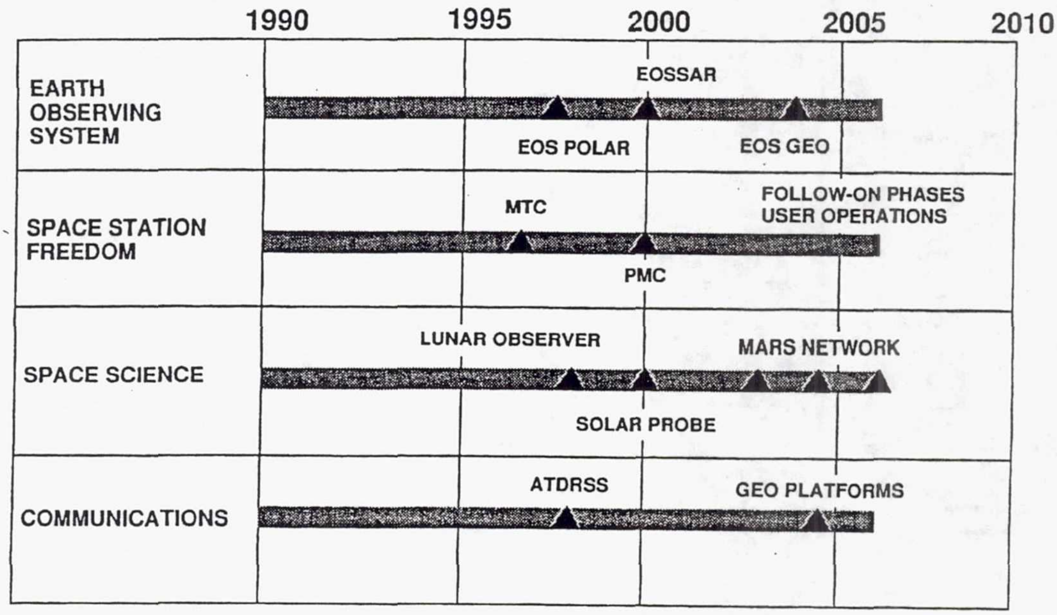
- Exploit Microgravity and Crew Interactive Capability to Advance and Validate Selected Technologies

DEEP SPACE MISSIONS

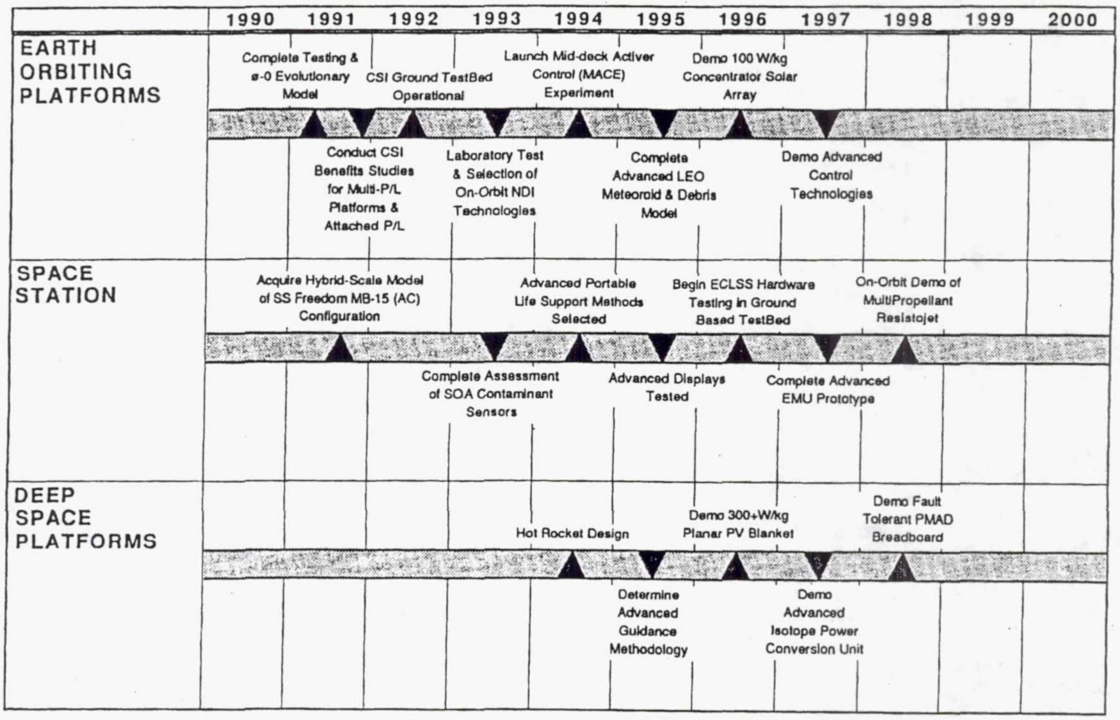
- Power and Thermal Management
- Propulsion
- Guidance, Navigation and Control

91-8053

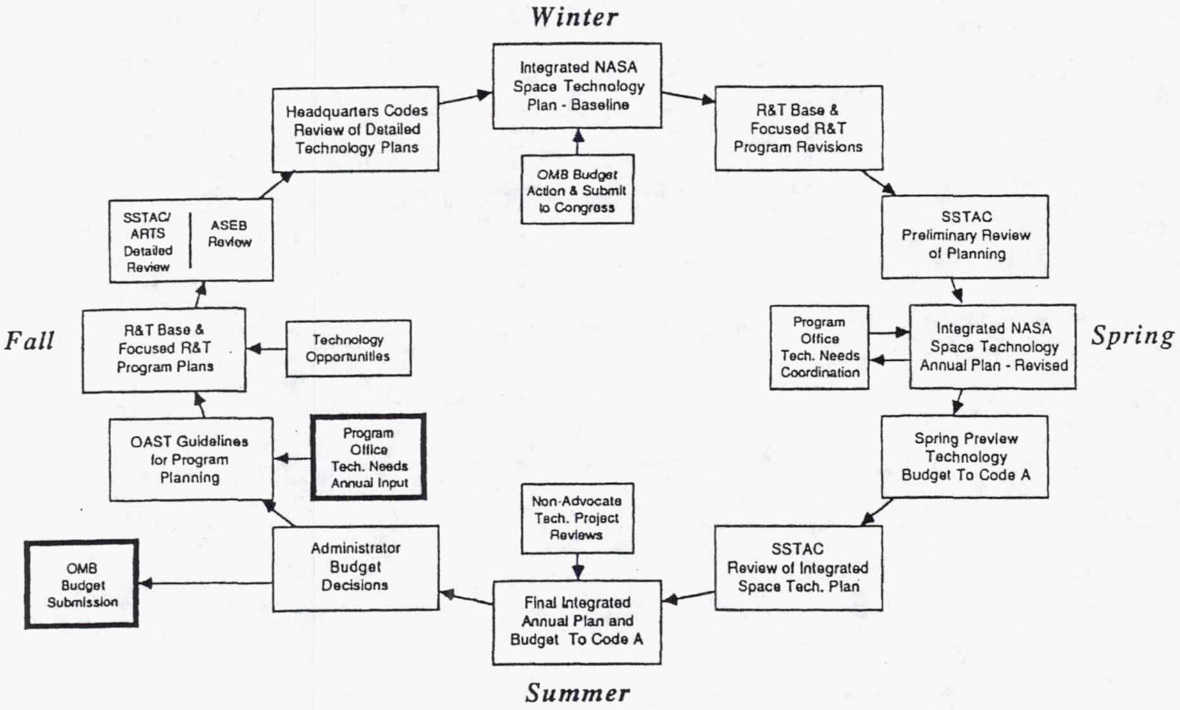
SPACE PLATFORMS TECHNOLOGY MISSION MODEL



SPACE PLATFORMS MILESTONES



SPACE TECHNOLOGY PLANNING CYCLE



March 25, 1991
JCM-7207b

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

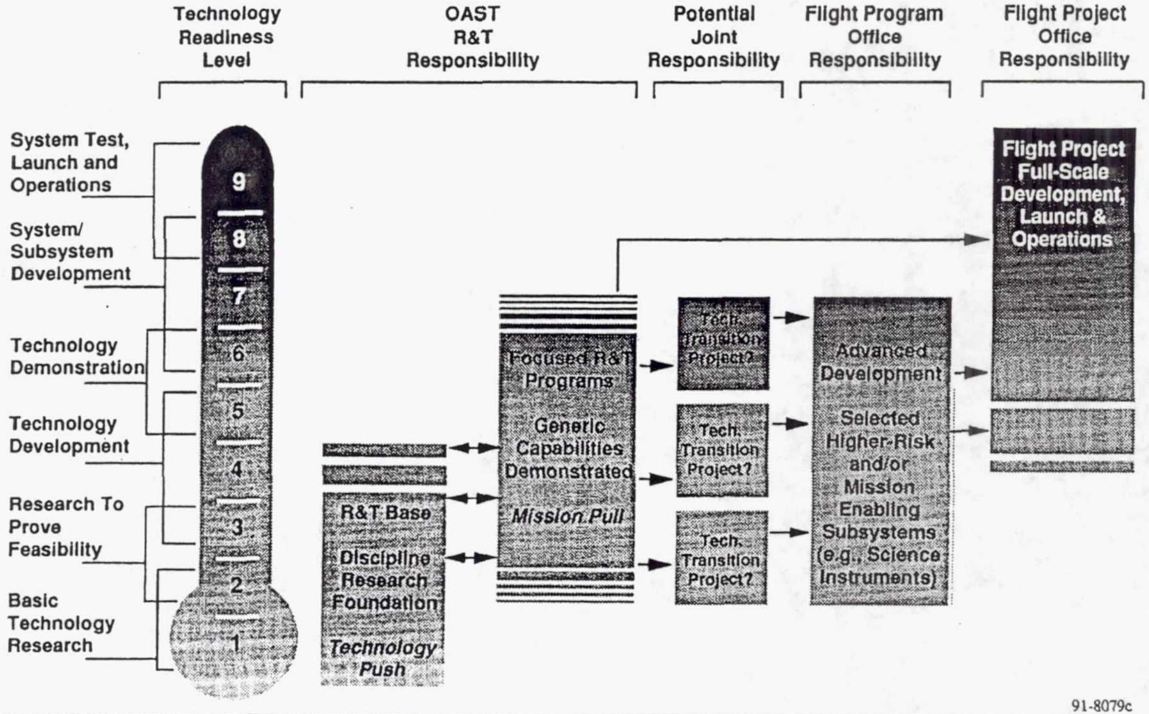
TECHNOLOGY READINESS LEVELS

Basic Technology Research	LEVEL 1	BASIC PRINCIPLES OBSERVED AND REPORTED
	LEVEL 2	TECHNOLOGY CONCEPT AND/OR APPLICATION FORMULATED
Research To Prove Feasibility	LEVEL 3	ANALYTICAL & EXPERIMENTAL CRITICAL FUNCTION AND/OR CHARACTERISTIC PROOF-OF-CONCEPT
Technology Development	LEVEL 4	COMPONENT AND/OR BREADBOARD VALIDATION IN LABORATORY ENVIRONMENT
	LEVEL 5	COMPONENT AND/OR BREADBOARD VALIDATION IN RELEVANT ENVIRONMENT
Technology Demonstration	LEVEL 6	SYSTEM/SUBSYSTEM MODEL OR PROTOTYPE DEMONSTRATION IN A RELEVANT ENVIRONMENT (Ground or Space)
System/Subsystem Development	LEVEL 7	SYSTEM PROTOTYPE DEMONSTRATION IN A SPACE ENVIRONMENT
	LEVEL 8	ACTUAL SYSTEM COMPLETED AND "FLIGHT QUALIFIED" THROUGH TEST AND DEMONSTRATION (Ground or Flight)
System Test, Launch and Operations	LEVEL 9	ACTUAL SYSTEM "FLIGHT PROVEN" THROUGH SUCCESSFUL MISSION OPERATIONS

MARCH 17, 1991
JCM-7410

INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM

TECHNOLOGY MATURATION STRATEGY



Technology Readiness Level

OAST R&T Responsibility

Potential Joint Responsibility

Flight Program Office Responsibility

Flight Project Office Responsibility

System Test, Launch and Operations

System/ Subsystem Development

Technology Demonstration

Technology Development

Research To Prove Feasibility

Basic Technology Research

9

8

7

6

5

4

3

2

1

R&T Base

Discipline Research Foundation

Technology Push

Focused R&T Programs

Generic Capabilities Demonstrated

Mission Pull

Tech. Transition Project?

Tech. Transition Project?

Tech. Transition Project?

Advanced Development

Selected Higher-Risk and/or Mission Enabling Subsystems (e.g., Science Instruments)

Flight Project Full-Scale Development, Launch & Operations

91-8079c

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"NEAR TERM" NEP MISSIONS AND SYSTEMS

Jim Gilland
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

NUCLEAR PROPULSION OFFICE NEP GOALS

- **NASA's Office of Space Science and Applications (OSSA) has identified NEP as first priority on its far term technology needs list to OAST**
- **NEP systems of interest to OSSA:**
  - TRL 5 by ~2000
  - 50 -100 kWe
  - $\alpha < 50$ kg/kWe
  - 7 year life
  - High Isp, η
- **NPO emphasis is on developing 10 - 20 kWe ion thrusters, PPU**
- **MWe NEP effort reduced in scope**

"NEAR TERM" SYSTEMS DEFINITION

- **Reactor: SP-100**
  - 2.5 MWt
  - 1350 K Outlet Temperature
  - 7 year life
- **Radiator**
  - Ti/K Heat Pipes
  - 5 - 10 kg/m^2 specific mass
  - < 900 K
- **PMAD**
  - SOA Si Electronics
  - T < 400 K

"NEAR TERM" SYSTEM DEFINITION (cont.)

- **Power Conversion**
  - Thermoelectrics
    - **~5% efficient**
    - **1350 K Hot Shoe Temperature**
  - Brayton
    - **SOA BRU**
    - **20 - 30% efficient**
    - **1050 K TIT**
    - **Possibility to extend to 1350 K**
  - Rankine
    - **SOA Moderate Power Reactor Experiment**
    - **20% efficient**
    - **1100 K TIT**
    - **Possibility to extend to 1350 K**

"NEAR TERM" SYSTEM DEFINITION (cont.)

- **MPD Thrusters**
  - 4.7 kg/kWe w/ Power Processing
  - Possibility for pulsed operation not yet assessed on a system level
  - Isp ~ 1000 - 7000 s
  - $\eta = 0.5$
  - Power levels from 100 to 1500 kWe total input power

REPRESENTATIVE NEAR TERM NEP SYSTEMS

PRELIMINARY

- **100 kWe SP-100/TE**
  - 1300 K
    - **35 - 51 kg/kWe**
- **500 kWe SP-100/Brayton**
  - 1100 K
    - **50.7 kg/kWe**
  - 1300 K
    - **35.7 kg/kWe**
- **500 kWe SP-100/Rankine**
  - 1100 K
    - **21 kg/kWe**
  - 1300 K
    - **16.4 kg/kWe**

Includes 4.7 kg/kWe MPD thruster subsystem (1 set of thrusters)

NEAR TERM NEP MISSIONS

- **Demo Missions (<100 kWe)**
  - LEO-GEO
    - **Van Allen Belt Science***
  - Lunar Science
    - **Lunar Mapper**
  - Mars Precursor
  - Interplanetary Robotic
    - **Main Belt Asteroid Rendezvous***

*To be discussed in this presentation

NEAR TERM NEP MISSIONS

- **Primary Missions (100 - 1500 kWe)**
  - Interplanetary Robotic
    - **Neptune Orbiter**
    - **Jupiter Grand Tour**
    - **Pluto Orbiter**
    - **Multiple Main Belt Asteroid Rendezvous**
    - **Comet Nucleus Sample Return***
  - Space Exploration Initiative Related
    - **Lunar Mapper**
    - **Lunar Cargo**
    - **Mars Probe**
    - **Mars Cargo***

*To be discussed in this presentation

DEMO MISSIONS

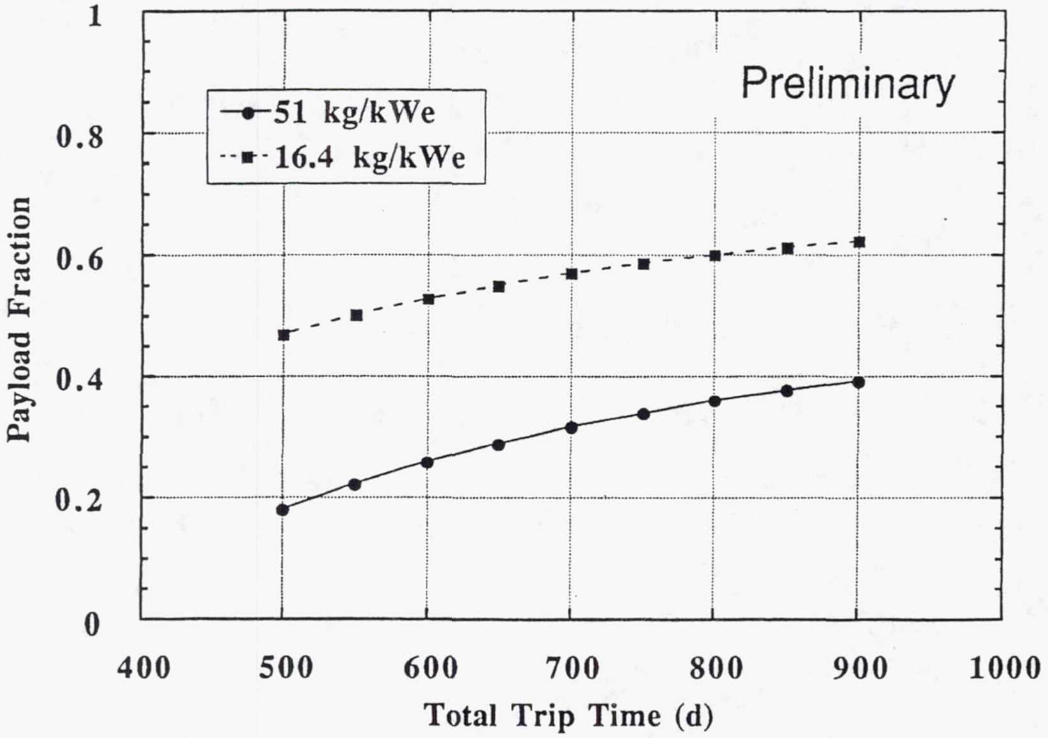
- **Observations Based Upon JPL, NASA LeRC studies**
- **Mission studies were based on Xe ion thrusters, SP-100 capabilities**
- **Low power SP-100 (<50 kWe) has high α, up to 200 kg/kWe**
- **Launch Vehicle constraints: Atlas IIAS, Titan III, Titan IV**
- **Possible missions applicable to MPD thrusters:**
  - Key factor: Isp $\leq$ 5000 s
  - Most outer planet missions require Isp of > 7000 s
  - Power $\leq$ 100 kWe
  - Missions:
    - **Comet Nucleus Sample Return**
    - **Main Belt Asteroid Rendezvous**
    - **Van Allen Belt Mapper**

PRIMARY MISSIONS

- **Observations Based Upon In-house NASA LeRC studies**
- **Preliminary JPL study also investigated near term Mars missions**
- **Power levels from 100 to 1500 kWe**
- **Specific Masses as given previously**
- **Mars Cargo Results Shown**
  - Best and Worst Case SP-100 Dynamic
  - Payloads and initial masses based on 1500 kWe system
  - 1500 kWe = 3 power modules grouped together

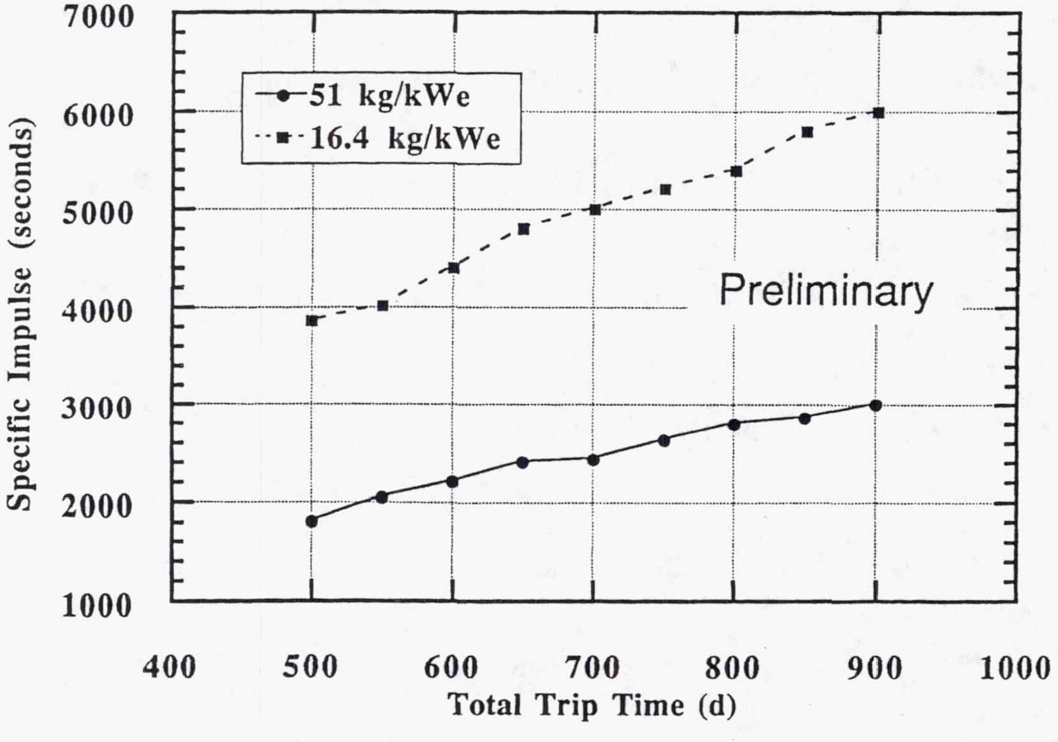
NEAR TERM NEP MARS CARGO MISSION

Optimal power, Isp - Trip time includes planetary spirals



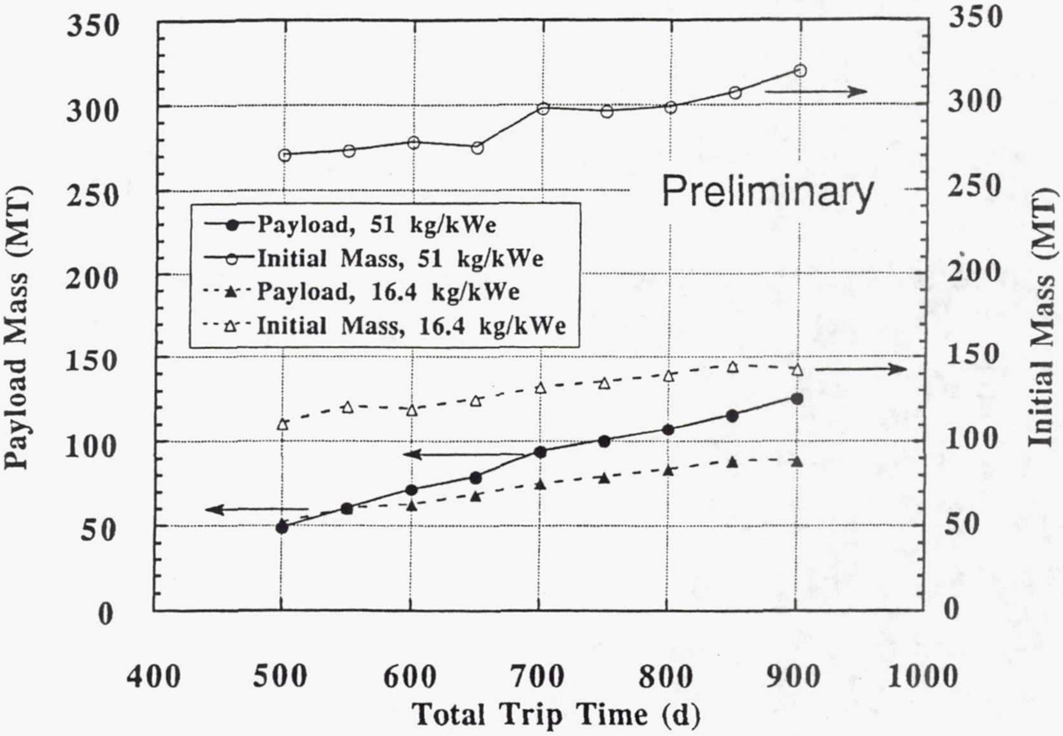
NEAR TERM NEP MARS MISSION ANALYSIS

Optimal power, Isp - Trip time includes planetary spirals



NEAR TERM NEP MARS MISSION

1500 kWe, trip time includes planetary spirals



SUMMARY

- **Near term missions impose new constraints on NEP technology**
  - High specific mass, low power
  - Constrained launch vehicles
  - Increased impact of efficiency, Isp on mission capability
- **For near term, <100 kWe missions, Ion propulsion is still primary choice based on state of technology and mission capability**

SUMMARY (cont.)

- **Some missions that could utilize MPD technology have been identified in preliminary fashion**
  - Earth orbital
  - Comet, asteroid belt exploration
  - Mars cargo vehicles
- **Key assumptions in studies to date**
  - 1 set of MPD thrusters - lifetime issues
  - 100 - 500 kWe MPD thrusters can achieve
    - **Isp ~ 1000 - 7000 seconds**
    - **α ~ 5 kg/kWe**
    - **η ~ 0.5**
  - Development time for MPD matches mission needs

THE MPD THRUSTER PROGRAM AT JPL

Keith Goodfellow, Tom Pivirotto, and Jay Polk
Jet Propulsion Laboratory
Pasadena, California

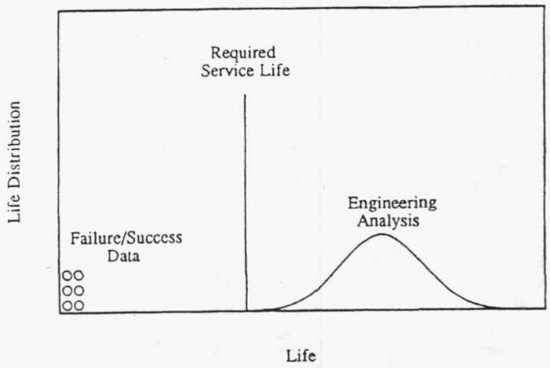
MPD THRUSTER ACTIVITIES AT JPL

- Engine Lifetime Assessment
  - Methodology for Determining Life
  - Electrode Modelling
  - Experimental Program

- Lithium MPD Thruster Development
  - Technology Review and Modelling
  - Mission Analysis (APC Group)
  - Technology Development

- Radiation-cooled, Applied-field Engine Testing
  - Anode Thermal Management
  - Pumping Speed Improvements with a Gasdynamic Diffuser
  - Dual-beam Thrust Measurements

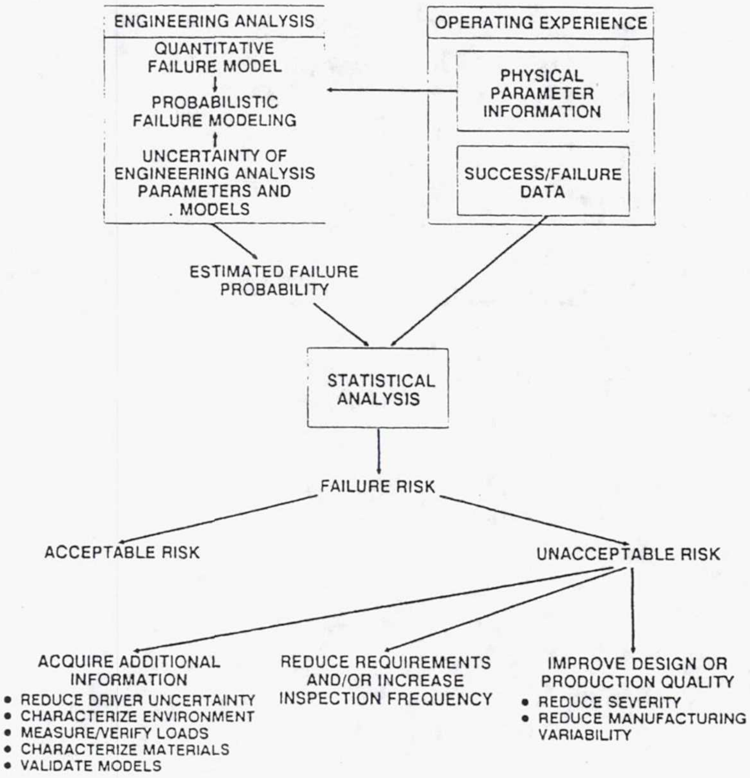
DEFINING ENGINE LIFETIME



Engine lifetime, requirements and operating experience

- CURRENT STATUS
  - Required service life is not well defined
  - Critical failure modes have not been identified
  - No theoretical or experimental characterization of life distribution
- IMPORTANT OBSERVATIONS
  - Life distribution characterization by system-level operating experience is not feasible
  - Engine lifetime is inherently probabilistic

PROBABILISTIC FAILURE ASSESSMENT



ENGINEERING ANALYSIS

QUANTITATIVE FAILURE MODEL

PROBABILISTIC FAILURE MODELING

UNCERTAINTY OF ENGINEERING ANALYSIS PARAMETERS AND MODELS

OPERATING EXPERIENCE

PHYSICAL PARAMETER INFORMATION

SUCCESS/FAILURE DATA

ESTIMATED FAILURE PROBABILITY

STATISTICAL ANALYSIS

FAILURE RISK

ACCEPTABLE RISK

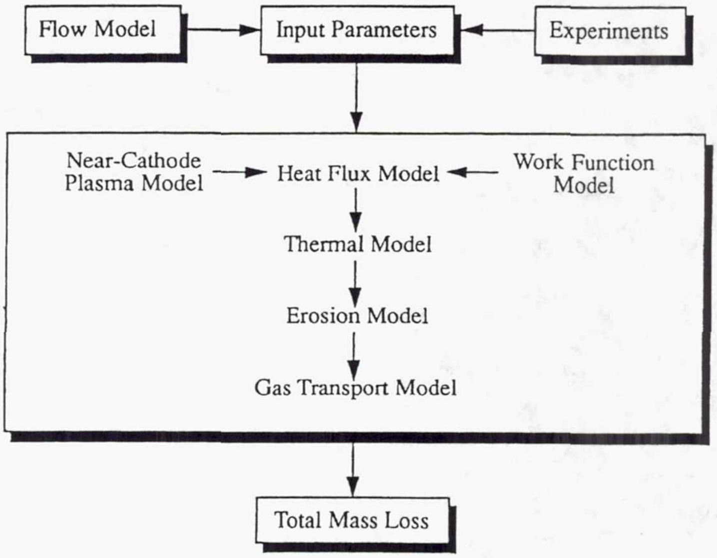
UNACCEPTABLE RISK

ACQUIRE ADDITIONAL INFORMATION
- REDUCE DRIVER UNCERTAINTY
- CHARACTERIZE ENVIRONMENT
- MEASURE/VERIFY LOADS
- CHARACTERIZE MATERIALS
- VALIDATE MODELS

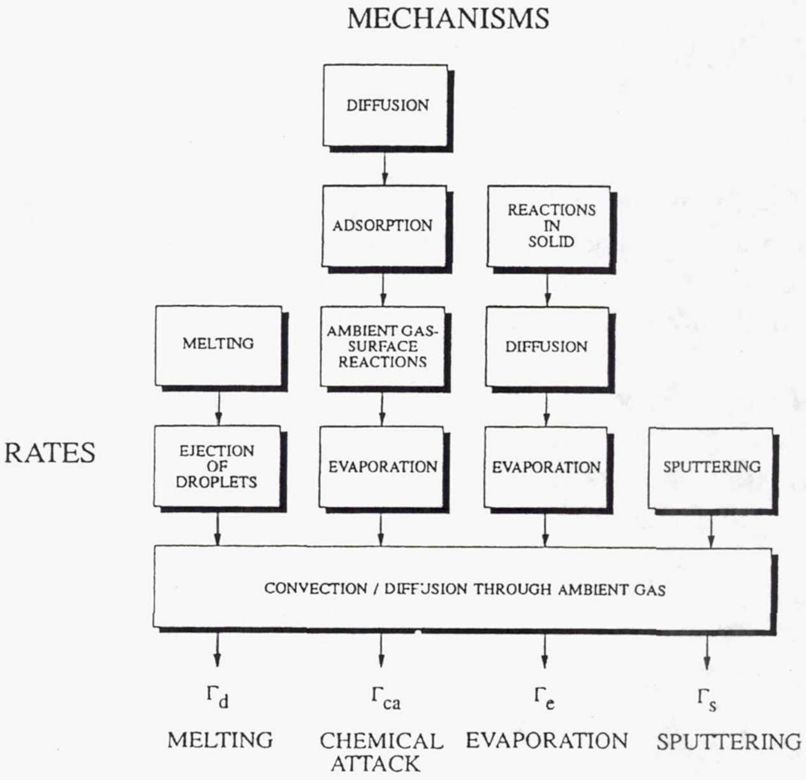
REDUCE REQUIREMENTS AND/OR INCREASE INSPECTION FREQUENCY

IMPROVE DESIGN OR PRODUCTION QUALITY
- REDUCE SEVERITY
- REDUCE MANUFACTURING VARIABILITY

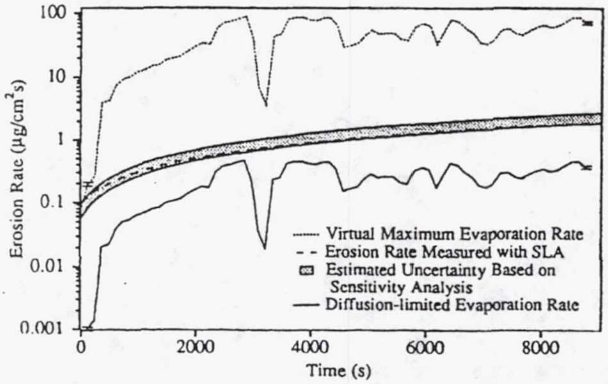
QUANTITATIVE CATHODE FAILURE MODELLING



CATHODE EROSION MODELLING



COMPARISON OF CALCULATED AND MEASURED CATHODE EROSION RATES



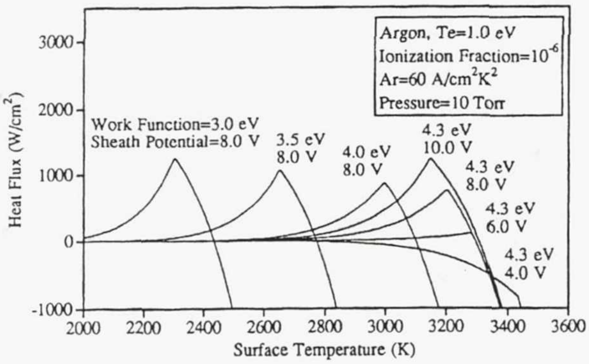
Cathode erosion measurements performed with Stuttgart thruster NCT-1 at 2500 A, 1.0 g/s of argon, 71 kWe and 20 Torr ambient pressure

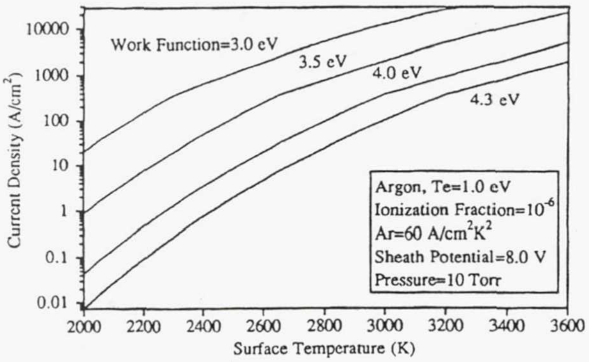
- Diffusion-limited evaporation of tungsten is the dominant mechanism
- Model underpredicts erosion rate by a factor of 6, reflecting uncertainties in transport rate through concentration boundary layer
- Calculated erosion rates are based on measured temperatures--thermal model required for fully predictive capability

CATHODE THERMAL MODELLING

- HT8 - 1D thermal model with variable grid spacing and non-linear thermal and electrical conductivity. Allows specification of radiation, conduction, convection and arc attachment boundary conditions on ends and inner and outer radii.
- AFEMS - Commercial 2D finite-element model with nonlinear material properties. Very flexible solid modeller for geometry specification, but definition of boundary conditions is more cumbersome than in HT8.
- Fully 2D version of HT8 under development.

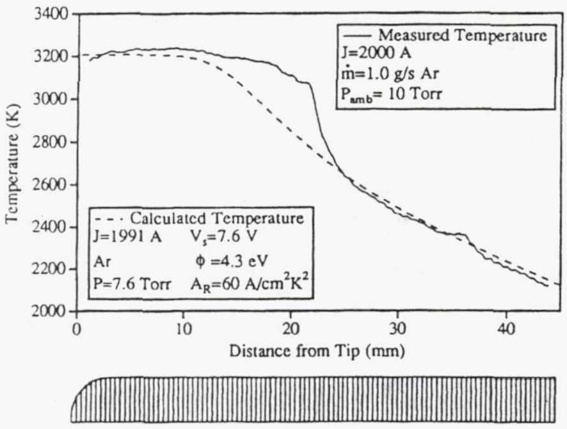
NEAR-CATHODE PLASMA MODELLING





- The model describes the electrostatic sheath, presheath and ionization zones
- Current and heat fluxes are calculated as functions of gas properties, thermionic properties, surface temperature and sheath potential
- Terms normally neglected in high-pressure noble gas arc models are included to allow accurate modelling of low-pressure alkali metal arcs

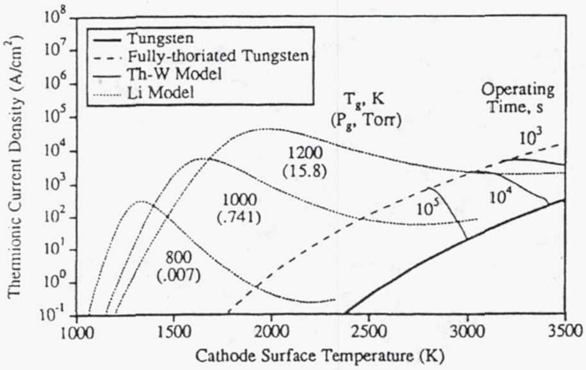
COMPARISON OF CALCULATED AND MEASURED TEMPERATURE DISTRIBUTIONS



Cathode model geometry and results

- The model includes radiation, conduction out the base and heat input over the first 20 mm from the near-plasma model
- The model reproduces the tip temperature and shaft behavior for reasonable values of the input parameters
- Width of the attachment zone and the high gradient in the middle are not predicted--this may be due to 2-D effects, axially varying gas properties, or convection

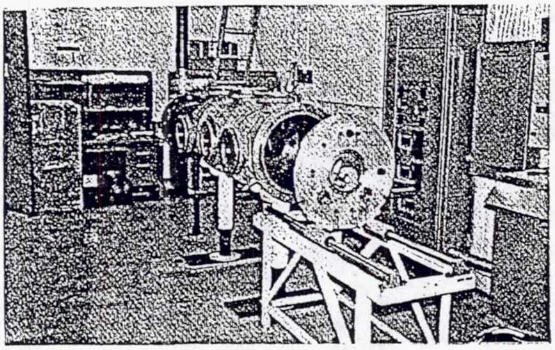
CATHODE WORK FUNCTION MODELLING

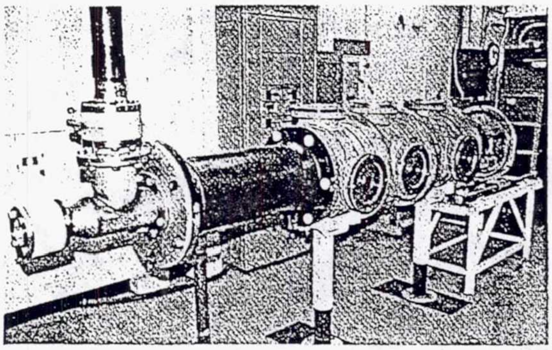


Emission capability of tungsten metal with Th and Li adsorbed on the surface.

- "Activator" may be electropositive material in the cathode bulk or in the propellant
- Two models were developed for cathode additive transport and propellant-surface interaction
- Th-W effect on work function is limited by depletion of thorium additive
- Li supply from propellant is unlimited, but surface coverage depends on gas pressure and temperature
- There is considerable uncertainty in model input parameters

CATHODE TEST FACILITY





CATHODE TEST FACILITY

- Demonstrate feasibility of new cathode concepts
- Measure cathode temperature distributions and erosion rates to validate models
- Measure model input parameters
- Collect success/failure data in long endurance tests

ANODE MODELLING

- Objective: Determine failure mechanisms, model life distribution and develop methods for thermal management
- Finite element model of existing anode design is complete
- Subsequent tasks:
  - Apply sheath analysis to anode region
  - Review existing data and theoretical treatments of magnetic field effects in the anode region
  - Formulate proper boundary conditions for anode thermal models
  - Develop an improved anode radiator design

LITHIUM MPD THRUSTER TECHNOLOGY REVIEW

(Presented at the SEI Technologies Conference, Sept. 1991)

- The review was motivated by Russian and US data from the 60's and 70's indicating substantial performance and cathode lifetime gains with alkali metal propellants

- Scope
  - Critical review of existing data
  - Analysis of the physical basis for performance and lifetime gains
  - Examination of systems and testing considerations

- Conclusions
  - The available data are persuasive and provide a sound rationale for renewed examination of alkali metal propellants, particularly lithium
  - Alkali metals offer a tremendous advantage in facility pumping requirements
  - The greatest risk is the potential for spacecraft contamination

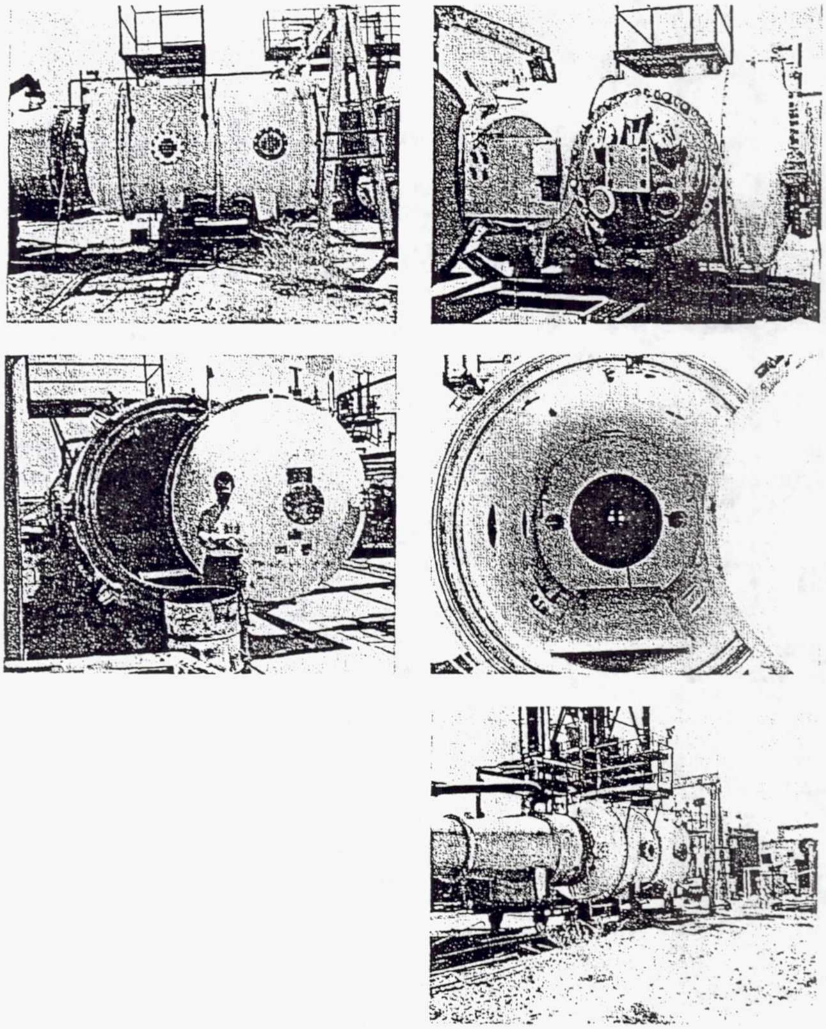
LITHIUM MPD THRUSTER TECHNOLOGY DEVELOPMENT AT JPL

- Funded by NPO in FY92 to develop a lithium feed system
  - Reservoir and vaporizer designed and under construction
  - Flow rate calibration system design complete, components under construction

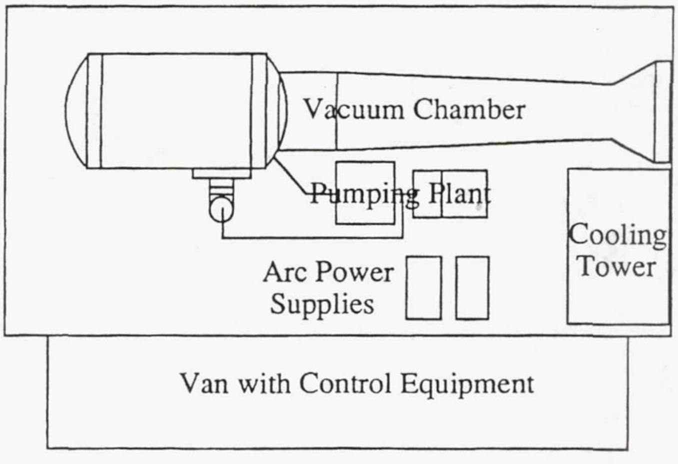
- Test facility design nearly complete, construction to be completed in FY93
  - 6' x 15' double-walled stainless chamber with 27' long extension to be used as a beam dump pumped by a 20" diameter oil diffusion pump

- Initial testing of 100 kWe-class radiation-cooled engine to begin in FY93

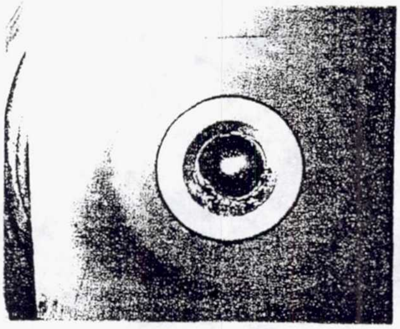
LITHIUM MPD THRUSTER TEST CHAMBER



LITHIUM MPD THRUSTER TEST FACILITY

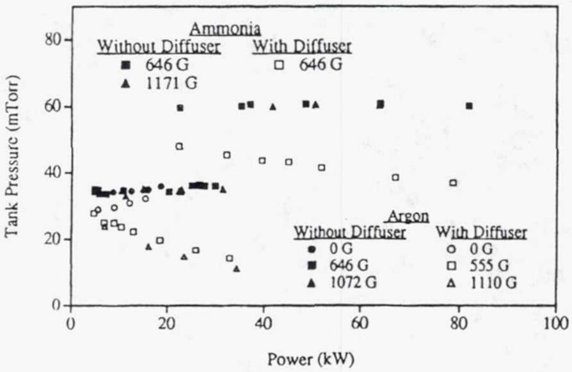


RADIATION-COOLED, APPLIED-FIELD ENGINE TESTING



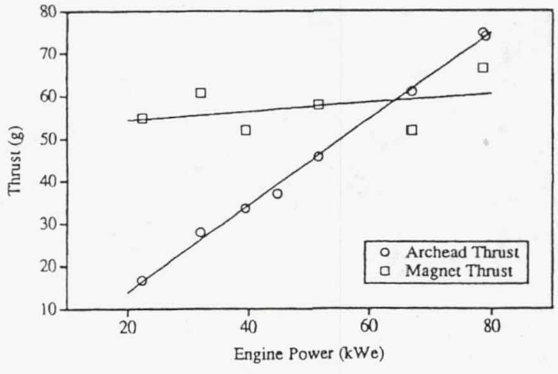
- Operation of radiation-cooled anode up to a power level of 80 kWe was demonstrated on ammonia with no further anode degradation beyond initial melting encountered in earlier testing with argon propellant
- The testing confirms the results of simple thermal modelling which indicated that the open-throated configuration could tolerate higher heat loads

MPD ENGINE PLUME DIFFUSER STUDIES



- Tank pressures are generally higher with ammonia compared to argon, but the diffuser still has a strong effect on the backpressure
- The gasdynamic function of the diffuser and its effect on thruster operation are still not well understood

PRELIMINARY THRUST MEASUREMENTS



- The measurements were made with ammonia propellant and an applied field strength of 646 G
- The magnet thrust appears to be approximately constant, while the engine thrust increases linearly with power
- Similar trends are observed when plotted versus J^2 and JB_z

MPD THRUSTER TECHNOLOGY

Roger M. Myers
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio 44142

IN-HOUSE PROGRAM ELEMENTS

- FOCUSSED ON STEADY-STATE THRUSTERS AT POWERS < 1 MW
- GOALS ARE TO ESTABLISH, EXTEND AND OPTIMIZE

  Thruster Performance
    - Direct performance measurements
    - Diagnostics
    - Modelling

  Thruster Lifetime
    - Alternative cathode concepts
    - Improved seal/insulator designs
    - Heat transfer measurements
    - Diagnostics

and

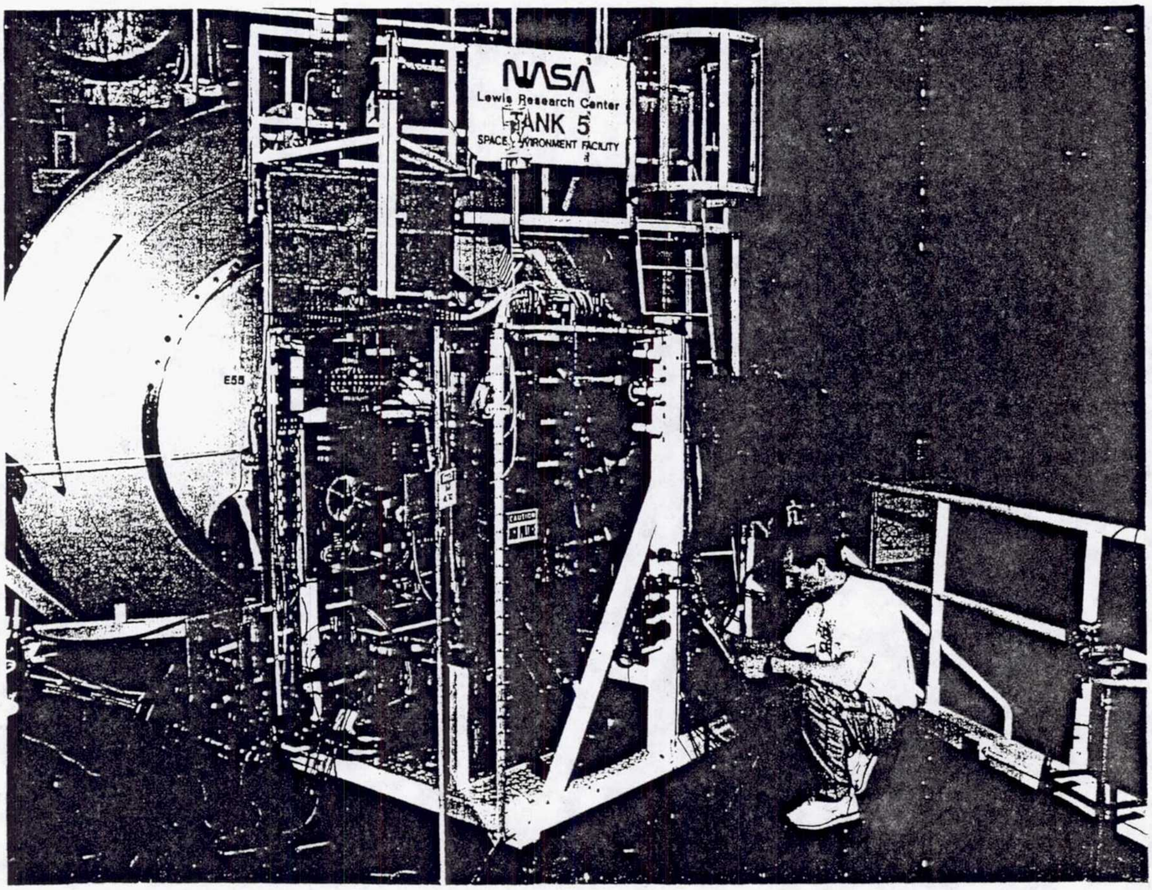
  Facility Capabilities
    - Cryopumping
    - Beam Dumps
    - Lithium facility design

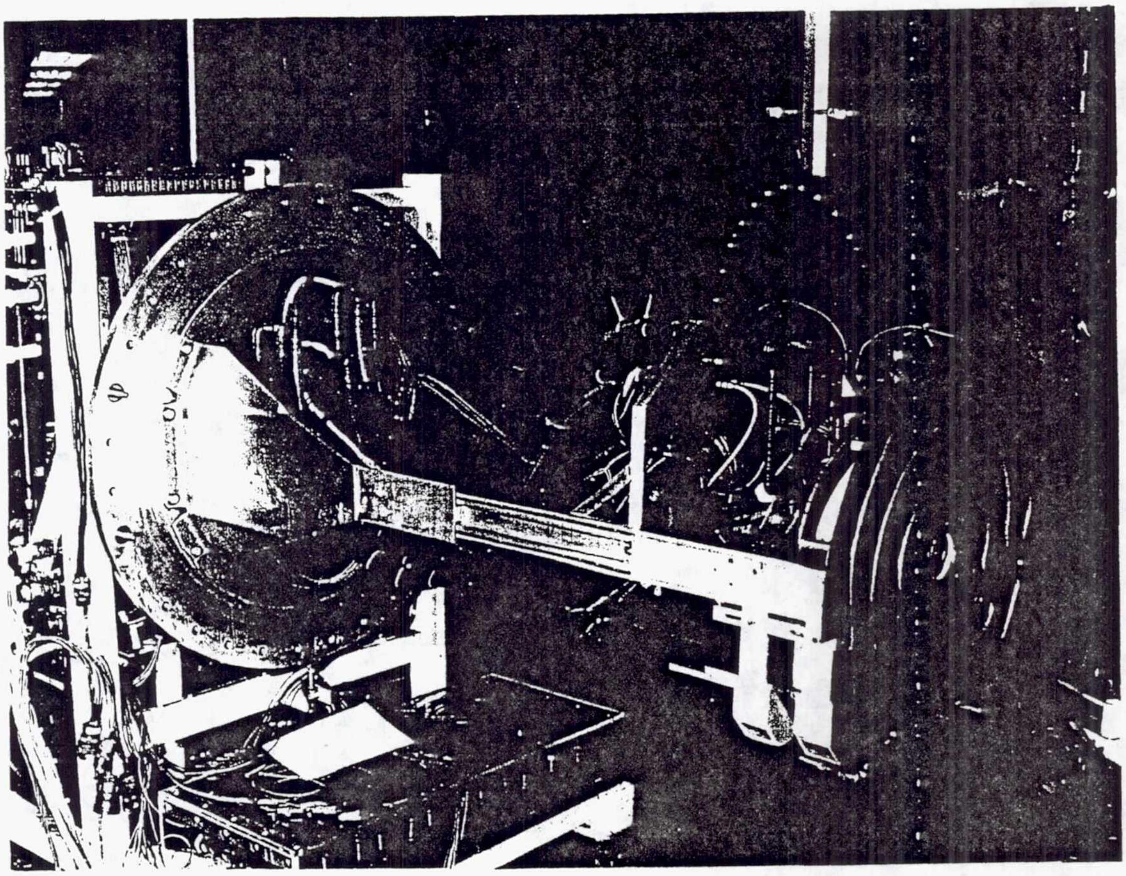
PERFORMANCE MEASUREMENTS
- Progress in Past Year -

- Established new facility for MPD thruster testing (Tank 5)
  - thermal and flow efficiency optimization
  - lifetime studies
  - cannot directly measure performance

- Established scaling laws for 100 kW class applied-field MPD thruster performance
  - Using measurements obtained at Tank 6 facility

- Improved MHD code to 2 Temperature formulation





Applied-Field MPD Thruster Performance Scaling

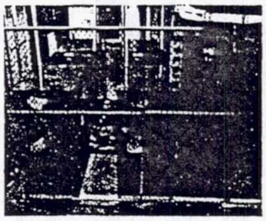
- Testing performed in Tank 6 test facility
  - Pressures below 5×10^{-4} T for all tests
  - Thrust stand accurate to 2%

- Tested 8 cylindrical thrusters at
  - argon flow rates of 0.025, 0.050, 0.10, 0.14 g/s
  - H_2 flow of 0.025 g/s
  - discharge currents of 750, 1000, 1250, 1500, 2000 A
  - applied-field strengths from 0 to 0.2 T

MPD Thruster Technology

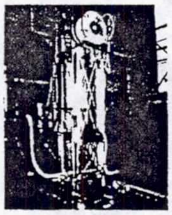
High Power MPD Thruster Test Stand

Power



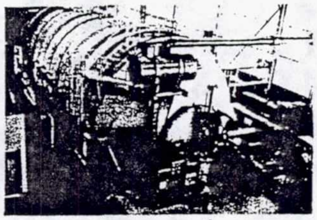
- 0.39 MW

Thrust stand

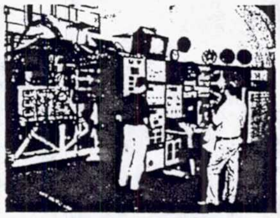


- 0.1 to 4 N

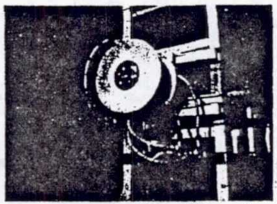
Vacuum facility



- 0.1 g/s at 3×10^{-4} TORR



Data/control

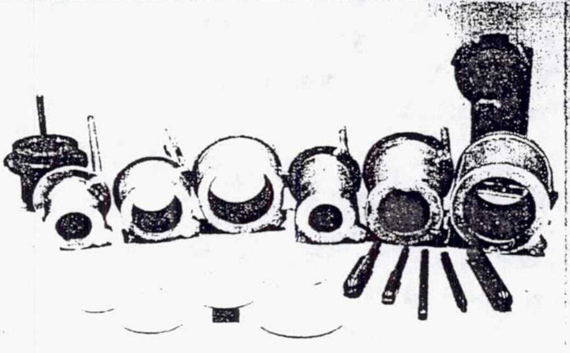


220 kW thruster

CD-91-54820

HIGH POWER ELECTRIC PROPULSION (MPD)

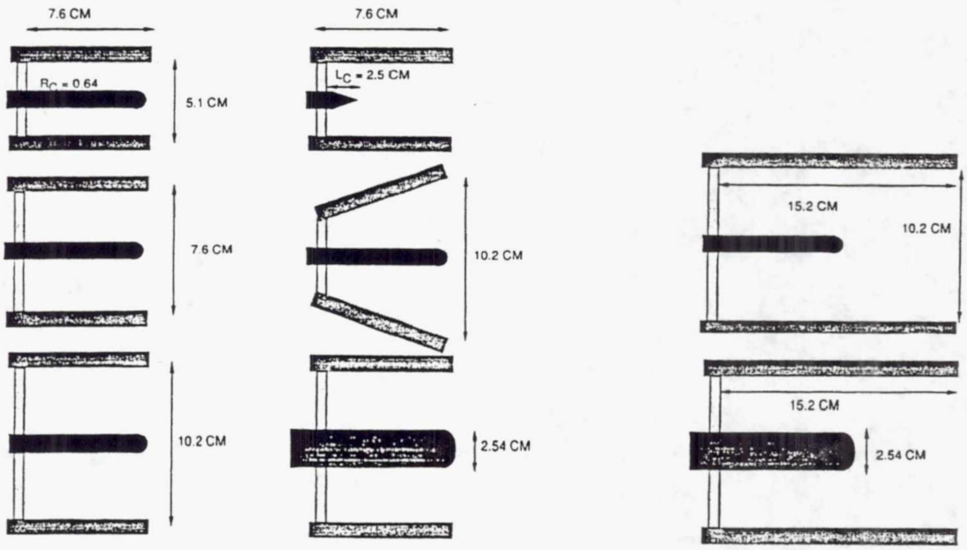
MPD THRUSTER RESEARCH AND TECHNOLOGY –THRUSTER SCALING AND MATERIALS EFFECTS–



- Hardware fabrication complete
  - 2, 3 and 4 inch diameter anodes both 3 and 6 inches long
  - 0.5 and 1 inch diameter cathodes
  - 2% Th and BaO impregnated tungsten cathodes
- Testing underway

CD-90-51110

MPD Thruster Geometries



Applied-Field MPD Thruster Performance Scaling

- Established stable operating envelopes
  - applied-field required
  - maximum J_d or B_z fixed by either cathode erosion or anode heat transfer

- Established empirical thrust scaling law

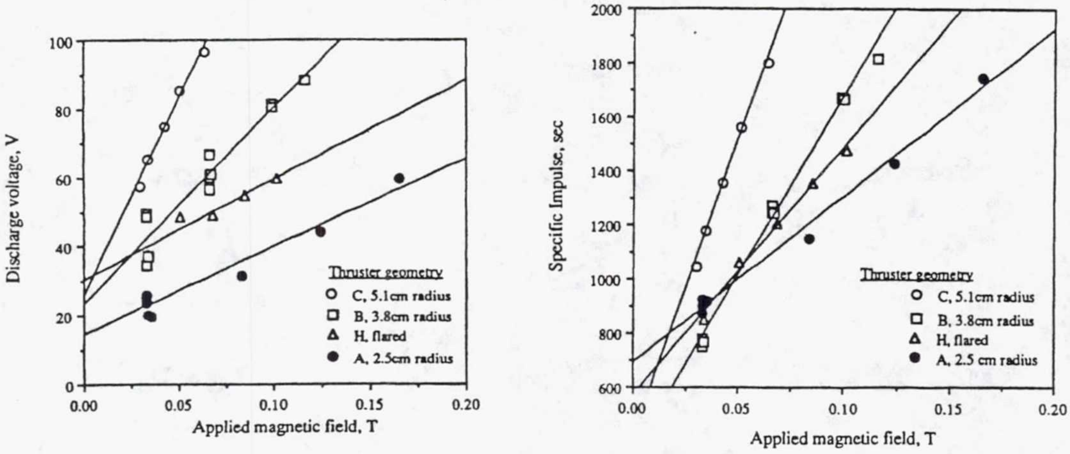
$$T = bJ_d^2 + \frac{R_a^2 J_d B_z}{k_1 L_c R_c} + f(L_a, R_a, \dot{m})$$

  - $I_{sp} \propto 1/\dot{m}$ (maximum was 2400 sec with Ar, 3700 sec with H_2)

- Voltage scaling much more complex
  - increased linearly with B_z
  - only slightly dependent on J_d
  - increased as $1/\dot{m}^n$, where n depended on geometry

EFFECT OF ANODE RADIUS

L_a = 7.6 cm, J_d = 1000 A, 0.1 g/s argon.



Discharge voltage and Isp ~ Ra^2

Applied-Field MPD Thruster Performance Scaling

Efficiency (η)

- Peak efficiency was 24%
- increased with B_z and J_d (but did not scale with J_dB_z)
- rate of efficiency increase with B_z increased rapidly with anode radius
- increased with flow rate

Applied-Field MPD Thruster Performance Scaling

Taking $\eta = \eta_{th}\eta_f$

- **Thermal Efficiency (η_{th})**
    - Defined as 1- $(P_a+P_c)/P$ (measured calorimetrically)
    - peak was 50%
    - increased with B_z, anode radius, and flow rate

- **Flow Efficiency (η_f)**
    - Defined as η/η_{th} (includes all plasma losses)
    - Peak was 67% with H_2 propellant, 60% with Ar
    - generally increased with B_z, decreased with R_a
    - no clear dependence on J_d or $\dot{m}$
    - power balance study showed Ar fully ionized, H_2 10% ionized

- Data showed η_{th} increased with R_a while η_f decreased, resulting in approximately equal maximum efficiencies.
- Must isolate physics to permit overall optimization.

Thermal Efficiency Scaling

- Governed by Anode Power Loss
    - Measured calorimetrically

- Isolated V_{an} using

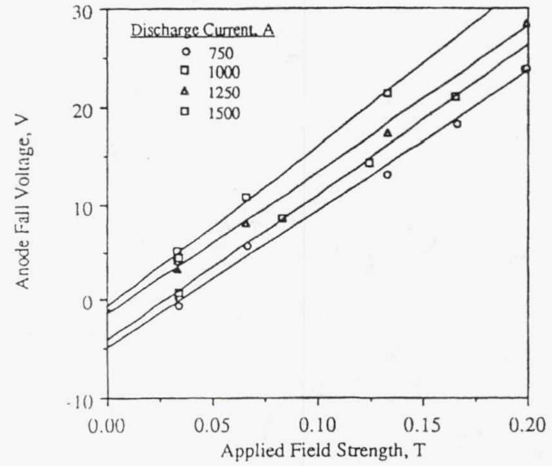
$$V_{an} = \frac{P_a - P_r^c}{J_d} - \left(\frac{5kT_e}{2e} + \Phi\right)$$

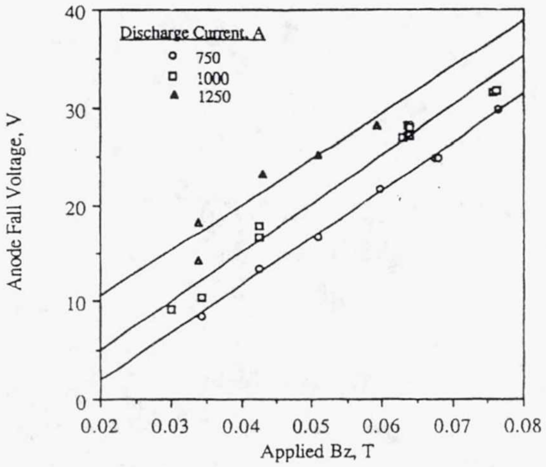
    - Cathode radiation contributed between 2 and 7 kW

- Found
    - V_{an} ranged from - 2 V to + 42 V
    - Increased linearly with B_z
    - Increased with anode radius
    - Decreased with increasing $\dot{m}$
    - minimum V_{an} increased with J_d

- ALL ANODE FALL MEASUREMENTS ARE CONSISTENT WITH MAGNETIZED FALL REGION

Anode Fall Voltage Measurements


$R_a = 2.54$, $\dot{m} = 0.1$ g/s


$R_a = 5.1$, $\dot{m} = 0.14$ g/s

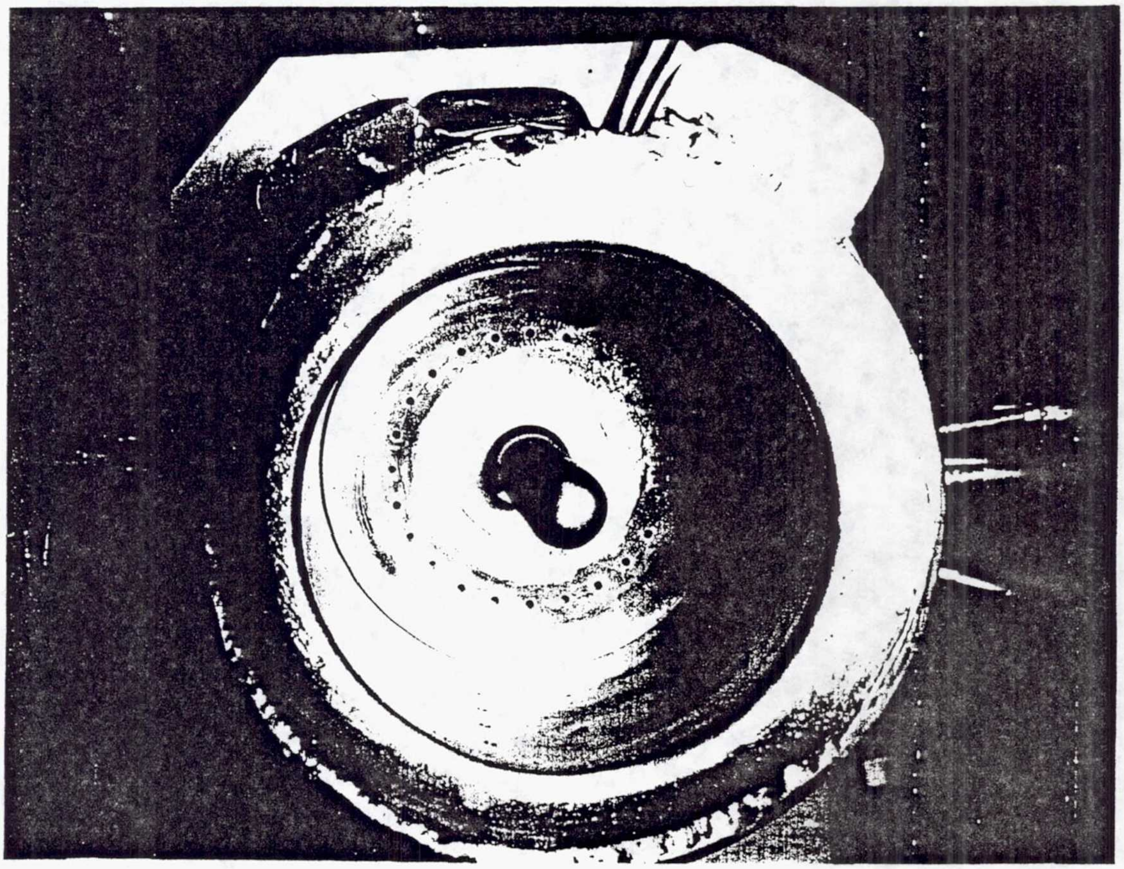
- Anode fall increases with Bz and Ra
- Anode fall decreases with increasing m

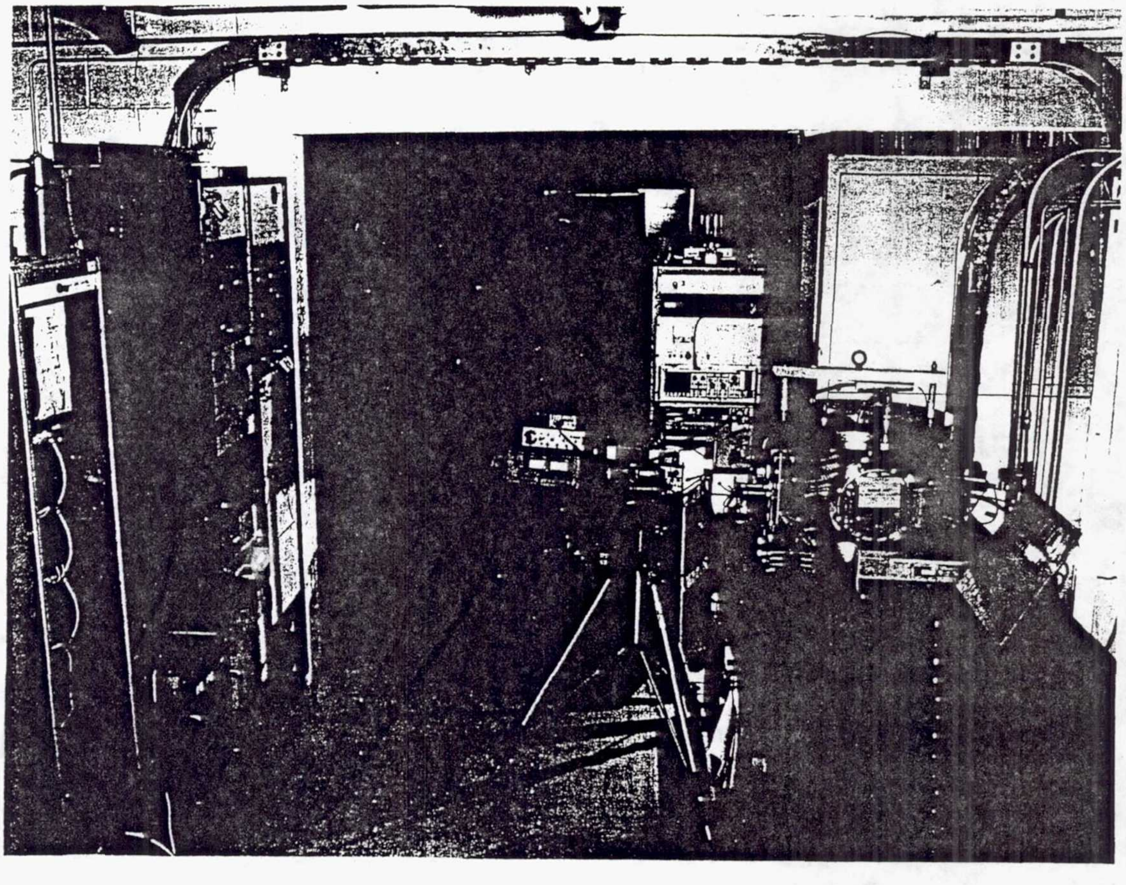
Anode Power Deposition Studies

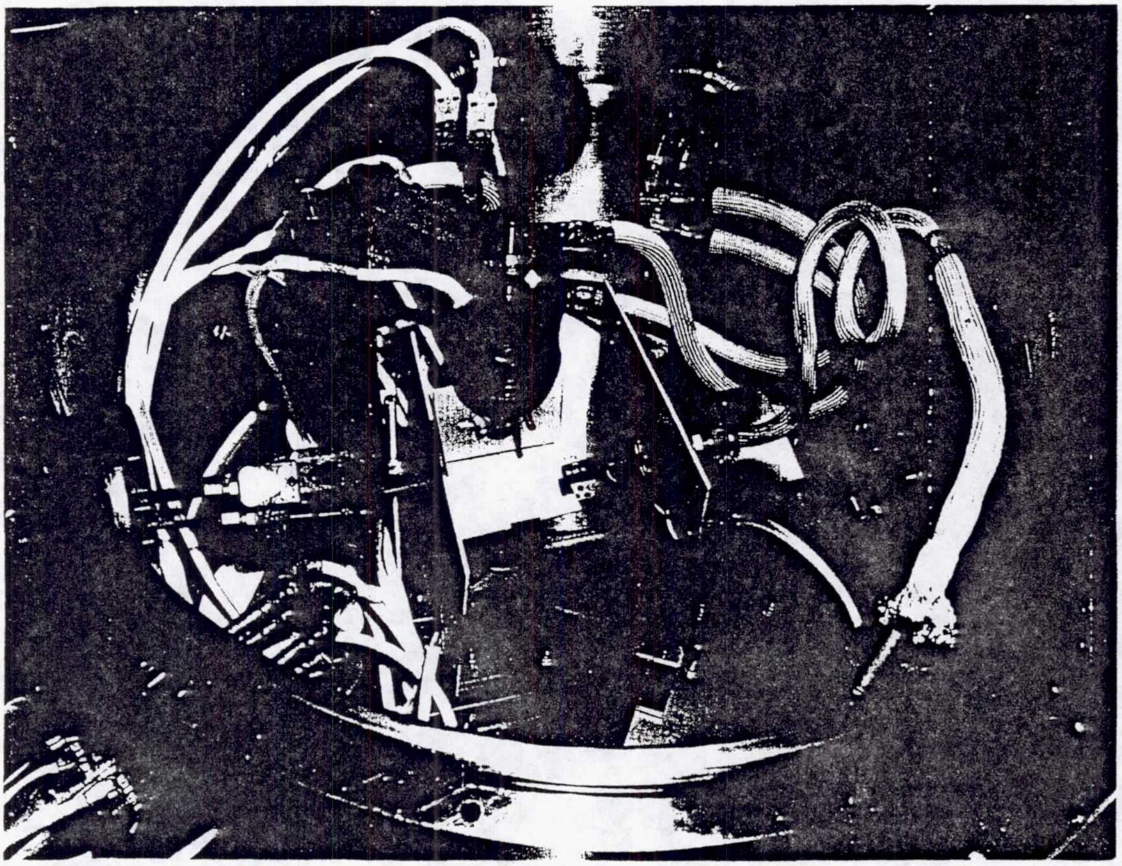
- Measurements of plasma properties at anode surface
  - designed, built, and tested thruster with diagnostics at anode surface
  - include electrostatic and pressure probes
  - will include spectroscopy and current density probes

- Non - cylindrical chambers
  - built and performed preliminary tests of converging anode thruster

- Established Bench-top experiment for fundamental studies
  - measured anode power deposition and relevant plasma properties as a function of pressure, current density, applied field strength and orientation, and anode work function.

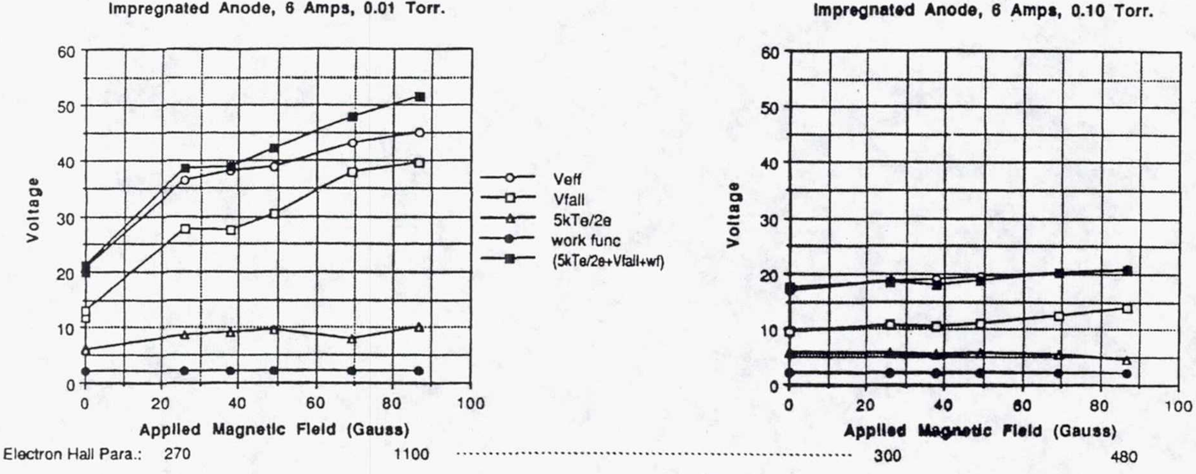






Anode Power Contributions

Effect of Applied Magnetic Field and Anode Pressure



1. Anode Power increases with increasing Applied Magnetic Field.
2. Fall Voltage increases with increasing Applied Magnetic Field.
3. Electron Temperature remains relatively unchanged.
4. Anode Power more sensitive to Applied Magnetic Fields at lower anode pressures.

FLOW EFFICIENCY STUDIES

- Includes ionization, viscous, and divergence losses, and unrecovered azimuthal kinetic power
  - ionization does not dominate for larger thrusters
  - evidence for spin includes helical sputter pattern on anode with large anode thrusters
- Low H_2 ionization fraction at 3700 sec I_{sp} indicates presence of some form of ion-neutral coupling
  - charge-exchange
  - momentum
- Established new diagostics capability in Tank 5 facility
  - improved probe motion control
- Measurements include
  - electron density and temperature
  - stagnation pressure
  - emission spectroscopy

- Must establish scaling of flow losses
  - may involve plasma/B-field separation

MPD THRUSTER PLASMA MODELING

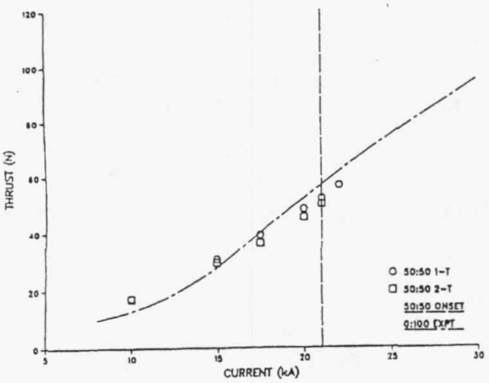
APPROACH

- 2-D, SELF-FIELD, STEADY-STATE CODE
- BASED ON SINGLE FLUID MHD EQUATIONS
- TWO-TEMPERATURE APPROXIMATION (T_e, T_i)
- CLASSICAL PLASMA TRANSPORT COEFFICIENTS
  - VISCOSITY
  - THERMAL CONDUCTIVITY
  - ELECTRICAL CONDUCTIVITY
- PRESENT MODEL ASSUMES FULL IONIZATION

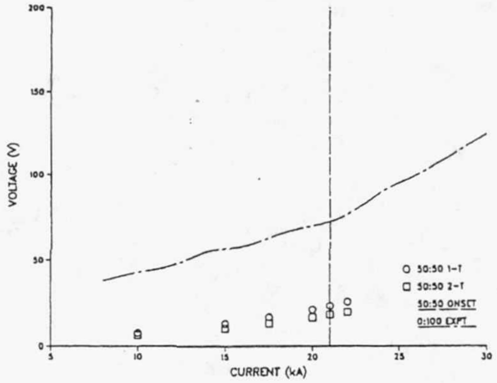
MPD THRUSTER PLASMA MODELING

1-T, 2-T MODEL COMPARISONS
PRINCETON EXTENDED ANODE MPD THRUSTER
(6 g/s Argon)

THRUST vs CURRENT



VOLTAGE vs CURRENT



- THRUST AGREES BELOW MEASURED ONSET VALUE
- CALCULATED VOLTAGE ONLY INCLUDES PLASMA FALL

MPD THRUSTER PLASMA MODELING

NUMERICAL EXPERIMENTS

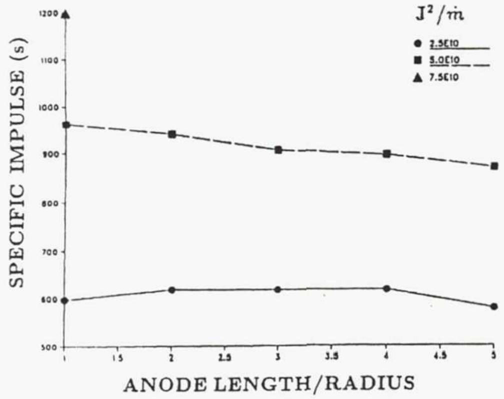
- EXTENDED ANODE MPDT: NO STEADY-STATE CODE CONVERGENCE FOR $J^2/\dot{m}$ VALUES ABOVE ONSET
  - POSSIBLE CORRELATION BETWEEN NUMERICAL STABILITY AND STABLE REGIONS OF MPD THRUSTER OPERATION
- NUMERICAL EXPERIMENTS PERFORMED TO EVALUATE GEOMETRIC SCALING EFFECTS ON MPD THRUSTER PERFORMANCE:
  - STRAIGHT CYLINDRICAL GEOMETRIES, $L_a = L_c$
    - $R_a = 2.5$ cm, $R_c = 0.5$ cm, $1 \leq L_a/R_a \leq 5$
    - $R_a = 5.0$ cm, $R_c = 0.5$ cm, $1 \leq L_a/R_a \leq 5$
    - $R_a = 5.0$ cm, $R_c = 1.0$ cm, $1 \leq L_a/R_a \leq 5$
  - UNIFORM GAS INJECTION, $\dot{m} = 1$ g/s (Ar)

MPD THRUSTER PLASMA MODELING

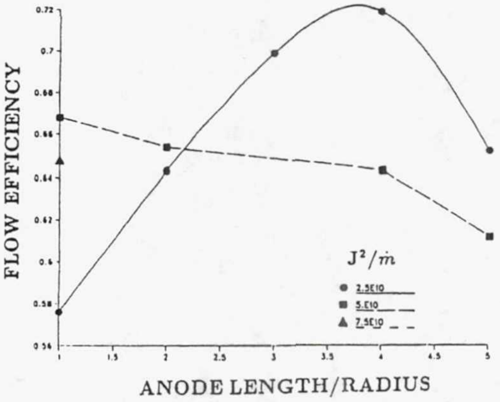
GEOMETRIC SCALING RESULTS

$R_a = 5$ cm, $R_c = 1.0$ cm, $L_a = L_c$, $\dot{m} = 1$ g/s (Ar)

SPECIFIC IMPULSE
vs
ANODE LENGTH/RADIUS



FLOW EFFICIENCY
vs
ANODE LENGTH/RADIUS



MPD THRUSTER PLASMA MODELING

NUMERICAL STABILITY REGIONS

- OSCILLATIONS OBSERVED IN STEADY-STATE, 2-T CODE SOLUTIONS UNDER CERTAIN OPERATING CONDITIONS
  - FUNCTION OF THRUSTER GEOMETRY, DISCHARGE CURRENT
- NUMERICAL STABILITY RELATION DERIVED:

$$\left(\frac{J^2}{\dot{m}}\right)_c \leq \frac{6.25 \times 10^9}{R_c}\left(\frac{L_c}{L_a}\right)\left[5 - \left(\frac{L_a}{R_a}\right) + 4\left(\frac{10R_c - R_a}{2.5}\right)\right] \qquad \frac{A^2 - s}{kg}$$

(NOTE: THRUSTER DIMENSIONS IN CENTIMETERS)

- TESTED AGAINST EXPERIMENTAL DATA BASE (PREBLE)
- STABILITY EQUATION PREDICTS MPDT ONSET (±20%) FOR:
  - GEOMETRIES WHICH FALL WITHIN MODEL CONSTRAINTS
  - 50:50 BACKPLATE INJECTION, ARGON PROPELLANT

MPD THRUSTER PLASMA MODELING

GEOMETRIC SCALING RESULTS

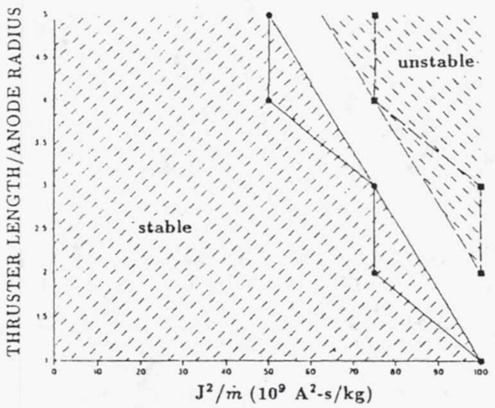
- HIGHEST I_{sp}, η_f FOR $R_a = 5$ cm, $R_c = 1$ cm, $L_a/R_a = 1$
  - $I_{sp} \approx 1400$ s, $\eta_f \approx 0.76$
  - NO STEADY-STATE CONVERGENCE FOR LARGER L_a/R_a
- GENERAL SCALING RELATIONS:
  - OPERATION AT LOW $J^2/\dot{m}$ REQUIRES LONG ELECTRODES FOR IMPROVED η_f
  - HIGH $J^2/\dot{m}$ REQUIRES SHORT ELECTRODES FOR STABLE OPERATION
  - SMALL DIAMETER THRUSTERS HAVE A LARGER RANGE OF STABLE OPERATION THAN THEIR LARGE-SCALE COUNTERPARTS
  - FOR THRUSTERS WITH EQUAL ANODE RADII, SMALLER ASPECT RATIOS PROVIDE A LARGER RANGE OF STABLE OPERATION
  - THRUSTERS WITH LARGE ASPECT RATIOS REQUIRE SHORT ELECTRODE LENGTHS FOR STABLE OPERATION

MPD THRUSTER MODELING

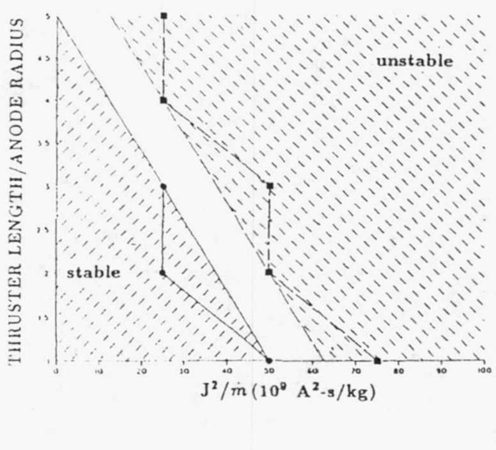
STEADY-STATE MODEL CONVERGENCE

$L_a = L_c$, $\dot{m} = 1$ g/s (Ar)

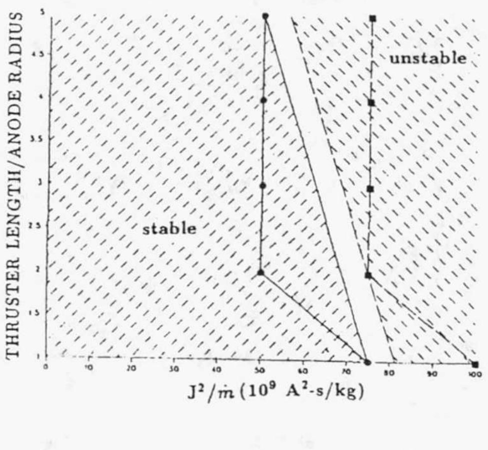
Ra=2.5 cm, Rc=0.5 cm



Ra=5.0 cm, Rc=0.5 cm



Ra=5.0 cm, Rc=1.0 cm

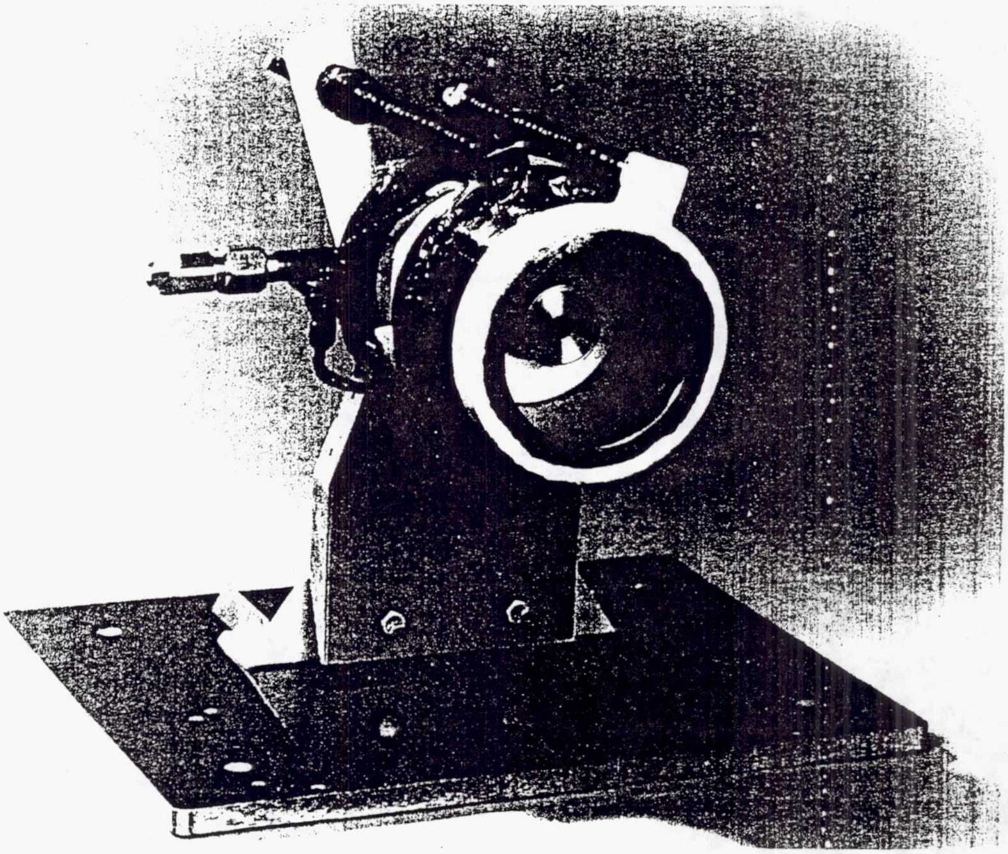


MPD Thruster Lifetime Studies
- Progress in Past Year -

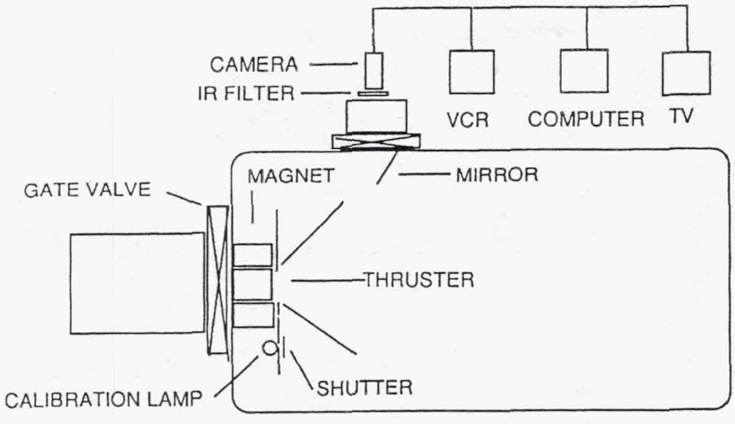
- Alternative Cathode Concepts
  - Extensive hollow cathode testing
  - Low work function rod cathode testing
  - Improved cathode cooling
  - Identified long-life pulsed cathode technology

- Initiated extensive thermal map of all thrusters during operation
  - Establish long term viability of seals/joints
  - Identify long term causes of thruster performance and lifetime degradation

- Diagnostics
  - *Cathode surface temperature measurements with in-situ calibration*
  - Internal probing of hollow cathodes (with OSU)

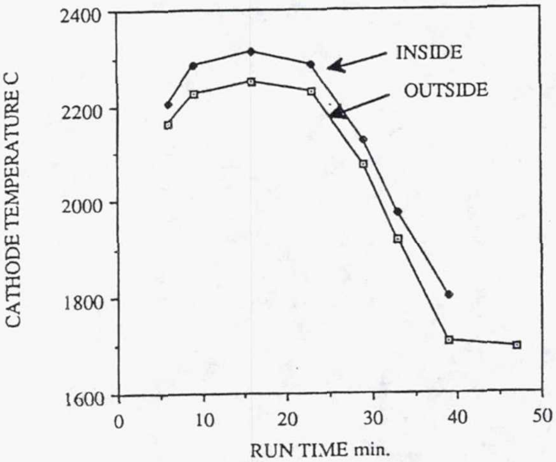


SCHEMATIC OF MPD CATHODE TEMPERATURE MEASUREMENT SYSTEM WITH IN-SITU CALIBRATION

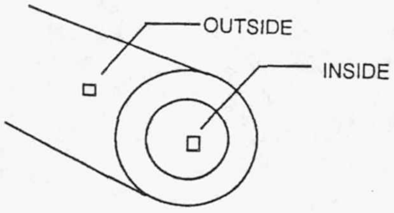


(NOT TO SCALE)

HOLLOW CATHODE TEMPERATURE MEASUREMENTS WITH IN-SITU CALIBRATION



HOLLOW CATHODE TEMPERATURES VS TIME
Discharge Current - 1000 A, Propellant flow rate - .1 g/s
Magnetic field coil current - 200 A



HOLLOW CATHODE TEMPERATURE MEASUREMENT LOCATIONS

PRELIMINARY TEMPERATURE MEASUREMENT RESULTS

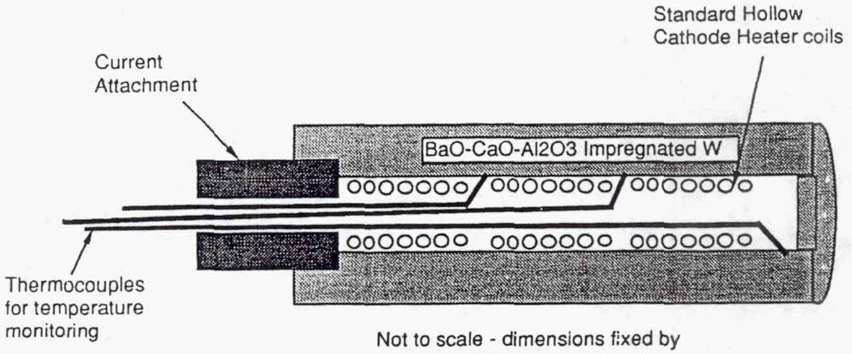
HOLLOW CATHODE TEMPERATURES INCREASE WITH:

- * INCREASING DISCHARGE CURRENT
- * INCREASING APPLIED MAGNETIC FIELD
- * DECREASING CATHODE FLOW RATE
- * ADDITION OF HYDROGEN TO ARGON

Long-Life Pulsed Cathode Technology

- Benefits
  - enables pulsed thruster systems
  - ease of power scaling via pulse frequency
  - helps eliminate uncertainties of quasi-steady testing
  - potential efficiency improvements
- Use internally heated low work function material
  - multiple heaters will permit axial temperature control
- Size cathode so that current density < 20 - 30 A/cm^2 during discharge
- Continuously monitor temperature to prevent overheating material
  - heater power can be adjusted to compensate for discharge power deposition

Long-Life Pulsed Cathode Technology



Not to scale - dimensions fixed by current and lifetime requirement.

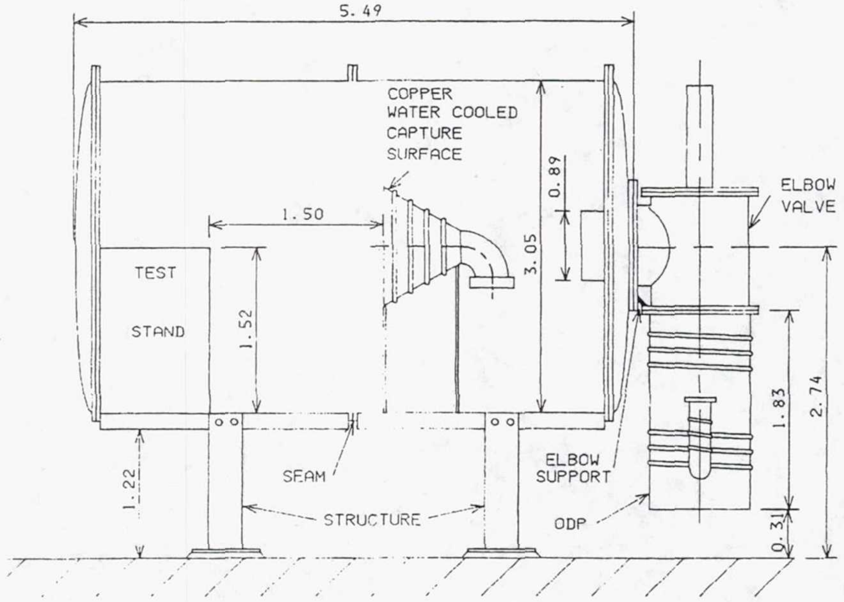
Use independent heater coils to permit axial temperature control. Monitoring temperature permits reduction in heater power as discharge power deposition increases

Facility Capabilities
- Progress in Past Year -

- Gaseous He cryosystem now operational
    - 41 m^2 of cryosurface
    - 300 W refrigeration system
    - demonstrated 387,000 l/s pumping speed (3 x 10^{-4} T at 0.2 g/s Ar)

- Lithium MPD thruster test facility design complete
    - 10' x 20' stainless steel tank
    - 50,000 l/s ODP for pump-out
    - use beam dump to minimize clean-up and safety issues

Lithium MPD Thruster Test Facility



INTERNAL AND EXTERNAL SCHEMATIC
DIMENSIONS IN METERS

MPD Thruster Performance Studies

- Plans -

- Increase thruster power level to 350 kW
  - expand operating envelope and establish performance scaling
- Establish effect of anode and applied-field shape on thermal and flow efficiencies
  - allow parallel transport into anode
  - establish magnitude of divergence and unrecovered azimuthal kinetic power losses
- Establish effect of propellant injection geometry on thermal efficiency
  - anode gas injection to reduce surface Hall parameter
- Improve MHD model by adding
  - Ionization effects
  - Applied-magnetic field
  - anomalous transport
- Measure performance of Lithium MPD thrusters
  - 20 - 50 kW radiation cooled thruster
  - use short-term tests to establish performance trends

MPD Thruster Lifetime Studies

- Plans -

- 100 hr at 100 kW test
  - establish capability of long term operation
- Improve surface temperature measurement system
  - implement 12 bit camera
  - improve emissivity correction
- Establish surface temperature data base for hollow and rod cathodes
  - effect of geometry and operating condition
- Identify and eliminate causes of insulator failure
  - BN cracking now a major cause of test failure
- Map hollow cathode plasma properties (with OSU)
  - verify hollow cathode scaling model
- Implement long-life pulsed cathode technology and test
  - cooperative program with Princeton University to measure performance effects.

FACILITIES
- PLANS -

- Demonstrate liquid He cryopumping for H_2 MPD thrusters
    - use dewar to store liquid He for batch processing
- Complete construction of lithium facility and measure thruster performance
    - establish requirements for plume backflow measurements
- Implement diagnostics needed for performance and lifetime optimization

LOS ALAMOS RESEARCH IN NOZZLE BASED COAXIAL PLASMA THRUSTERS

Jay Scheuer, Kurt Schoenberg, Richard Gerwin,
Ivars Henins, Ronald Moses, Jr., and Glen Wurden
Los Alamos National Laboratory
Los Alamos, New Mexico

COAXIAL THRUSTER RESEARCH

Outline

- Research Approach
- Perspectives on efficient MPD operation
- NASA and DOE supported research
    - Ideal MHD plasma acceleration and flow
    - Electrode phenomena
    - Magnetic nozzles
- Future research directions and plans

COAXIAL THRUSTER RESEARCH

Collaborators and Contributors

- Cris Barnes
- Robin Gribble
- John Marshall
- Don Rej
- Blake Wood
- Tom Jarboe, U. Washington
- Robert Mayo, N.C. State

COAXIAL THRUSTER RESEARCH

Research Approach

NEAR TERM FOCUS:

- Apply coaxial plasma gun research experience to optimizing thruster efficiency and specific impulse
- Ascertain scaling properties in terms of size and power
- Investigate performance and thruster design at power levels and sizes applicable to "near term" missions like orbital transfer
  - In steady-state
  - For adjustable duty-cycle (pulsed)
- Apply insights to the design of more efficient MPD thrusters

LONGER TERM FOCUS:

- Pursue MMWe coaxial thruster optimization for farther term propulsion missions and other applications

Efficient MPD Operation

Perspectives

In addition to frozen flow losses, efficiency is limited by two processes:

- Macro plasma acceleration and detachment
  - Efficient operation ⇛ High grade plasma
  - High grade plasma ⇛ Ideal MHD
  - Ideal MHD ⇛ Economy of scale
- Electrode phenomena
  - Electrode fall losses are strongly coupled to magnetic configuration

These processes are coupled by the Electrical Effort (Morozov Hall parameter) *

$$\Xi \equiv \left(\frac{m_i}{e}\right)\frac{I}{\dot{M}} \approx \left(\frac{c}{\omega_{pi}}\right)\frac{1}{\Delta}$$

* Schoenberg, et al., AIAA 91-3770 (1990)

EFFICIENT MPD OPERATION

Perspectives (continued)

- Good MHD performance drives $\Xi << 1$ (relevant to ion acceleration losses)

- Minimization of electrode phenomena also drives $\Xi << 1$ (relevant to electrode losses)

- Plasma stability considerations places bounds on Ξ
  - Upper bound set by Lower Hybrid Drift Instability
  - Lower bound set by beta limits (Raleigh-Taylor, Kelvin-Helmholtz) in high grade plasma systems

These perspectives lead
to an optimization approach

EFFICIENT OPERATION AND CONTROL

Magnetic Nozzle

Dominance of MHD leads to the efficacious use of magnetic nozzles for optimization of:

- Macro plasma acceleration and detachment
- Electrode phenomena
- Plasma stability

NASA and DOE SUPPORTED RESEARCH

Unoptimized "As-was" Experiments

- Power range 10-40 MW
- Unoptimized gun
- Unoptimized 2.5 MJ capacitor bank
  - 1 ms, round-top discharges
- Unoptimized $B_{r,z}$ (nozzle) field
  - Applied field coil in center electrode (cathode)
- Wide range of diagnostics
  - Multi-chord interferometry
  - Temporally and spatially resolved bolometry
  - Langmuir and magnetic probes
  - Temporally and spatially resolved IR calorimetry
  - Neutral particle spectroscopy

NASA and DOE SUPPORTED RESEARCH

Plasma Acceleration and Flow

Previous work has derived parametric expressions for plasma acceleration, flow, and detachment*

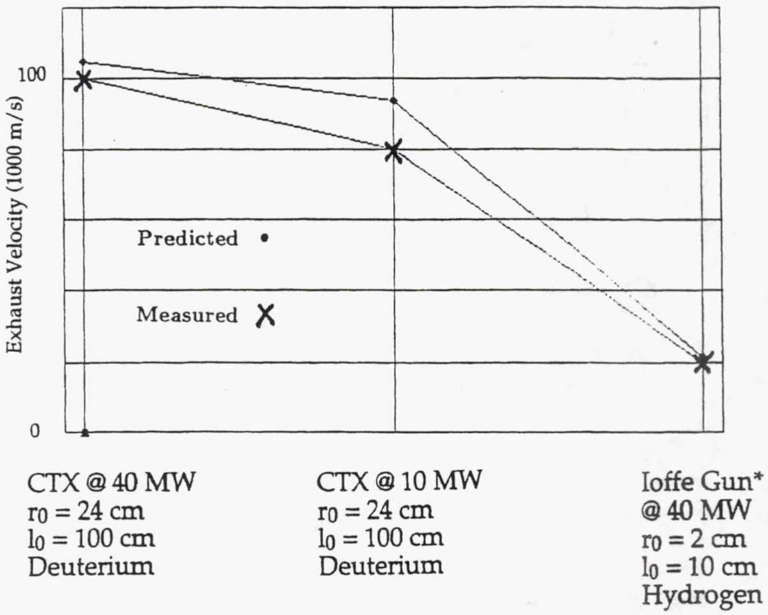
- Experiments have shown that plasma flow is accelerated to the magnetosonic velocity in agreement with theory
- High grade plasma observed
  - Magnetic Reynolds number ≈ 1000
  - $\Xi < 0.5$
- Coaxial gun research shows remarkable agreement between MHD flow predictions and experiment over a wide range of size and power

* Gerwin, et al., AFOSR Report AL-TR-89-092, (1990),

Schoenberg, et al., AIAA 91-3770 (1990), and

Moses, et al., Proceedings of 9th Symposium on Space Nuclear Power Systems (1992).

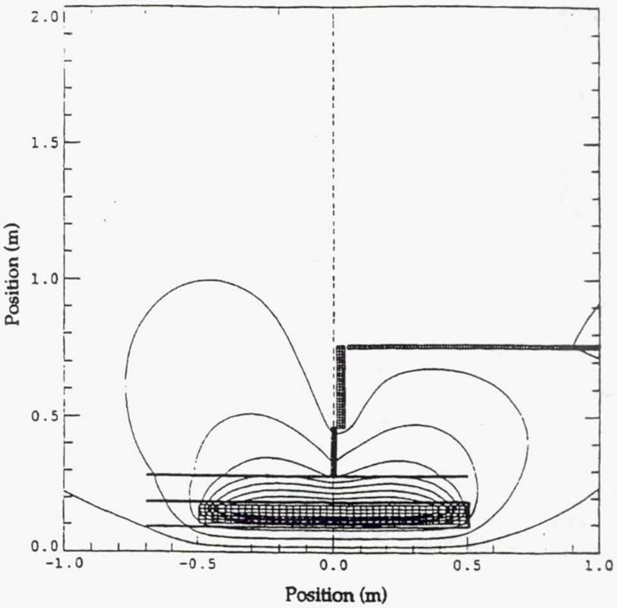
COAXIAL GUN FLOW VELOCITY



* Afanas'ev et al., Sov. Phys. Tech. Phys., 36, 505 (1991)

NASA AND DOE SUPPORTED RESEARCH

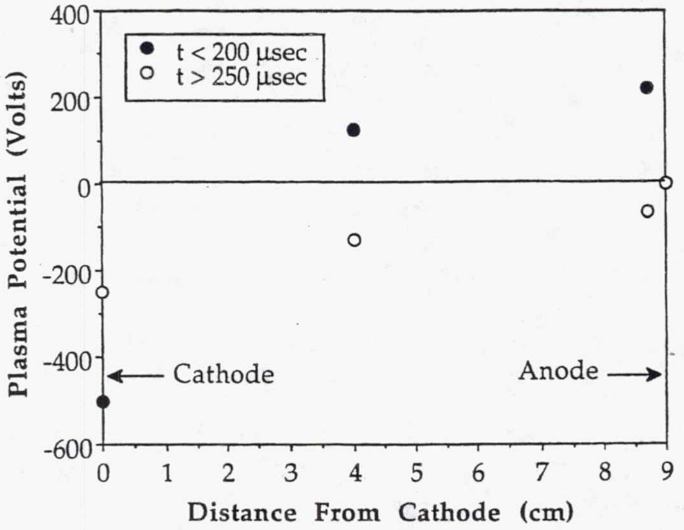
Electrode Phenomena



- Calculation of vacuum field at time of shot
- Field lines connect anode to cathode
- Field lines distort due to plasma flow

ANODE FALL

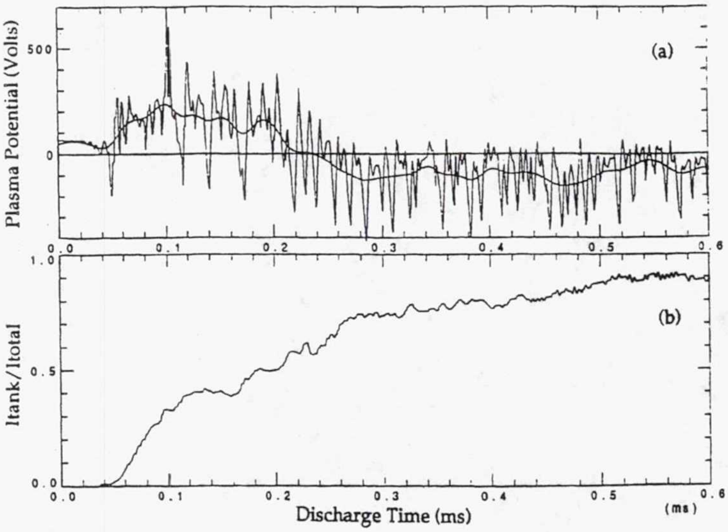
Plasma Potential Measurements



- 40 MW shots
- Floating Langmuir probe measurements
- Anode fall **reversed** for t < 200 μs

ANODE FALL

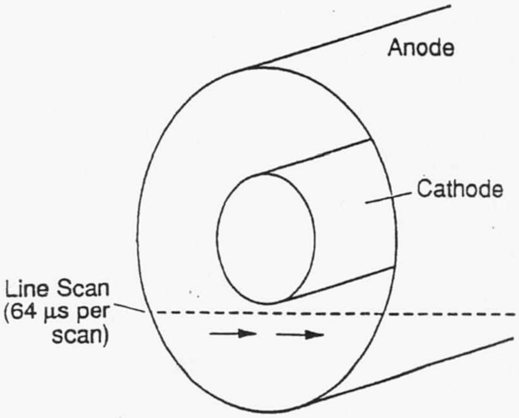
Evolution of Magnetic Field Structure



- Field lines connect cathode to anode at early times
- As discharge evolves, plasma stretches field lines thereby connecting cathode to tank wall

INFRARED ELECTRODE CALORIMETRY

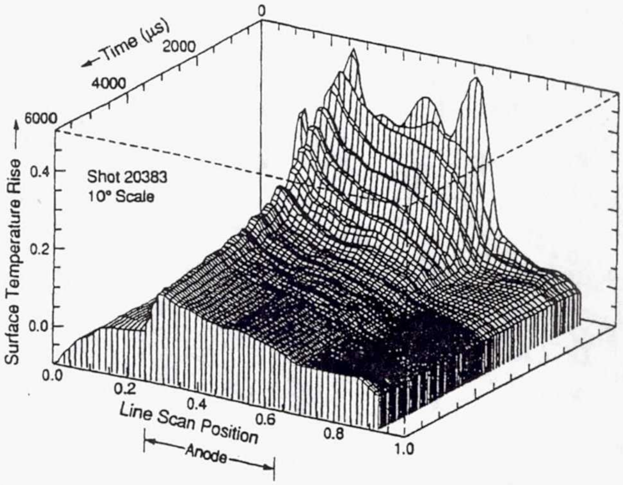
Experimental Setup



- Infrared video camera in line scan mode used to measure electrode temperature
- Temperature rise converted to energy flux

INFRARED ELECTRODE CALORIMETRY

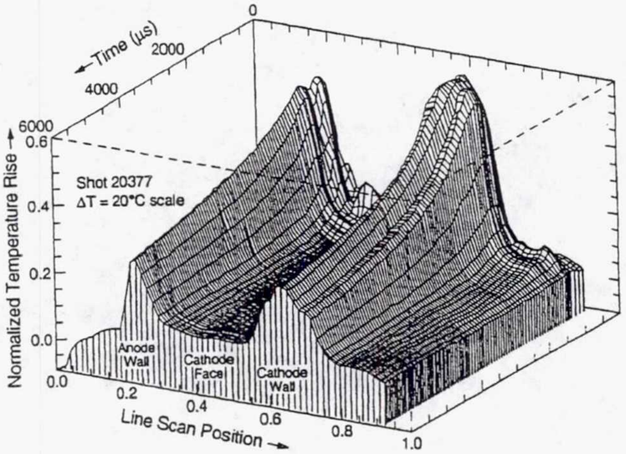
Results for 15 MW Shot



- Energy flux ≈ 13 MW/m^2 deposited on anode for 15 MW shot

INFRARED ELECTRODE CALORIMETRY

Results for 40 MW Shot



- Energy flux ≈ 30 MW/m^2 deposited on anode for 40 MW shot

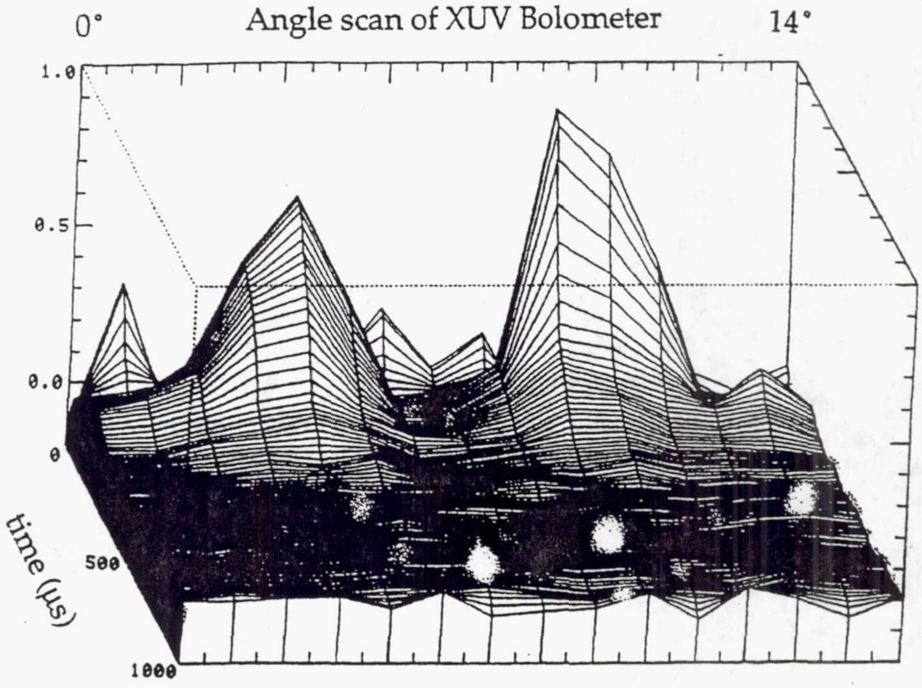
INFRARED ELECTRODE CALORIMETRY

Interpretation of Results

A comparison of measured energy flux to that predicted by the anode fall data has been made.

- For 40 MW discharge $P_{anode} \approx \Gamma_{thi} \times 200$ eV = 40 MW/m^2
- Reasonable agreement with IR data

BOLOMETRY



- XUV photodiode used to measure absolute radiation losses *
- Radiative power loss of 3-6% for 10-40 MW shots

* Maqueda and Wurden, to be published in Rev. Sci. Inst.

ELECTRODE PHENOMENA

Conclusions

- Magnetic configuration can affect/control anode fall
- Temporally and spatially resolved electrode calorimetry in reasonable agreement with power loss to anode from ion flux
- Radiative losses small (less than 10%)
- Global power balance estimates in progress

COAXIAL THRUSTER RESEARCH

Future Research Directions and Plans

- New facility design for 10 MW, 10 ms, flat-top (quasi-steady state) operation with mass flow control
- Electrically isolate anode from tank wall
- Repeat electrode loss, plasma flow, power balance, and spatial magnetic field measurements on unoptimized gun under quasi-steady-state operation
- Theory/modeling support to evolve capabilities
- Design and test of an optimized gun with new magnetic nozzle
- Apply research conclusions to MPD thruster design

REVIEW OF RECENT WORK ON MPD THRUSTERS AT MIT

Daniel Hastings
Massachusetts Institute of Technology
Cambridge, Massachusetts

Outline

- Basic Philosophy of MIT SPPL work
- 2-d numerical MPD simulations: E. Niewood; Ph.D
- Analysis of MPD boundary layers; J.M Chanty; Ph.D
- Ignition of MPD thrusters; E. Sheppard; Ph.D

Basic Philosophy

- Develop a basic research program to consider some of the underlying physics issues associated with MPD thrusters
  - Complete analysis of classical 2-d flow inc. Hall effect, viscosity, ion slip etc..
  - Correct appreciation for the boundary conditions associated with the various types of boundary layers
  - Understand the ignition process in an MPD thruster

MPD Simulations

A good numerical simulation would be useful to help:

- determine important physical effects
- predict performance
- determine plasma parameters at many locations
- design better thrusters

Existing Multidimensional Simulations

- Sleziona et. al at IRS. - Axisymmetric simulation with non-equilibrium temperature and frozen or equilibrium ionization.
- LaPointe at NASA Lewis - Axisymmetric one fluid simulation with fluid transport. Complex geometries.
- Caldo et. al at Princeton - Axisymmetric simulation with thermal and ionizational non-equilibrium. Inviscid. Includes anomalous transport.

Previous SPPL Modeling

- Numerical axi, MHD simulation - Chanty, 1987
- Analytical 1-d, 1-fluid solution - Martinez 1987,1992
- Numerical 1-d, 2-fluid simulation- Niewood 1989,1991
- Numerical 2-d, 2-fluid simulation- Niewood 1991
- Numerical 2-d, 2-fluid simulation- Miller 1991
- Numerical axi, 2-fluid simulation- Niewood 1991

Present Focus

Recent and current modeling focuses on desire to

- include as much of relevant physics as possible
- obtain solutions at high power and in electromagnetic regime
- determine importance of Hall effect, particularly with regard to starvation and anode voltage drops.

Status At Last Meeting

Two dimensional two fluid simulation developed including:

- Non-equilibrium ionization.
- Thermal non-equilibrium.
- Electron heat conduction.

Near anode voltage drops shown to be similar to those observed experimentally.

Progress

Additions to model include:

- Axisymmetric formulation.
- New ionization model. Old Hinnov- Hirschberg model overpredicted ionization and recombination. New model based on examination of detailed kinetics by Sheppard.
- Other cylindrical geometries.

Progress

- Neutral slip. Separate momentum equations in each direction for ions and neutrals. Collisional drag between species couples velocities.
- Catalytic wall boundary conditions. All ions which reach the wall return to the plasma as neutrals.

Progress

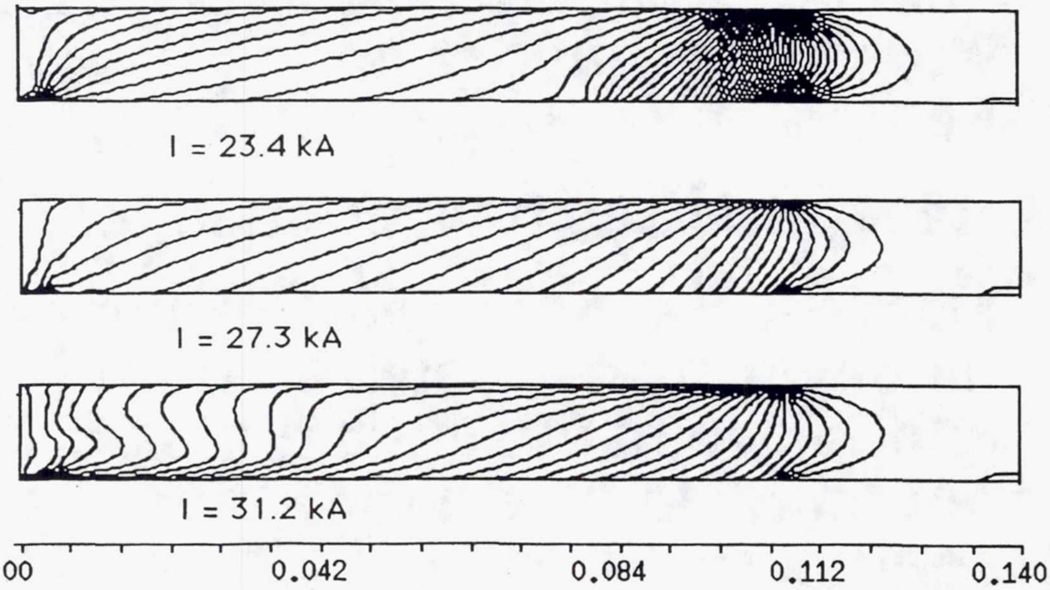
- New viscosity model. Must include substantial slip. Based on work by Fernandez and Fernandez.(Physics of Fluids, July 1987)
- Heavy species heat conduction.
- Magnified anode layer. Simpler model is solved between last interior point of simulation and boundary to give anode boundary conditions.

Results: Different Cases

Four cases under examination.

- Case 1 - Thruster length = 0.14m, electrode length = 0.1m, interelectrode gap = 0.02 m, cathode outer radius = 0.052 m, mass flow = 4 g/s, current = 23.4 kA. Converged solution obtained.
- Case 2 - Same as Case 1 with current = 27.3kA. Stable solution obtained, converging.
- Case 3 - Same as Case 1 with current = 31.2 kA. Solution is stable, but oscillating, not converging.
- Case 4 - Thruster length = 0.1m, electrode length = 7.6cm, interelectrode gap = 1.6 cm, cathode outer radius = 0.48cm, mass flow = 1 g/s, current = 3.4kA. Solution stable, converging?

Results: Current Contours



Results: Voltage and Voltage Drops

Case 1: I = 23.4 kA, Vtot = 8.1V,
Vanode ~ 0

Case 2: I = 27.3 kA, Vtot = 14.6 V,
Vanode ~ 2.6 V

Case 3: I = 31.2 kA, Vtot = 33 V,
Vanode ~ 18 V

Case 4: I = 3.4 kA, Vtot ~ 6 V,
Vanode < 0

Results: General

- Hall effect leads to skewing of the current lines and substantial starvation of the near anode region.
- These effects in turn could be responsible for the large anode voltage drops observed experimentally.
- A better understanding of starvation, its causes, and its effects could lead to significantly improved efficiency for MPD thrusters.

Results: General

- Anode starvation could cause extreme sensitivity to small tank back pressures.
- Anode injection, or some other technique to reduce starvation, could lead to substantially improved efficiency.
- Slip leads to low electrode ionization fractions.
- Slip may lead to cathode fall voltages.

Future Work

- Get more converged solutions.
- Model more complex thruster geometries.
- Obtain better understanding of voltage drops.
- Include anomalous transport.
- Include second ionization.
- Determine ways to increase efficiency.

VI: Formulation

- Mass Conservation

$$\nabla \cdot (\rho \mathbf{u}) = 0$$

- Momentum Conservation

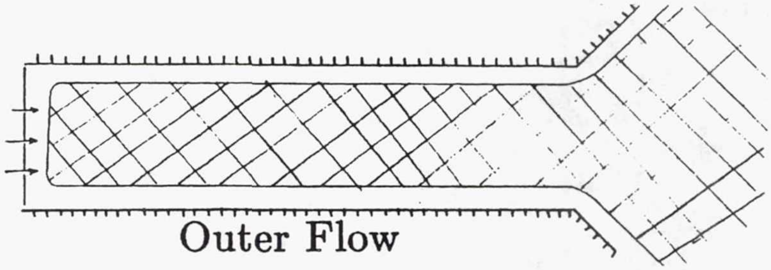
$$\rho \ (\mathbf{u} \cdot \nabla)\mathbf{u} + \nabla(p + b^2) = 0$$

- Energy Conservation

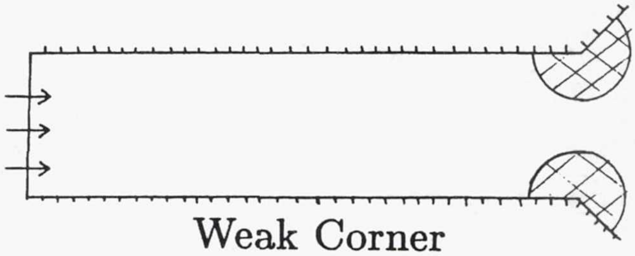
$$\frac{1}{\gamma - 1}\rho^\gamma \ (\mathbf{u} \cdot \nabla)\left(\frac{p}{\rho^\gamma}\right) = \frac{2}{R_m}(\nabla b)^2$$

- Magnetic Field Convection

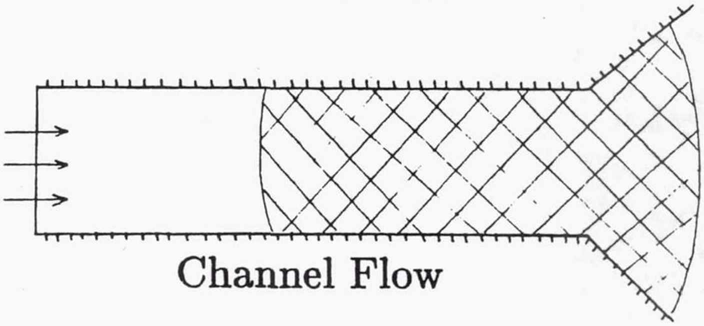
$$\rho \ (\mathbf{u} \cdot \nabla)\left(\frac{b}{\rho}\right) = \frac{1}{R_m}\nabla^2 b$$



Outer Flow



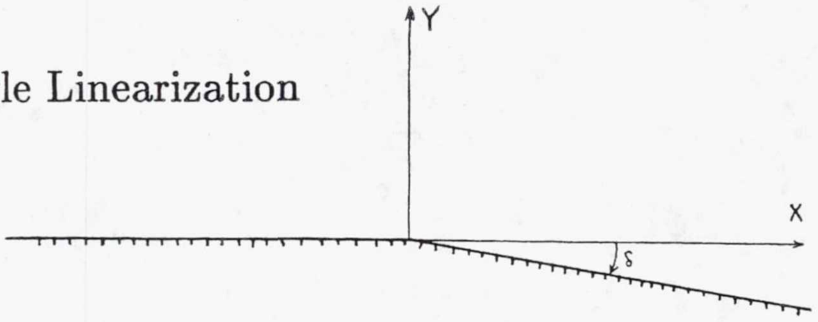
Weak Corner



Channel Flow

XII. Weak Corner: Resistive Plasma Model

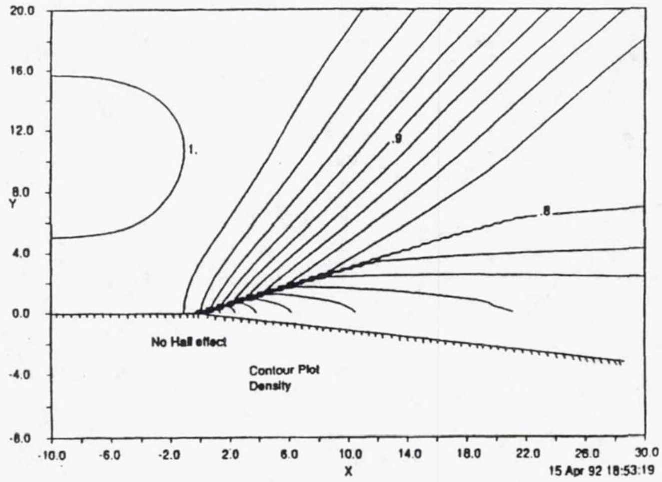
- Small Angle Linearization

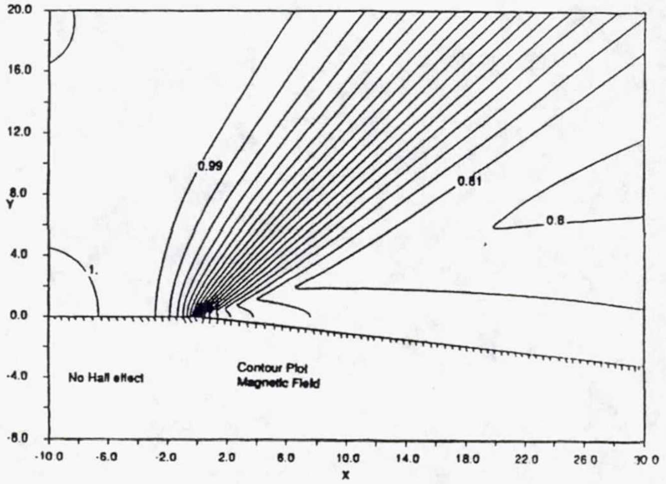


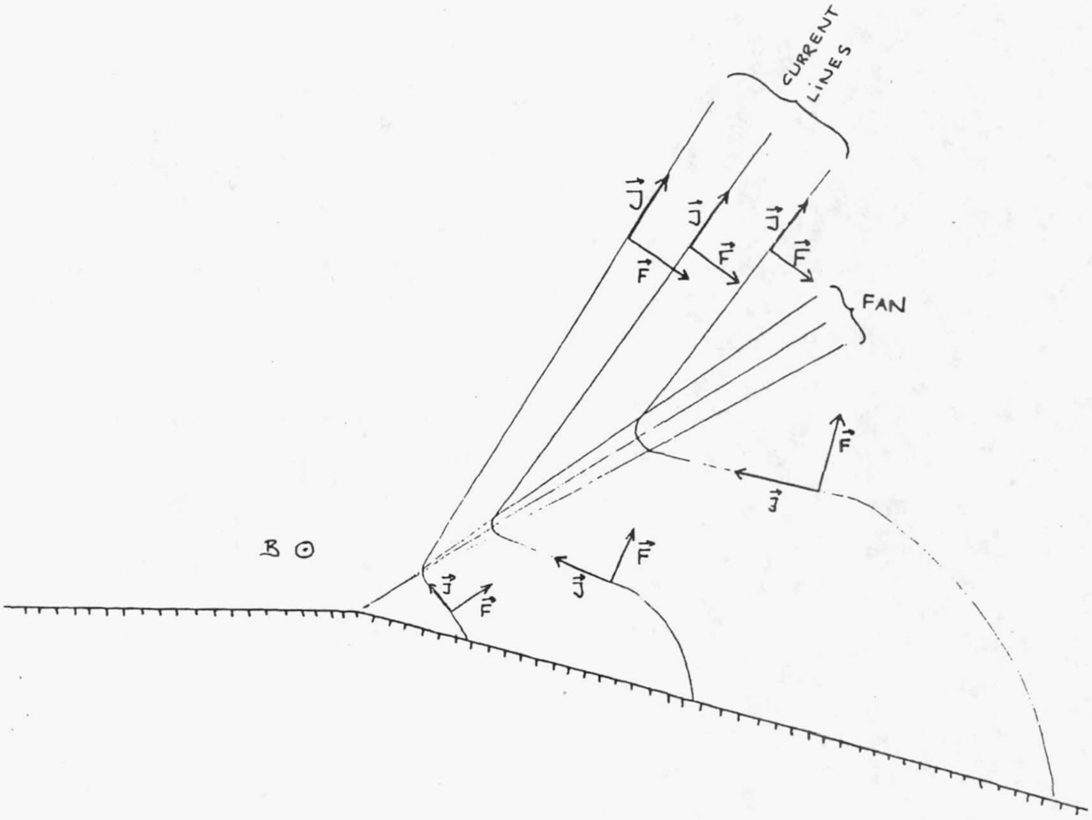
- 4-th Order Linear Operator

$$\left\{\frac{\partial}{\partial X}\left((1-M_v^2)\frac{\partial^2}{\partial X^2}+\frac{\partial^2}{\partial Y^2}\right)-\frac{M_v^2}{M_a^2}\left((1-M_a^2)\frac{\partial^2}{\partial X^2}+\frac{\partial^2}{\partial Y^2}\right)\nabla^2\right\}v_1=0$$

- Properties: $M_v > 1$, Hyperbolic and Elliptic
- Solution: Fourier Transformation along X, Transfer of Boundary Conditions

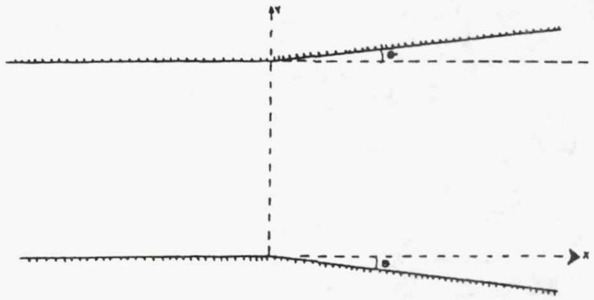




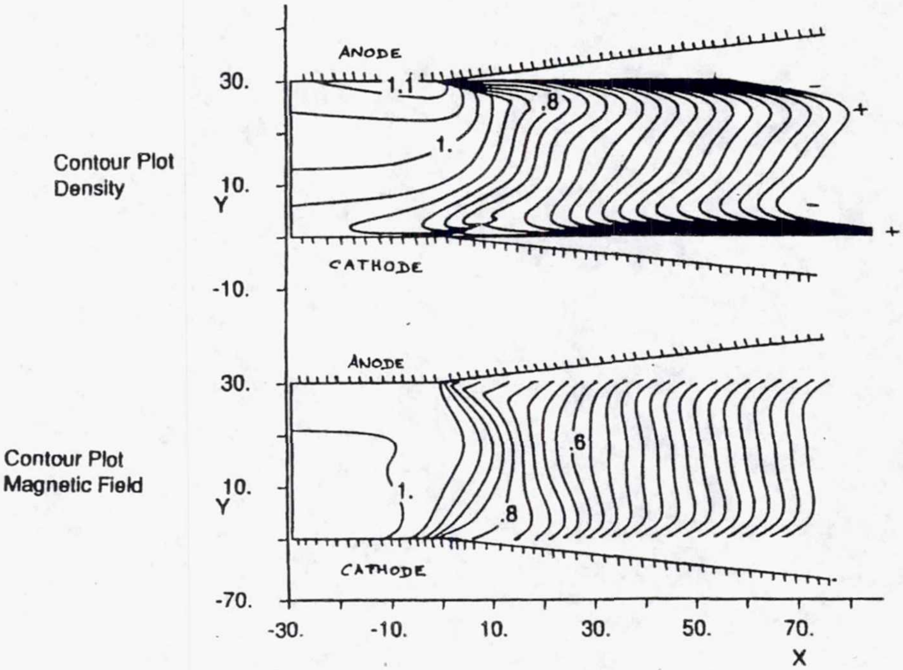


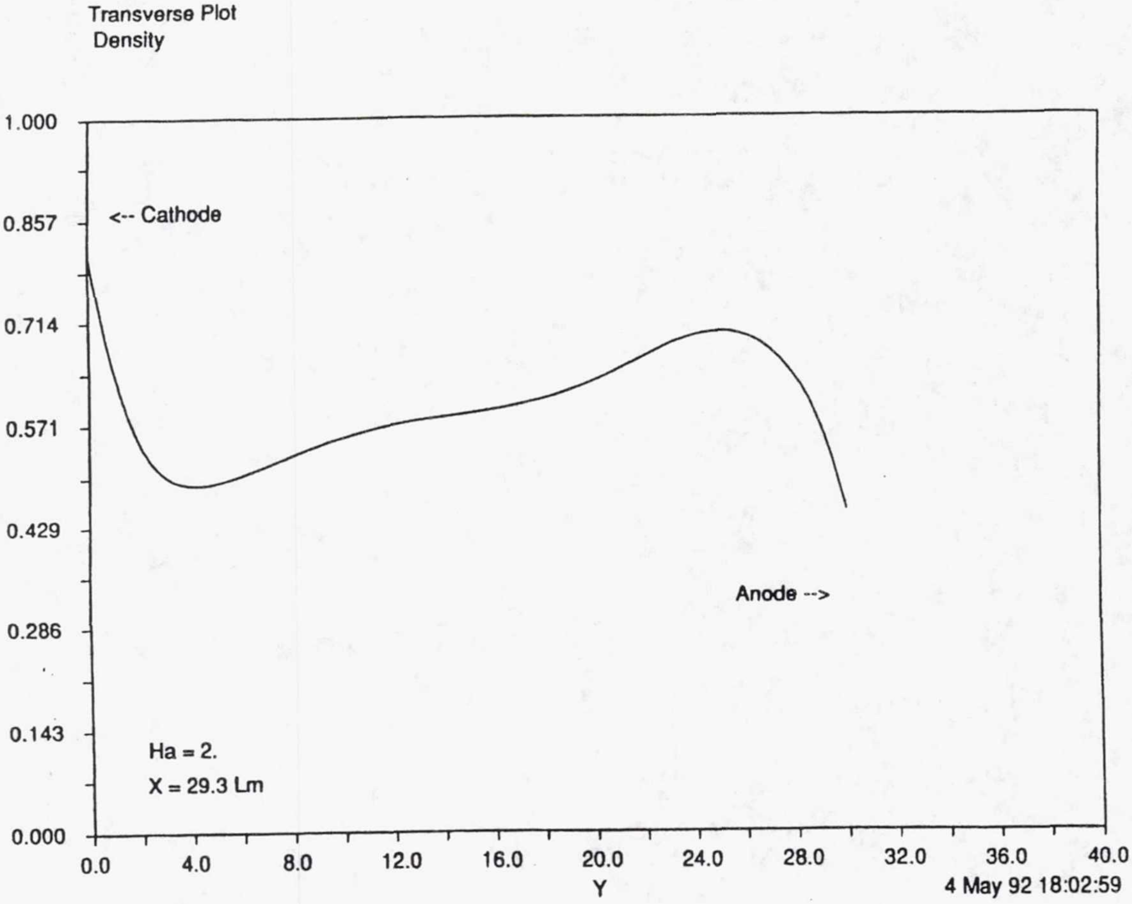
XIV. Channel Flow: Problem Definition

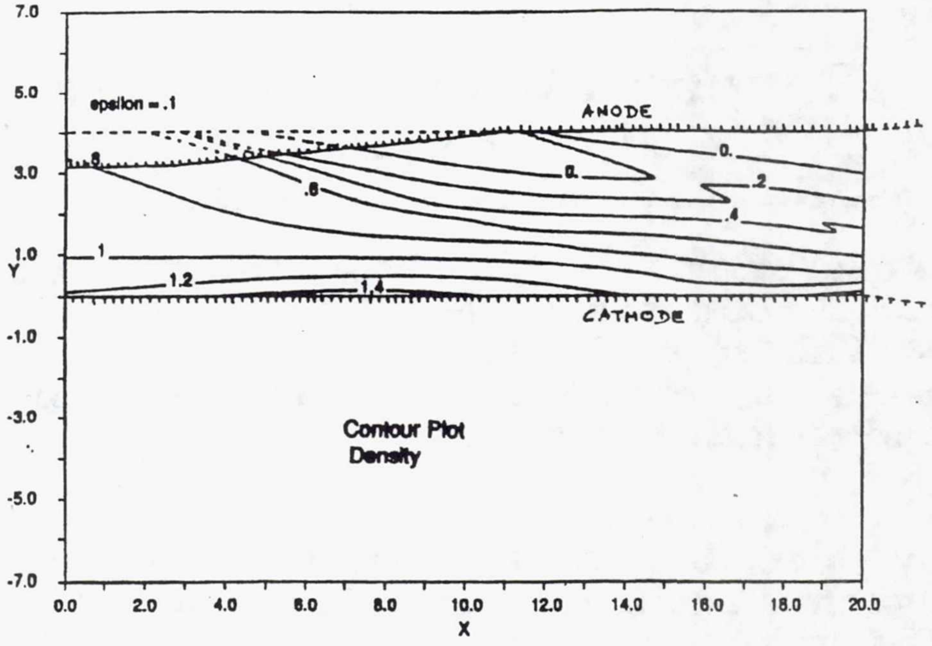
- Geometry

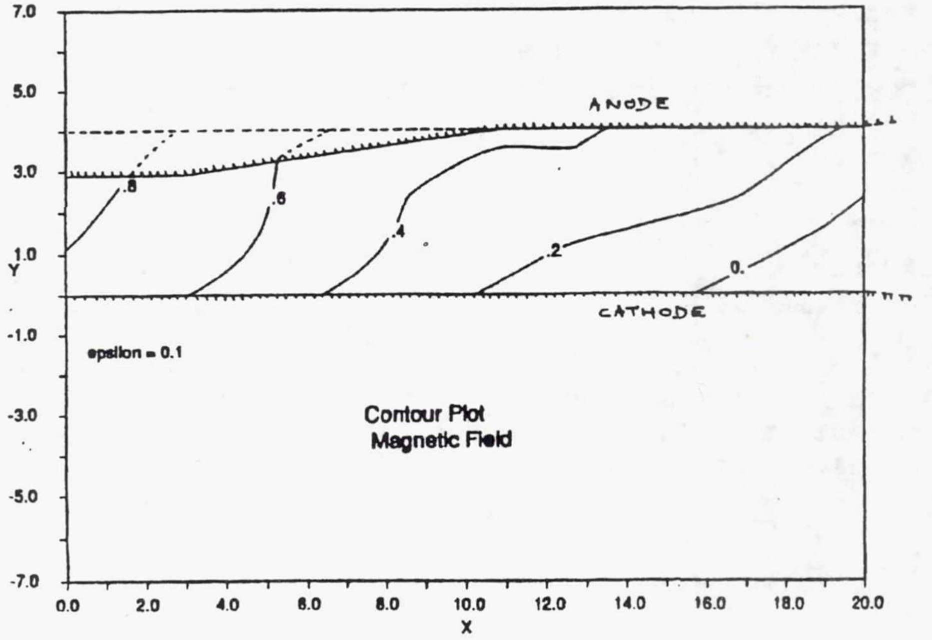


- Formulation: Analogous to Weak Corner
- Incoming Flow: $M_V > 1$
- Include Hall Conductivity


Contour Plot
Density
Contour Plot
Magnetic Field
ANODE
CATHODE
ANODE
CATHODE
1.1
.8
1.
1.
.8
.6
–
+
–
+
30.
10.
Y
-10.
30.
10.
Y
-70.
-30.
-10.
10.
30.
50.
70.
X


Transverse Plot
Density
1.000
0.857
0.714
0.571
0.429
0.286
0.143
0.000
<-- Cathode
Anode -->
Ha = 2.
X = 29.3 Lm
0.0
4.0
8.0
12.0
16.0
20.0
24.0
28.0
32.0
36.0
40.0
Y
4 May 92 18:02:59





XV. Linearized Channel Flow: Discussion

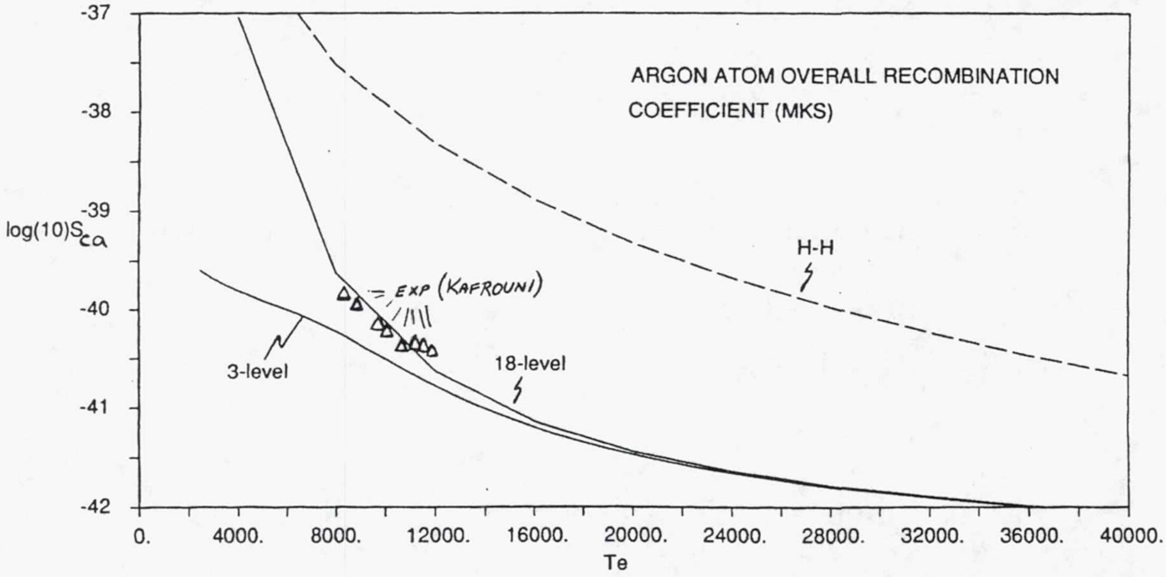
- Effect of Hall Conductivity
  - mass depletion, boundary layers
- Effect of Channel Height
  - large channel: one-dimensional model valid
  - narrow channel: expansion starts upstream of the exit

Nonequilibrium Ionization Work

- Model atoms (A,H) and ions (A) as sets of excited states, and use a Bates-Kingston-McWhirter model for volumetric production rates for each state. (includes collisional and radiative processes)
- Calculate the excited state populations and overall collisional rate coefficients (assuming dynamic equilibrium of the excited states and neglecting radiation).
- Apply these rate models to the problem of steady-state inlet ionization in MPD thrusters.

Nonequilibrium Ionization

Assuming the excited states are in dynamic equilibrium, and neglecting radiation, overall ionization and recombination coefficients are calculated. Shown here are results from three and 18 level argon atomic models and Hinnov-Hirschberg as reference:



Inlet Ionization

- Consider the problem of steady-state, self-sustained initiation of ionization in a propellant injected into an MPD thruster. (the gas/plasma transition)

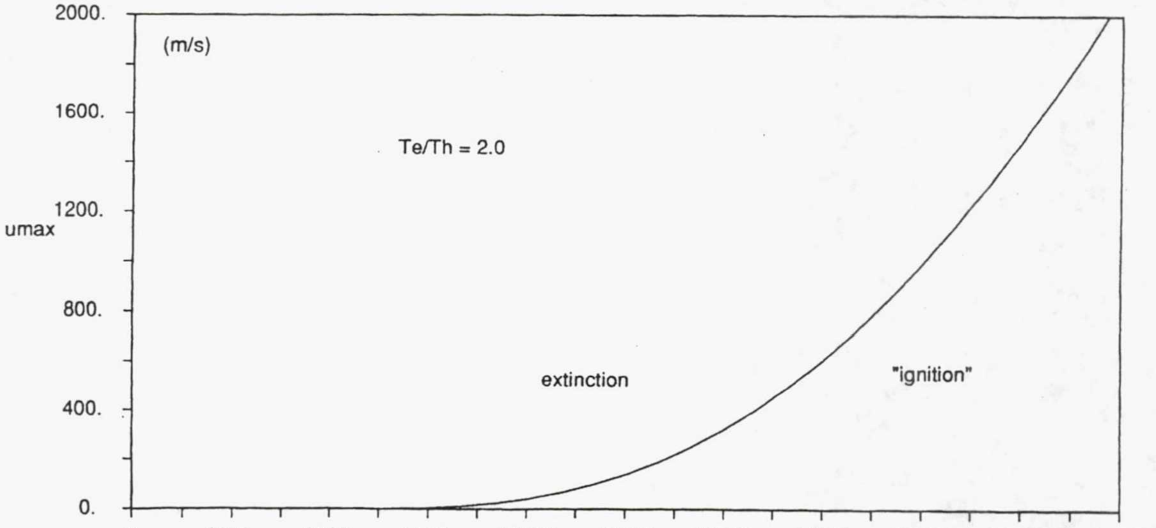
- Hypothesize that this "ignition" occurs due to a combination of back diffusion of electron-ion pairs and radiation from the downstream plasma.

- Ionization via electron-atom collisions may be one-step (direct ionization) or multi-step (through the excited states).

- Radiation may also be one-step or multi-step.

Inlet Ionization

For "ignition" in a finite length in a collisions-only 1-d the ionization mfp must be smaller than the axial back-diffusion scale length. This imposes a limit on the injection speed:



Inlet Ionization

Current and Future Work:

* Consider in detail the roles of temperature variation and the rapid acceleration near the inlet of an MPD thruster in the ignition process.

* Look into the roles of the individual excited states (modelled as lumped levels):

- Under what conditions will the excited states be out of dynamic equilibrium? (low Te, ne) What is the effect on ignition?

- What is the influence of radiation - photoexcitation and and photoionization - on the ignition process?

MAGNETOPLASMADYNAMIC THRUSTER FLOWS: PROBLEMS AND PROGRESS

Peter J. Turchi
The Ohio State University
Columbus, Ohio

MPD THRUSTER WORKSHOP

OVERALL STRATEGY FOR MPD THRUSTER DEVELOPMENT

NEEDS

Efficiency

Lifetime

PROBLEMS	APPROACHES
Exhaust flow	Magnetic nozzle
-- Angular spread	-- Flow collimation
-- Frozen flow	-- Expansion control
	Design/control of thrust chamber plasma
Electrodes	Design/control of near-electrode plasma
-- Voltage drops	-- Hollow cathode
-- Heat transfer	-- Anode MPD flow
-- Erosion	

MPD THRUSTER WORKSHOP

ACTIVITIES IN THE OSU AERO/ASTRO ENGINEERING DEPARTMENT

HIGH POWER MPD FLOWS

-- Godzilla

  Gigawatt, quasi-steady, LC-ladder pulseline (3 kV matched-load, with 333 kA for 1.6 msec; also 111 kA for 4.8 msec, etc.)

MODERATE POWER MPD THRUSTERS AND COMPONENTS

-- Magnetic nozzle experiments

  Qualitative spectroscopic studies

  Long pulse, applied field (York)

-- Hollow cathode studies

  Theoretical modeling

  Experiments at NASA LeRC in both MPD and ion engine regimes

-- Applied-field MPD flow modeling

  MACH2 code adapted to steady, applied-field operation

  Examination of flow near the anode

MPD THRUSTER WORKSHOP

TOPIC	PARTICIPANT
Magnetic nozzle spectroscopy	T. Umeki, MS student, Ohio State
Hollow cathode studies	A. Salhi, PhD student, Ohio State
	R. Myers, M. Mantenieks, NASA LeRC, (for experiments)
Anode flow studies	P.G. Mikellides, PhD student, Ohio St
	N.F. Roderick, Professor, Dept. of Chemical and Nuclear Engineering, University of New Mexico

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MPD THRUSTER WORKSHOP

QUALITATIVE SPECTROSCOPIC STUDIES OF MAGNETIC NOZZLE FLOW

MOTIVATION

-- Build on earlier studies, based on electrostatic probes, pressure probes, magnetic probes, and single-point laser scattering, to estimate energetics of magnetic nozzle flow field.

-- Attempt to capture larger region of flow field through spectroscopic flow-visualization.

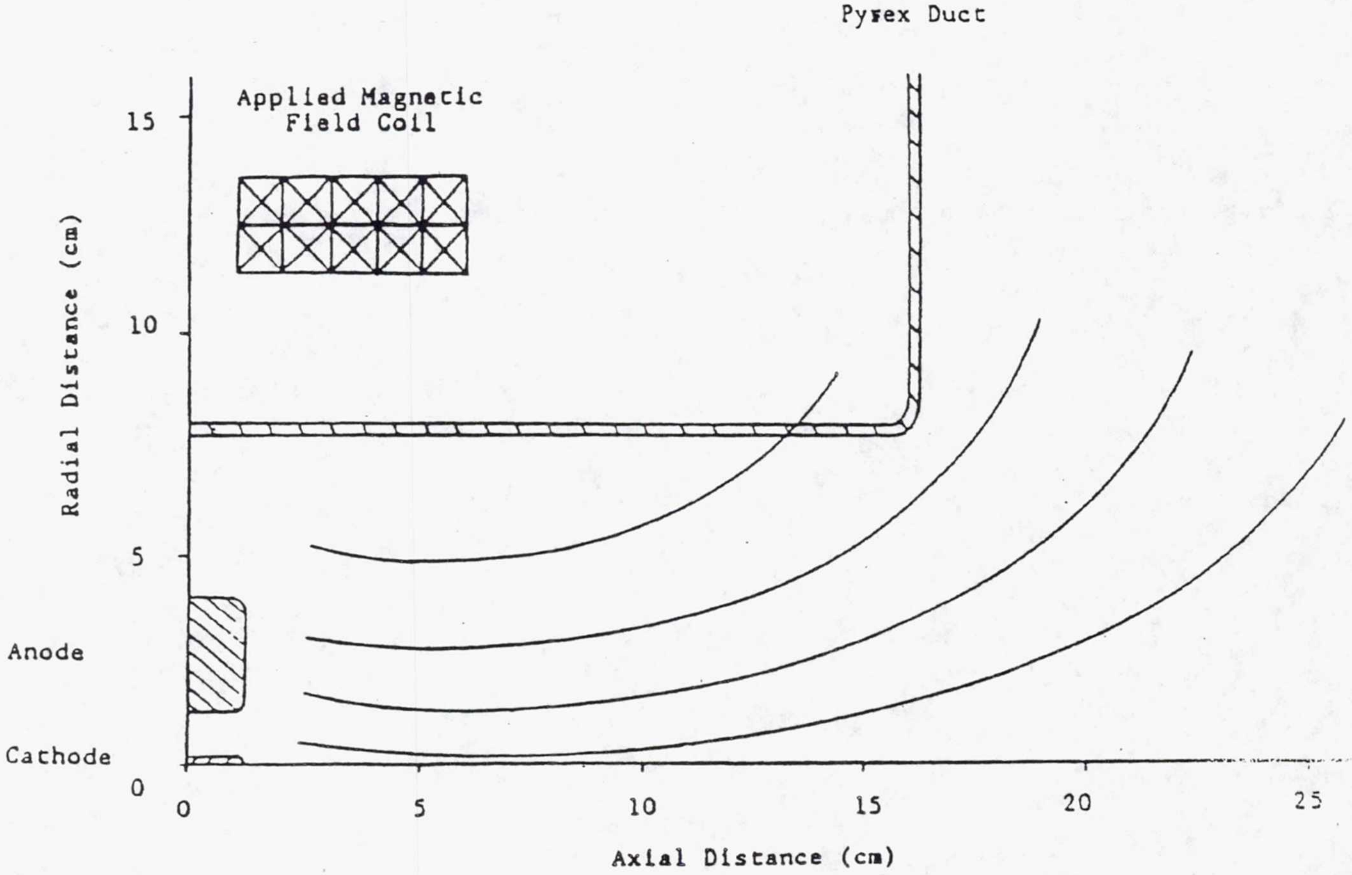
APPROACH

-- Combine spectroscopy with photographic imaging in order to obtain (qualitatively) line intensities as function of position in flow field.

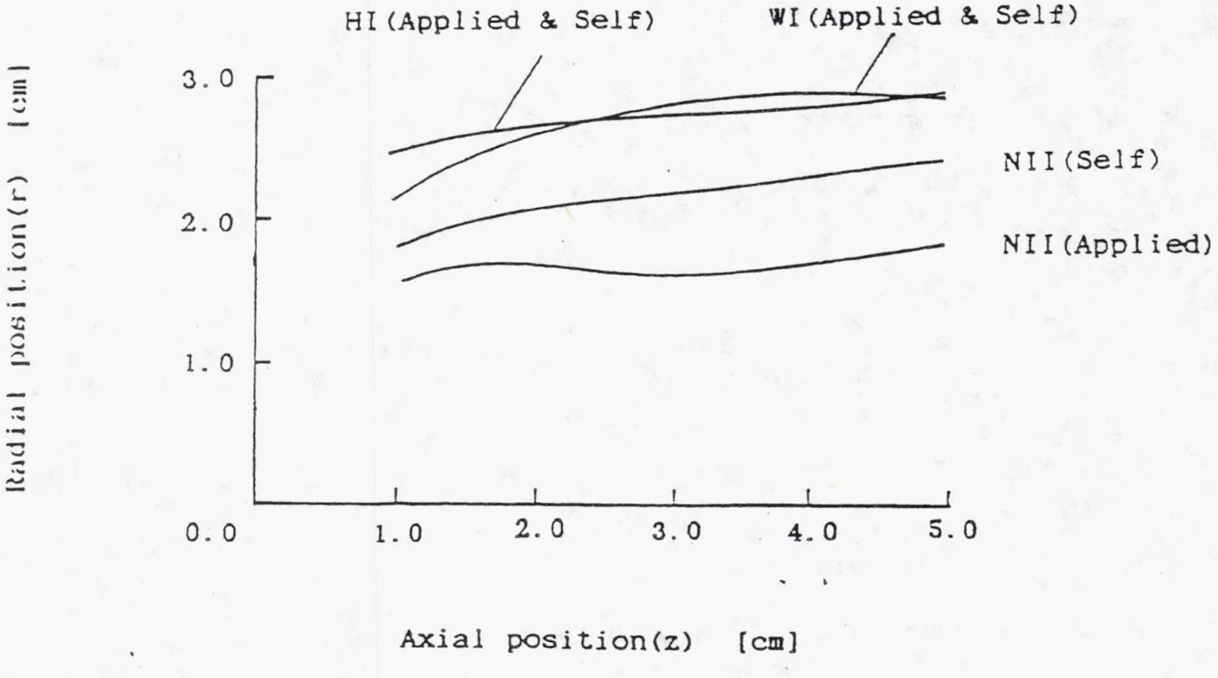
-- Perform photoelectric measurements of selected lines.

-- Compare with available probe data (at downstream positions).

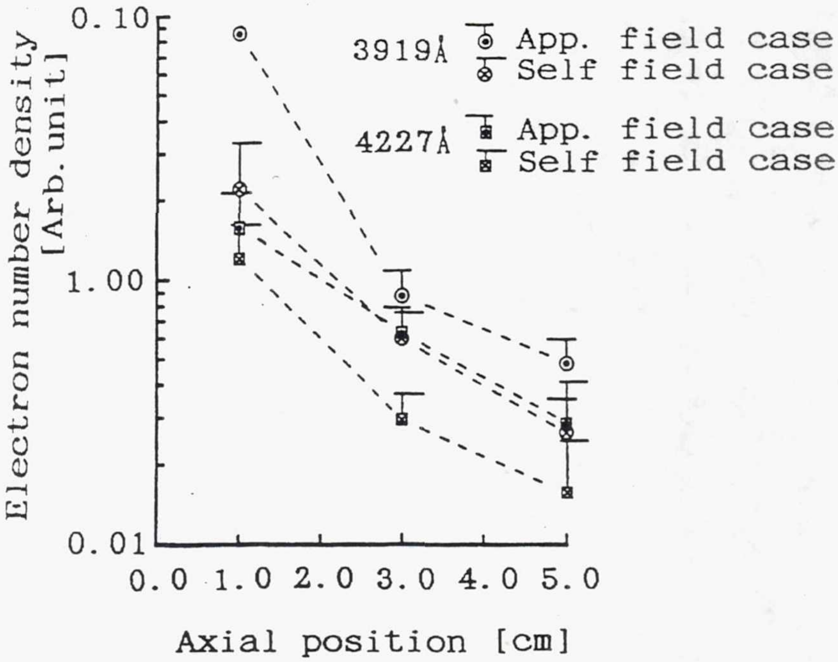
-- Examine distributions of derived plasma parameters (e.g., electron temperature, electron and heavy particle densities).



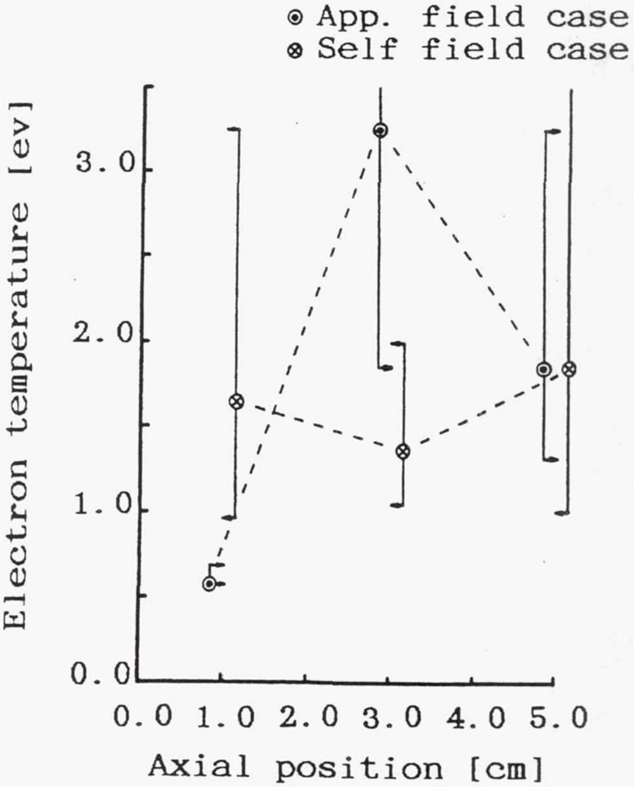
Applied magnetic field lines



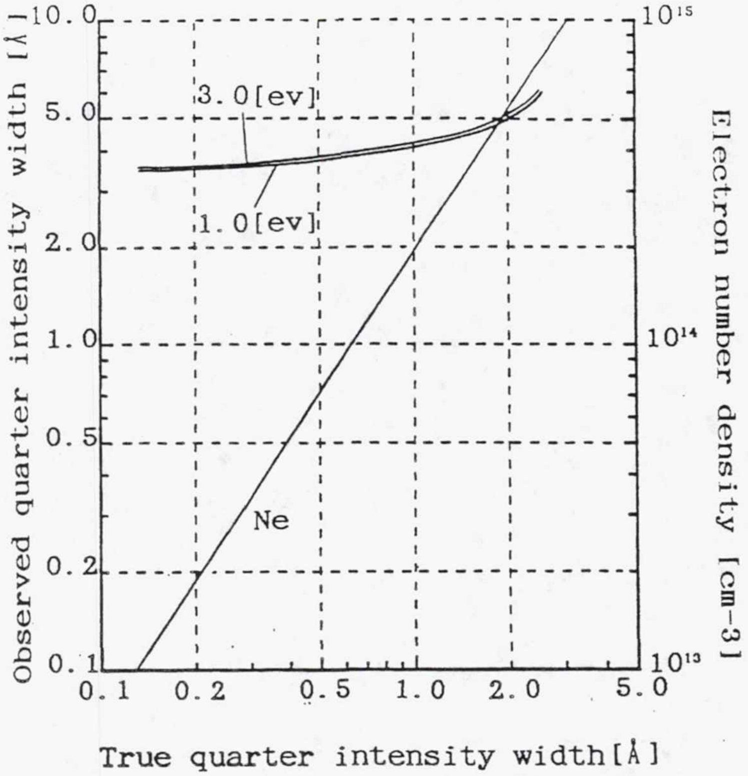
Species distribution



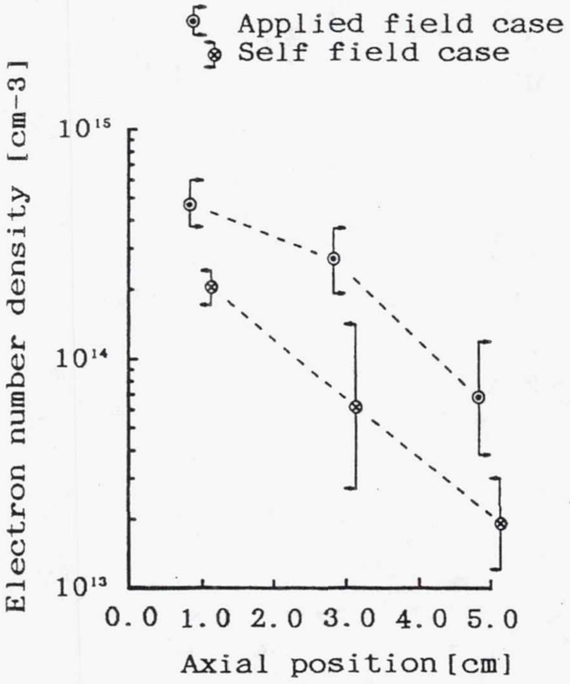
Chordal averaged radiator number density on the axial position



Electron temperature on the axial position (chordal averaged on axis)



H_β quarter intensity width for the electron number density



Electron number density on the axial position from Stark broadening (chordal averaged on axis)

MPD THRUSTER WORKSHOP

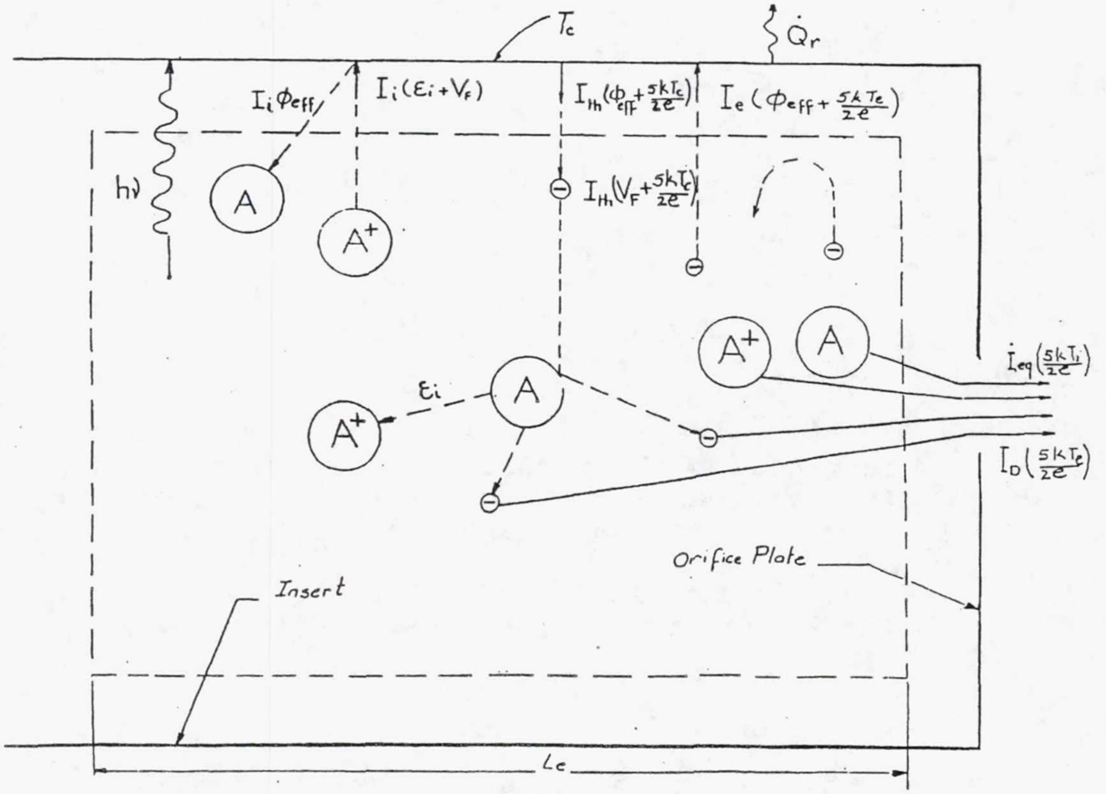
HOLLOW CATHODE STUDIES

MOTIVATION

- Improve cathode performance in MPD arcjets by controlling the plasma near the cathode surface, (rather than merely accepting the plasma conditions provided by the thrust chamber flow).
- Extend understanding of hollow cathode design to embrace both low current and high current regimes.

APPROACH

- Start theoretical modeling from the notion of reducing losses from the vicinity of the cathode by operating in a hohlraum, and at high current density.
- Cast model in terms of operating values of current, and mass flow rate, material properties, and cathode dimensions. Extend from first-principles only as needed to encompass new aspects of operation.
- Compare theory with existing data, and generate new data to test model.



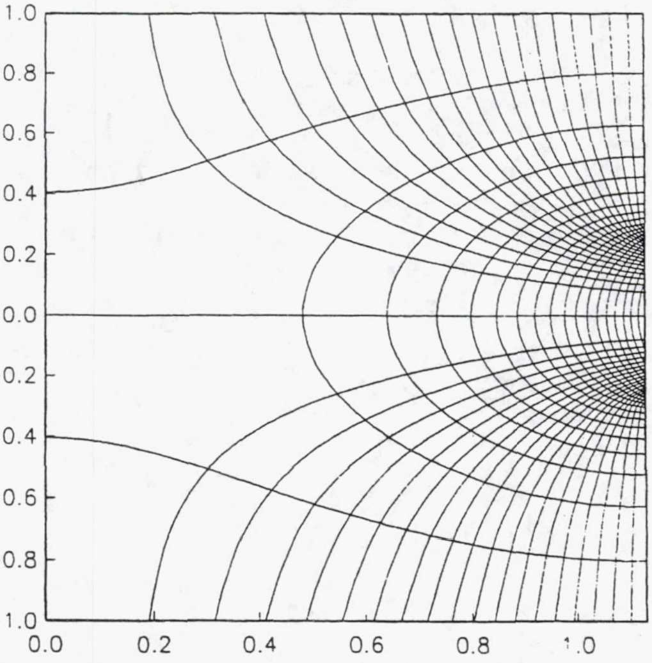


FIGURE 31: Equipotential and Current Lines (I_D = 3.3 A)

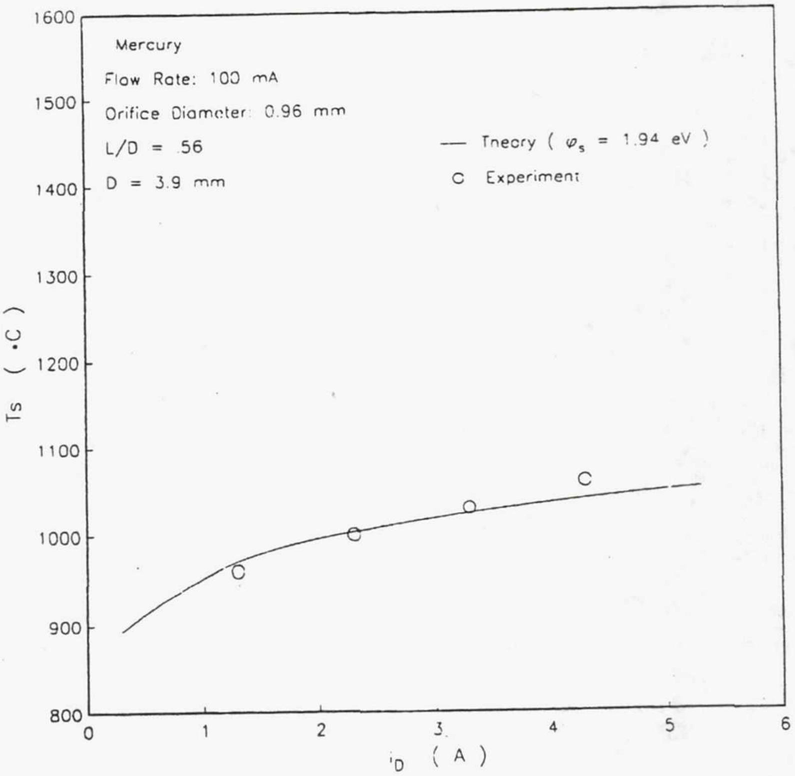


Figure 1 : Effect of Discharge Current on Emission Surface Temperature

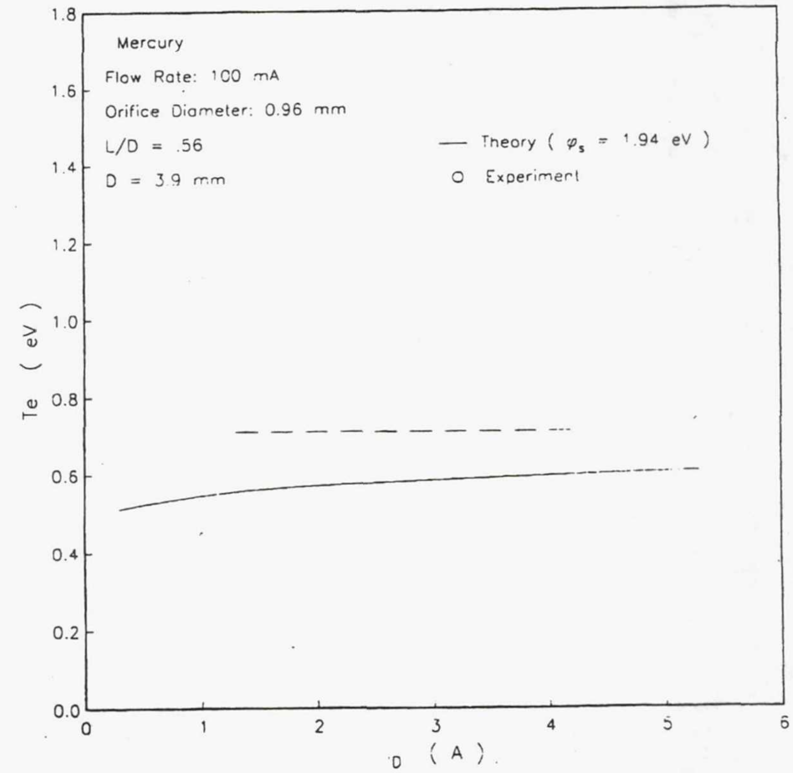


Figure 2 : Effect of Discharge Current on Electron Temperature

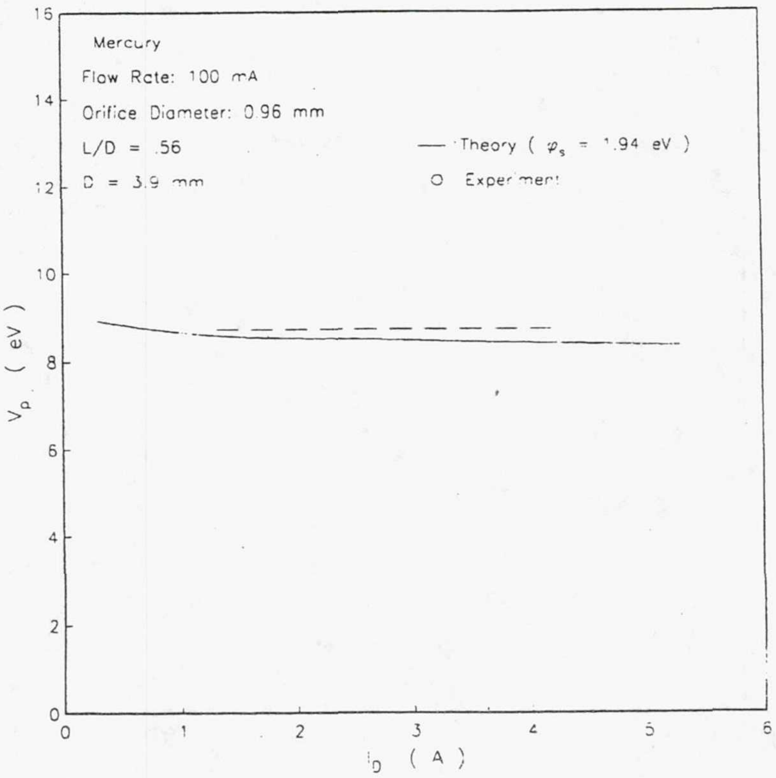


Figure 3 : Effect of Discharge Current on Plasma Potential

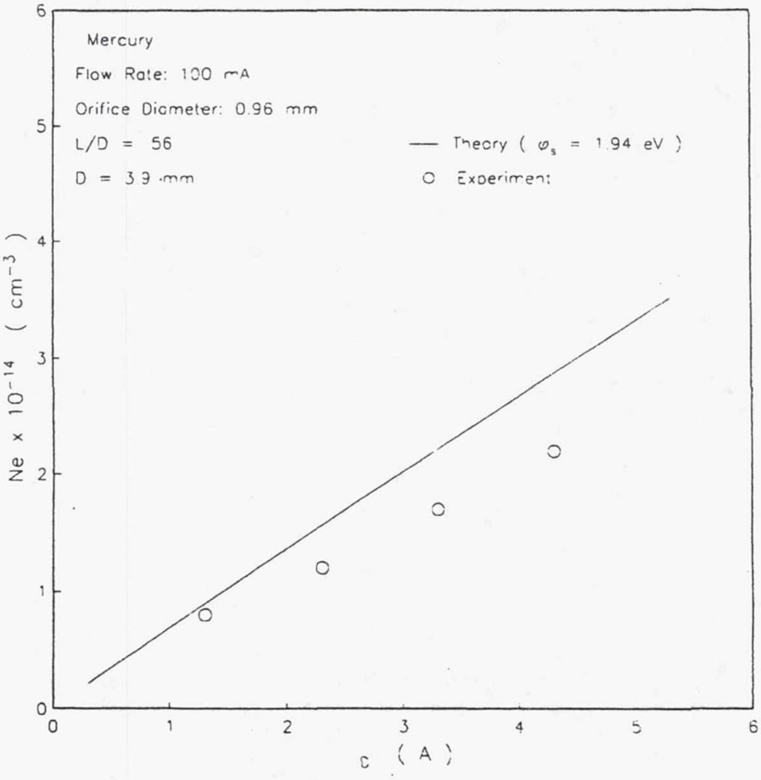


Figure 4 : Effect of Discharge Current on Plasma Density

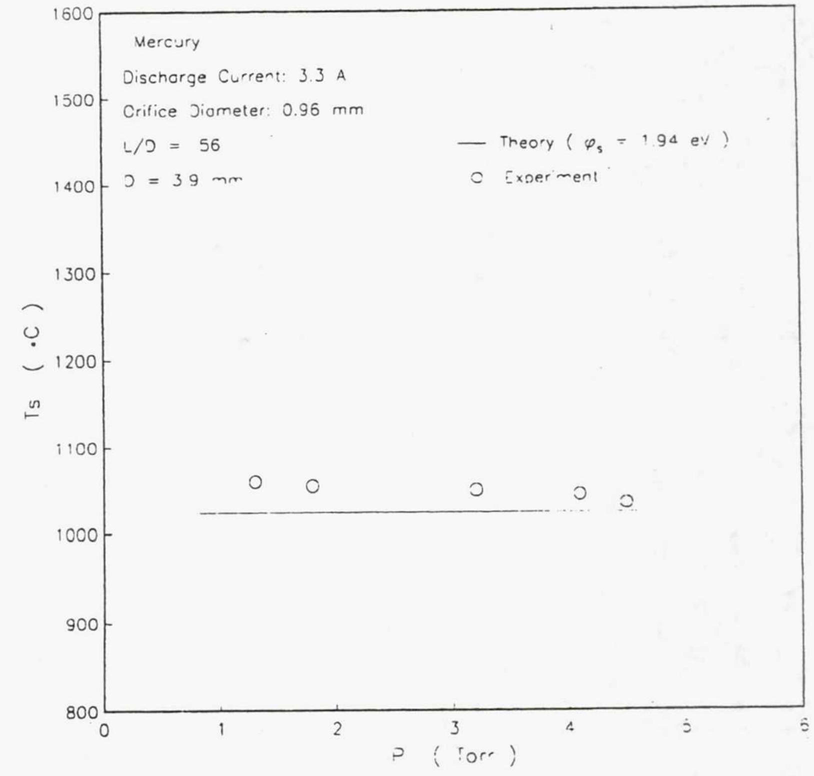
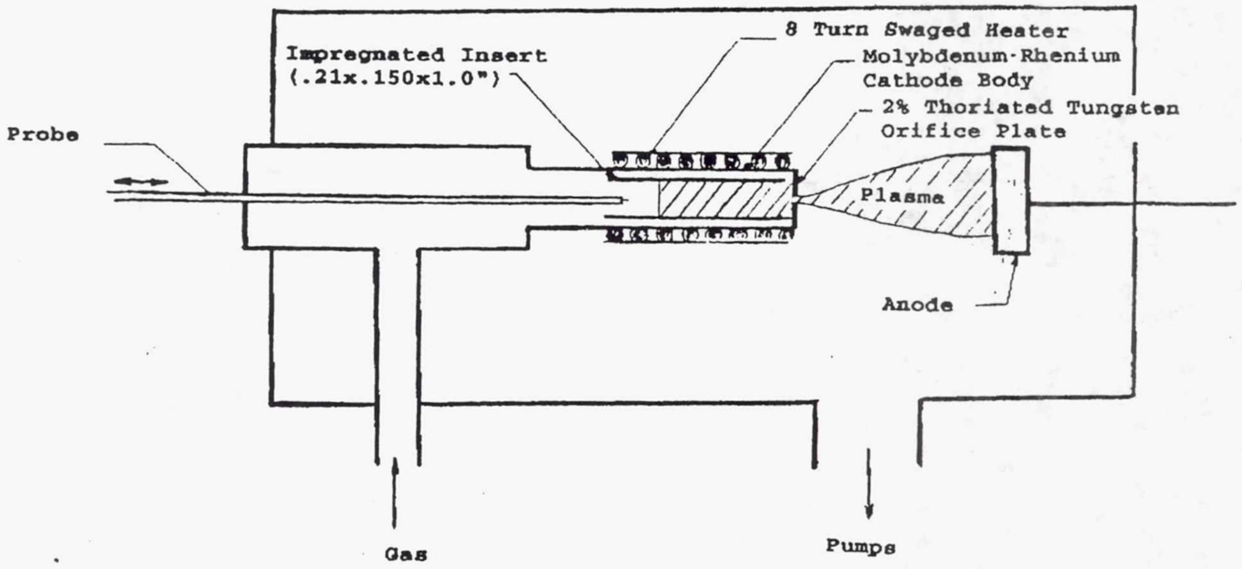


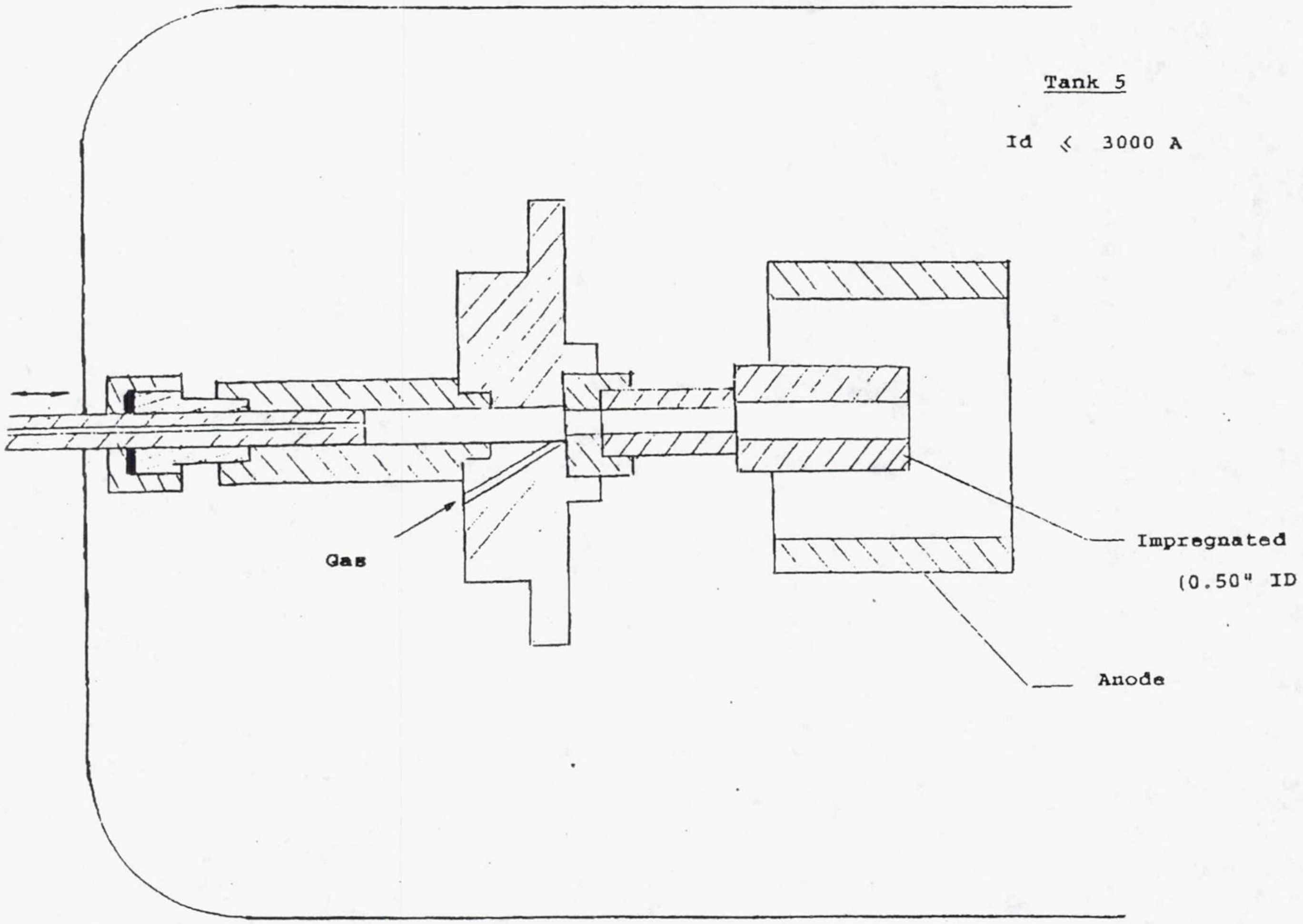
Figure 5 : Effect of Pressure on Emission Surface Temperature

Bell Jar 6

Id ≤ 30 A



A Typical Experimental Arrangement of HCA



Schematic Representation of Hollow Cathode

MPD THRUSTER WORKSHOP

ANODE FLOW-FIELD STUDIES

MOTIVATION

-- Present moderate power MPD arcjets appear to be losing substantial fractions of the input power near the anode. We need to understand the MPD flow field near the anode in order to improve performance.

APPROACH

-- Accept that there are too many competing mechanisms in the vicinity of the anode surface to proceed confidently in predicting the flow-field densities, temperatures, Hall parameters, etc.

-- Use a state-of-the-art MHD code (MACH2) to perform the arithmetic in a self-consistent fashion to describe the flow-field. Develop and extend models (and MACH2) from this description of the flow-field.

-- Explore flow-field behavior to develop candidates for improved performance.

MPD THRUSTER WORKSHOP

NEW THINGS IN MACH2 SINCE LAST YEAR'S WORKSHOP

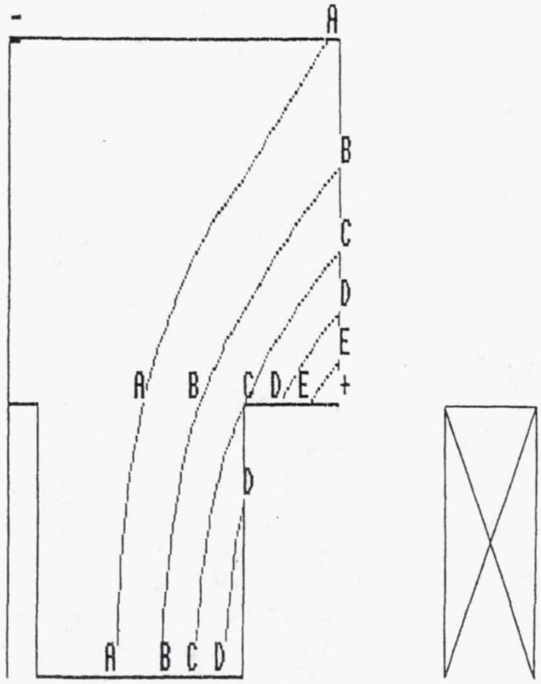
-- Two-temperature (heavy-particle vs electron) equation-of-state is now available within SESAME tables.

-- Magnetic field generation routines and boundary conditions for steady-state poloidal (rz) magnetic fields due to both plasma currents and external field coils have been added.

-- Magnetic fields due to external coils with (specified) time-varying currents are also included.

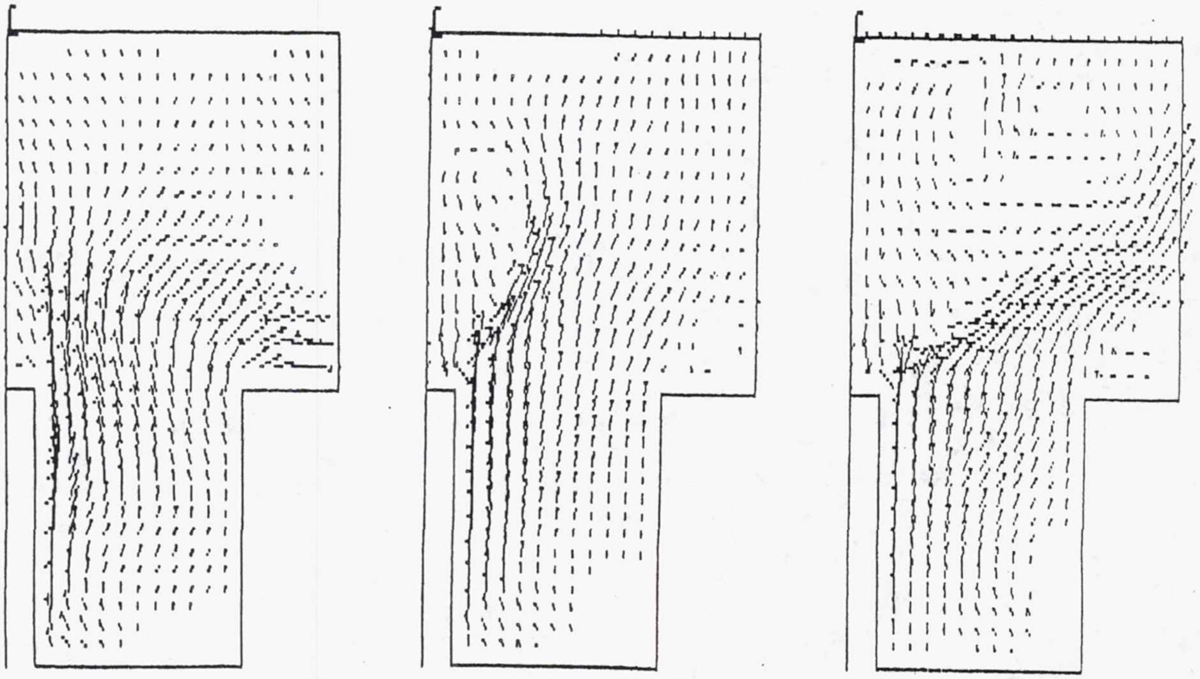
MACH2 STUDIES OF APPLIED FIELD MPD ARCJET

PROPELLANT : ARGON
MASS FLOW RATE : 0.1 g/s
DISCHARGE CURRENT : 1000 Amp



MAGNETIC FLUX

MACH2 STUDIES OF APPLIED FIELD MPD ARCJET



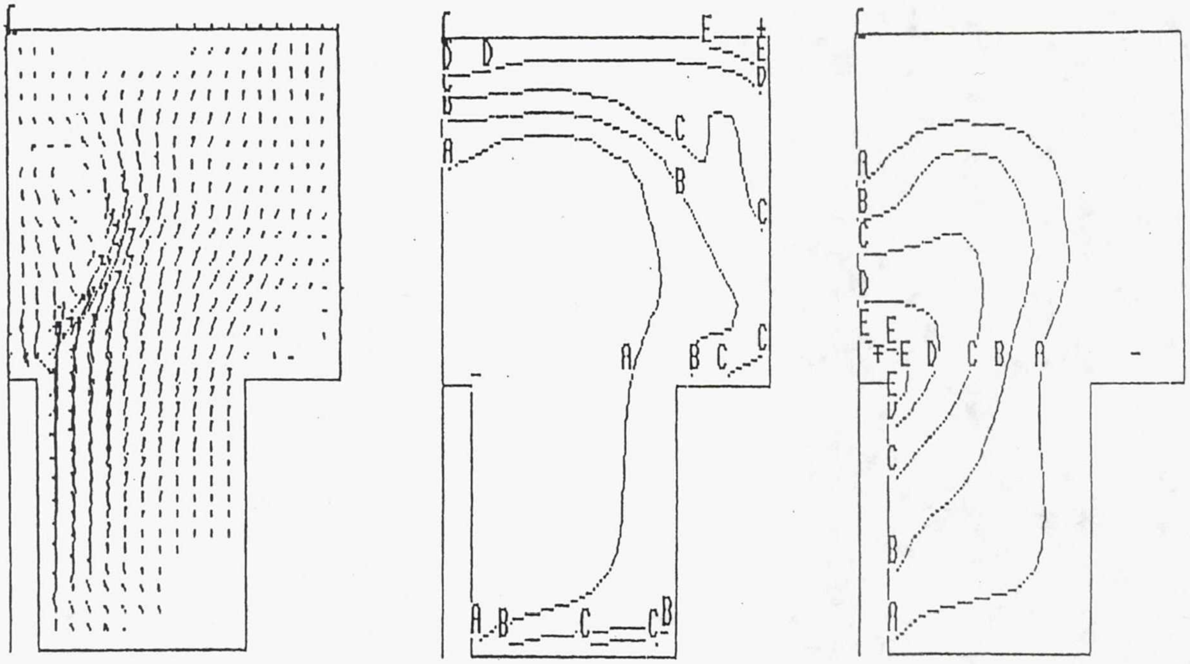
T = 40 µsec

T = 80 µsec

T = 200 µsec

MACH2 STUDIES OF APPLIED FIELD MPD ARCJET

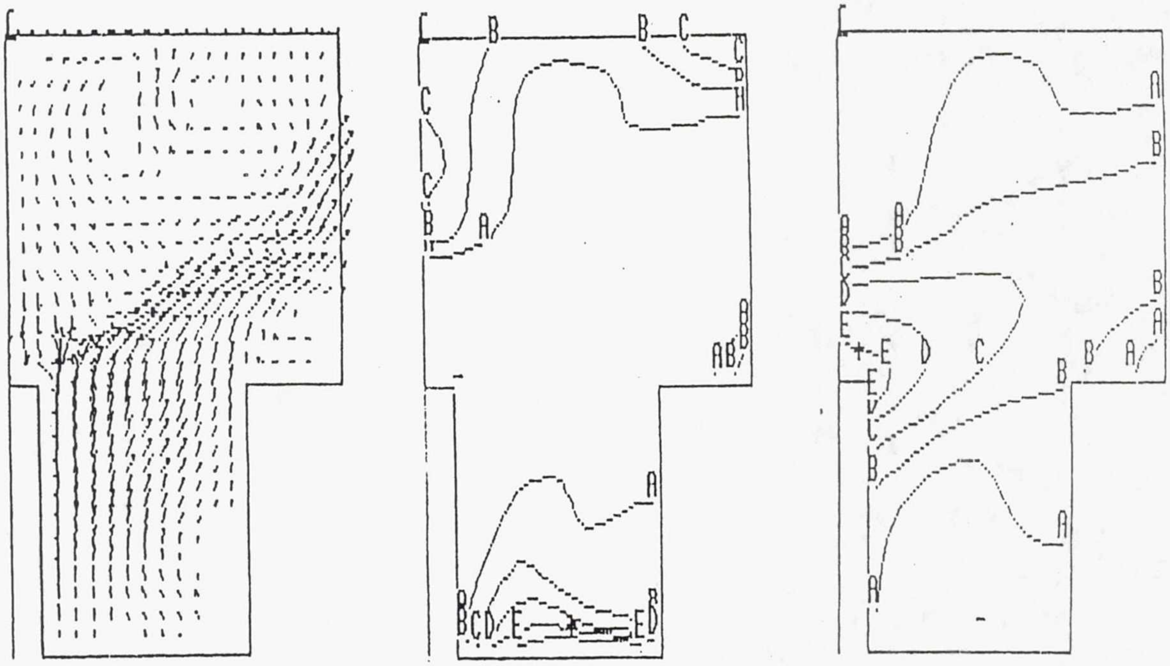
TIME = 80 μsec



VELOCITY DENSITY TEMPERATURE

MACH2 STUDIES OF APPLIED FIELD MPD ARCJET

TIME = 200 μsec



VELOCITY DENSITY TEMPERATURE

MPD THRUSTER WORKSHOP

ISSUES

PHILOSOPHICALLY

"Ah Love, if you and I with Fate but could conspire
To grasp this sorry scheme of things entire,
Would not we shatter it to bits,
And remold it nearer to the heart's desire"

\- Omar/Fitzgerald

PROGRAMMATICALLY

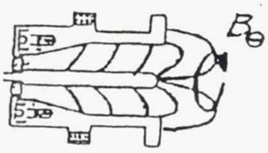
Designing what we want vs Cataloging what we have

SCALING AND APPLIED FIELD STUDIES OF MPD THRUSTERS WITH LASER DIAGNOSTICS

Thomas M. York
The Ohio State University
Columbus, Ohio

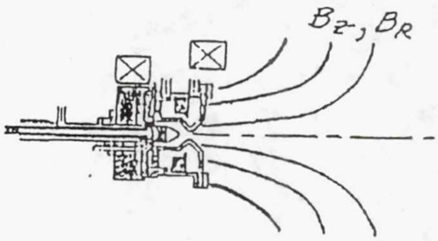
Scaling of Plasma Thrusters- Match High Efficiency Thrusters To Available Power

Self-Field MPD



Erosion Limited
Power Limited
Efficiency Limited
Physical Mechanisms for Limits not Understood
Self-Field Magnetic Expansion Effects Interdependent with Gas Heating

1/4-Scale Applied-Field MPD



Fields Influence Erosion
Fields allow Better Expansion at Low Power
Fields Enhance Expansion and Efficiency
Physical Mechanisms not yet Understood
Applied-Field Magnetic Nozzle Independently Controllable from Gas Heating Source

Scaling Of Arcs And MPD-Arcs

Properties And Functions:

Size: L

Mass Flow: $\dot{m}/Acs$

Em Velocity: $U_{em} = \left(\frac{I^2}{\dot{m}}\right)\frac{\mu_o}{4\pi}\ln\left(\frac{Ra}{Rc}\right)_{EFF} \quad \alpha \frac{I^2}{\dot{m}} = \frac{j^2r^2z^2}{\dot{m}} \quad \alpha \frac{\vec{j} \times \vec{B}}{\dot{m}/Acs} z$

Force Density: $j \times B \quad \alpha \frac{I^2}{r^2 z} = j^2 z$

Power: $IV = I^2R$

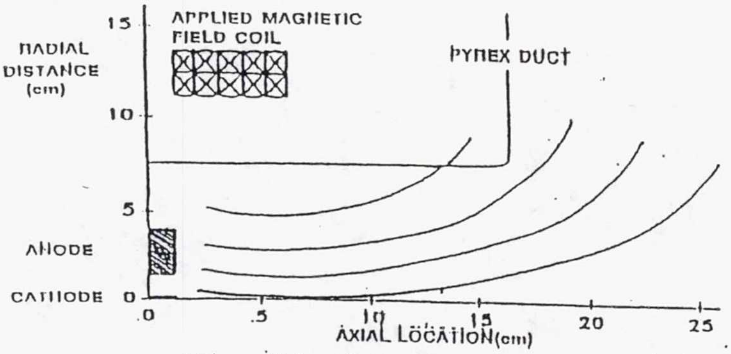
Eth Velocity: $U_{eth} = \left(\frac{2I^2R}{\dot{m}}\right)^{1/2} \quad \alpha \left(\frac{I^2}{\dot{m}} R\right)^{1/2} \quad \alpha \left(\frac{j^2\ z^2}{\dot{m}/Acs} R\right)^{1/2}$

1/4-Scale Thruster:

($\vec{j} \times B$ and $\dot{m}/Acs$ constant)

1F $L = L_{fs}/4$ $I_{1/4} = I_{fs}/8$
1F $L = L_{fs}/4$ $j_{1/4} = j_{fs} \times 2$
1F $L = L_{fs}/4$, R = const. $U_{eth} = U_{eth}$ (fs)/2 (Electrode drop dominant)
1F $L = L_{fs}/4$, σ = const. $U_{eth} = U_{eth}$ (fs) (Plasma drop dominant)

Magnetic Nozzle Studies



1/4 SCALE THRUSTER, FIELD COIL AND APPLIED MAGNETIC FIELD LINES

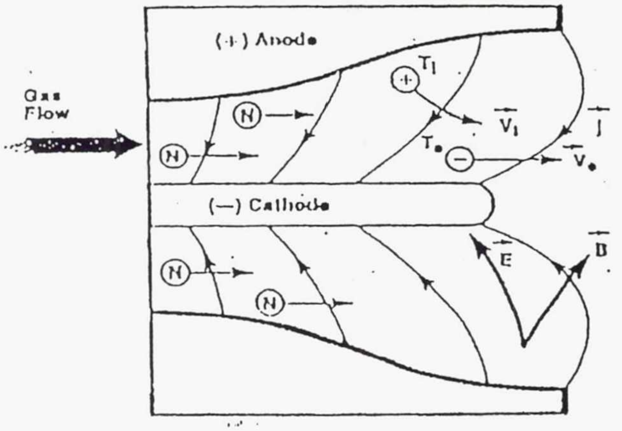
Reported:

- Self-Field plasma expands to low pressure in 5 cm (plasma $\dot{m}$ lost). Applied-field plasma expansion is controlled and has large $\int pdA$ thrust.
- Applied fields can be optimized for Uex max or high thrust with low Uex. This will allow optimization of Uex for mission requirements.

Being Completed:

- New switches and battery supply allow: .1-2sec nozzle field generation to study effects of field penetration into thrust chamber
- New coil design will change nozzle shape to study effects of extended length, gradual expansion, detachment, etc.

Advanced Diagnostic Techniques Needed For Obtaining Particle Velocity, Density, Temperature And Current Distributions In Plasma Thrusters



Need to Measure:

- Electron, Ion and Neutral Densities
- Electron and Ion Temperatures
- Current Densities
- Species
- Potential and Magnetic Field
- Velocity Profiles

Non-Intrusive Laser Diagnostics For Arcs And MPD-Arcs

THOMSON SCATTER FOR Ne , Te
- 2J Ruby system used to measure Ne , Te on 1/4 scale
- Confirmed Ne , Te indications of Langmuir in B
- Established point reference for multi-beam interferometer

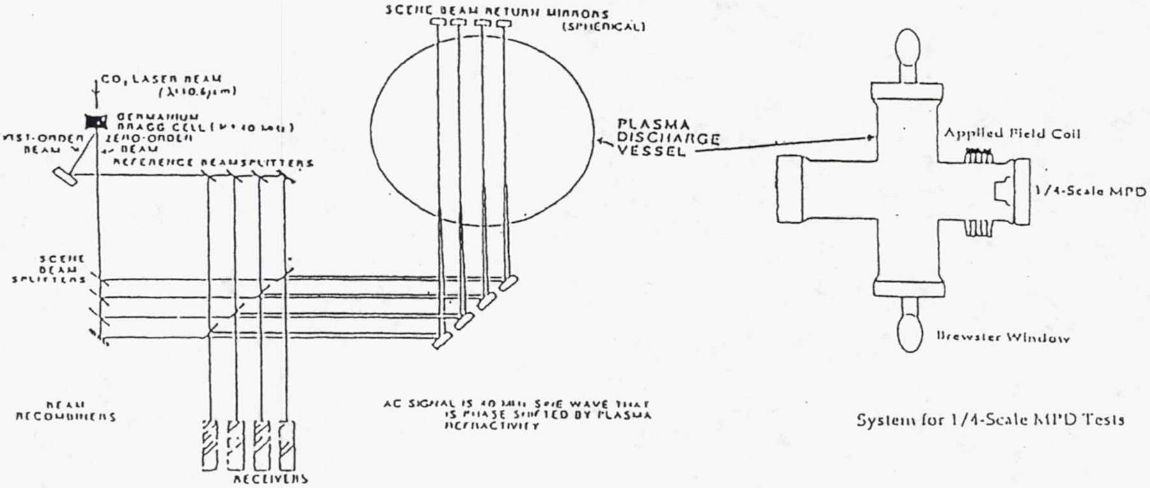
THOMSON SCATTER FOR (ELECTRON) FLOW VELOCITY
- 2J Ruby system used to get $V \gtrless$ Sonic on experiment
- Electron velocity confirmed equal to ion velocity
- Could be applied to ARC and MPD-ARC

MULTIBEAM INTERFEROMETER FOR Ne(r) = f(z) PROFILES
- 50W CO2 CW system being used with 4 beams on chords
- Abel inversion allows Ne(r)
- Allows comprehensive view of applied field effects

DIAGNOSIS OF Ne FLUCTUATIONS FOR TRANSPORT STUDIES
- 50W CO2 CW System can be used for ARC and MPD-ARC studies
- FIR wavelengths and new detectors possible
- Fluctuations between .01 and 1. cm with 1 kHz - 10GHz in plasma with 10^{10} - 10^{17} cm^{-3} possible.

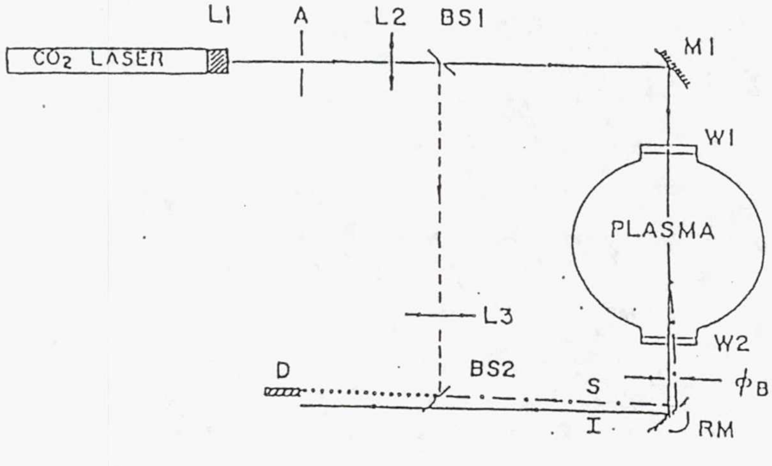
MAGNETIC FIELD AND CURRENT DENSITY WITH FARADAY ROTATION
- Laser beam rotated $\propto$ B, as $\theta < \lambda_0^2$ Ne B dZ
- Long λ_0 generates high sensitivity (118.8 m possible)
- Need interferom. determination of Ne dZ to unravel

Schematic of Multi-Beam Interferometer For Electron Density Profile Determination



System for 1/4-Scale MPD Tests

Schematic of Diagnostic System to Determine Density Fluctuations Magnitude and Orientation To Define Anomalous Transport



A schematic diagram for small angle CO_2 laser scattering from a plasma. A rotating mirror RM scans the scattered radiation S at angle ϕ_B to be coincident with the LO beam at BS2 and detector. The fluctuation of wavelength λ is determined from $\phi_B = 2\mathrm{Sin}^{-1} (\lambda_o / 2\lambda)$

OL-AC PHILLIPS LABORATORY MPD THRUSTER RESEARCH PROGRAM

Dennnis L. Tilley
Phillips Laboratory
Edwards Air Force Base, California

RESEARCH EMPHASIS:

IDENTIFY METHODS TO SIGNIFICANTLY INCREASE THE EFFICIENCY OF THE MPD THRUSTER

ACTIVITIES IN THE PAST YEAR:

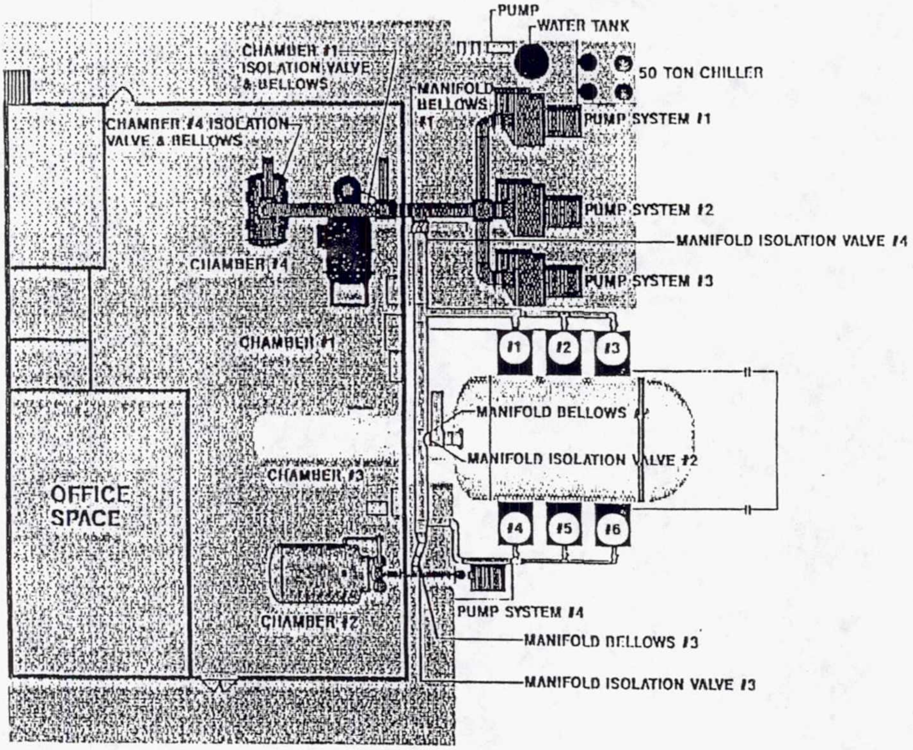
- FACILITY CONSTRUCTION
- QUADRUPLE LANGMUIR PROBE MEASUREMENTS

PRESENT RESEARCH EFFORTS:

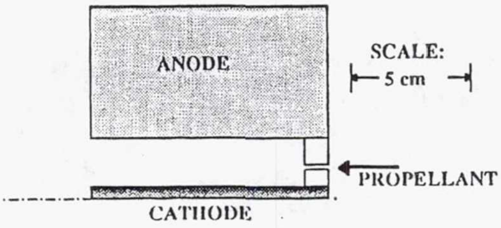
- HOLLOW/POROUS ANODE MPD THRUSTER
- THE MEASUREMENT OF THE IONIZATION FRACTION INSIDE OF THE MPD THRUSTER
- THE EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF MICROTURBULENCE ON MPD THRUSTER PERFORMANCE

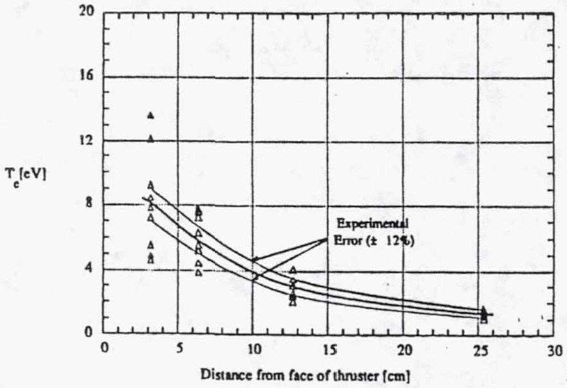
Electric Propulsion Facility Layout....

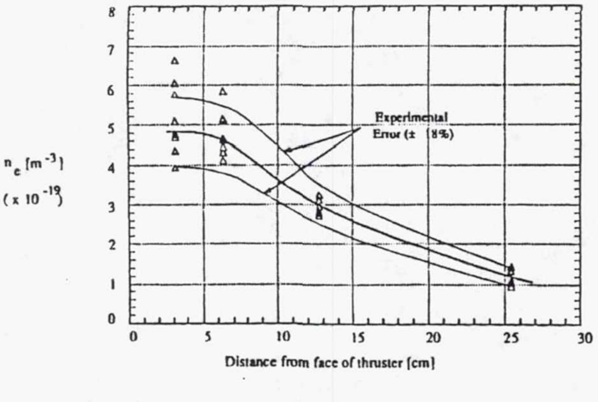
A1201.02

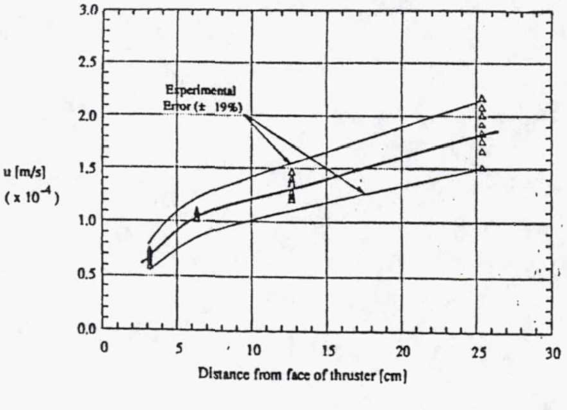


QUADRUPLE LANGMUIR PROBE MEASUREMENTS IN THE PLUME OF A MW LEVEL MPD THRUSTER. Argon, P=1.5 MW, J=11 kA, mdot=2 g/sec (in collaboration with S. DelMedico and R. Burton of U. of Illinois)









HOLLOW/POROUS ANODE MPD THRUSTER

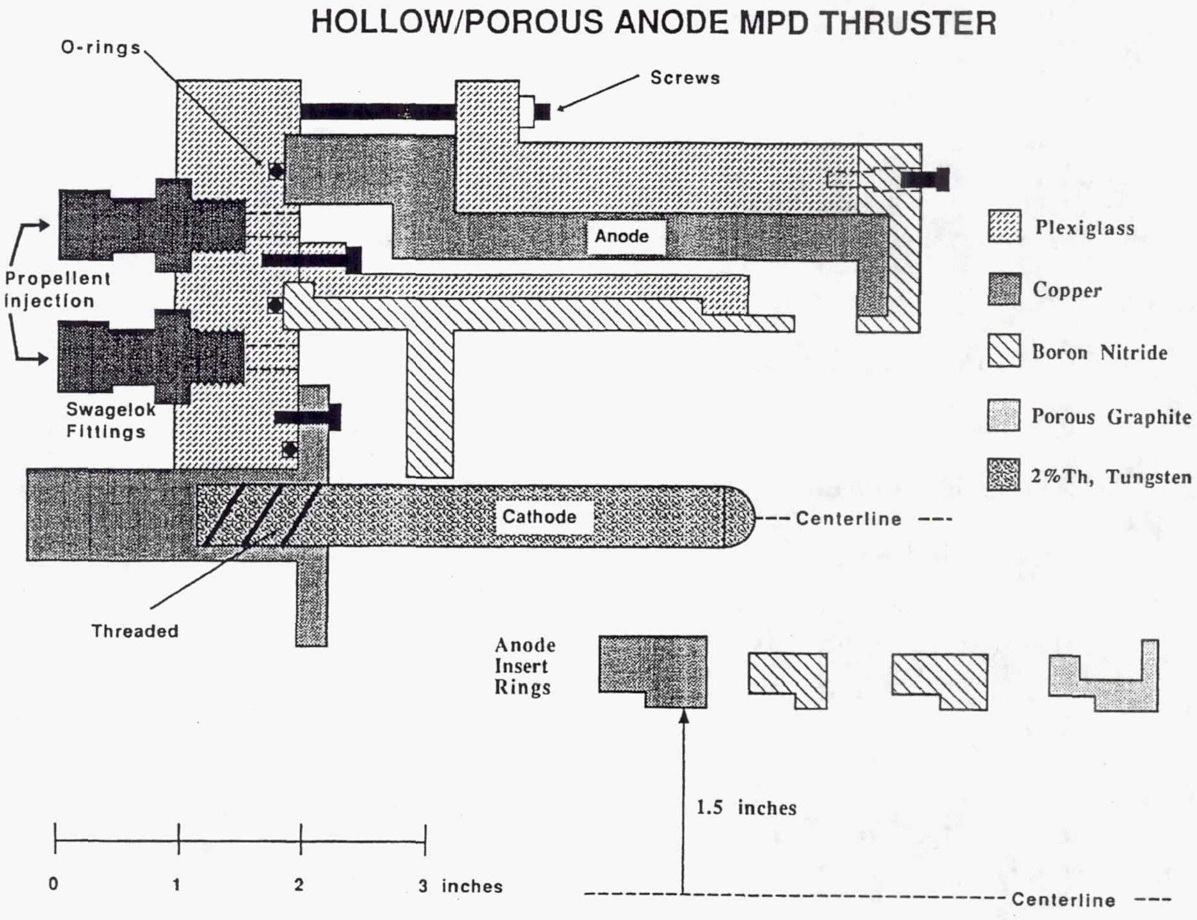
Objective: Investigate the effect of actively reducing the electron Hall parameter, Ω_e, in the anode region of the MPD thruster

Motivation: To significantly reduce the power flux to the anode surface

Approach:

- Design and test a Q.S. MPD thruster with propellent injection near the anode surface
- Measurements:
  - V-J curves versus propellant distribution fraction
  - Langmuir and Magnetic field probes will be used to verify a reduction of Ω_e and the fall voltage
  - Potential distribution throughout the thruster
  - Thrust measurements

(in collaboration with A. Gallimore of Univ. of Michigan)



IONIZATION PROCESSES

Objective: The measurement of the ionization fraction inside of the MPD thruster

Motivations:

- To provide insight into the ionization front phenomenon
- To evaluate the electrothermal instability model for the critical current
- To evaluate collision-radiative models for excited state distributions

Approach:

- Electron Temperature: Relative line intensities
- Electron number density: Stark Broadening
- Ground state neutral density: Absolute line intensities of excited states plus modelling

(in collaboration with M. Jolly and M. Martinez-Sanchez of M.I.T.)

MICROTURBULENCE

Objective: To experimentally investigate the effect of microturbulence on MPD thruster performance.

Motivations:

- To evaluate anomalous transport models
- To evaluate MHD codes incorporating anomalous transport
- To identify methods to reduce losses associated with microturbulence

Near-Term Approach:

- Experimentally determine the locations inside of a MW level MPD thruster where various forms of microturbulence operate. (in collaboration with E. Bowman and S.N.B. Murthy of Purdue Univ.)

Far-Term Approach:

- Experimentally measure, and compare with theory, the microscopic and macroscopic properties of the plasma affected by microturbulence (e.g., f_e, T_i, η)

RECENT ADVANCES IN MPD THRUSTER RESEARCH AT PRINCETON

Robert G. Jahn and Edgar Y. Choueiri
Princeton University
Princeton, NJ

EPPDyL Staff and Research Activities

Research Staff	**Position**	**Research Activities**
Robert G. Jahn	Lab. Director	Principal Investigator
Arnold J. Kelly	Lab. Manager	ES sprays & Plasma Propulsion
Waldo Von Jaskowsky	Research Consultant	Plasma Spectroscopy
Edgar Choueiri	Research Associate	Plasma Propulsion, & Space Plasma Physics

Students	**Level**	**Research Activities**
Alec Gallimore (currently at the U. of Michigan)	Ph.D.	Anode Power Deposition
Kevin Diamant	Ph.D.	Anode Region Wave Processes
Dennis Tilley	M.S.	Plasma Instabilities in the kW level MPD Thruster
Thomas Randolph	M.S.	Thruster Ionization Processes
Jeffrey Fillmore	M.S.	Lithiated Cathode Plasma Thruster Research
Giuliano Caldo	M.S.	Plasma Thruster Numerical Modelling
Scott Wunsch	B.S.	Coordinate Transformations for Plasma Thruster Numerical Modelling
Tim Kniker and Robert Braugner	B.S.	MPD Thruster Performance Measurements using the EPPDyL Thrust Stand
Brian Kantsiper	B.S.	Modelling of Critical Ionization Velocity (CIV) Experiments in Space
John Kline	B.S.	Computer Control of the MPD Thruster Testing and Diagnostics Facility at EPPDyL

Summary of Last Year's Findings

ANODE:

(Gallimore)

* Anode losses are **dominant** at power levels between 2 kW and 30 kW, **Important** between 30 kW and 200 kW and an **Engineering Challenge** above 200 kW.

* Anode fall and hence anode power fraction scale with the electron Hall parameter, Ω_e .

PLASMA:

(Choueiri, Tilley)

* The existence of current-driven micro-instabilities **(LHCDI)** has been established theoretically and experimentally and was found to be largely **independent** of power level for similar devices operating at the same ξ . ($\xi^2 \sim J^2/\dot{m}$).

* It was speculated that these micro-instabilities might play an important role in **frozen flow** and **anode** losses.

CATHODE:

(Polk, Chamberlain)

* **Evaporation** is the dominant mechanism for cathode erosion.

* **Low work-function** cathode can decrease the cathode erosion rate by orders of magnitude.

Summary of this Year's Activities & Findings

(Details and supporting data are on the following viewgraphs)

*** The scaling of anomalous resistivity with the Hall parameter.**
(Choueiri)

*** The relation between anomalous resistivity and the anode drop.**
(Gallimore, Diamant)

*** The presence of micro-turbulence in the anode region.**
(Diamant)

*** Numerical simulations with anomalous transport.**
(Caldo, Wunsch, Choueiri)

*** The use of magnets to reduce anode dissipation.**
(Gallimore)

*** Performance testing with the new anode.**
(Kniker, Braugner)

*** The mechanisms behind the ionization sink.**
(Randolph, Kantsiper, Choueiri)

*** Lithiated cathode research.**
(Fillmore)

Previous and Current Understanding

The energy invested in ionization and the anode region dissipation (especially at low power) seem to be the most important causes of inefficiency for the MPD thruster. Consequently we have an on-going research program for each of these two problems.

Last year

Existence of Microinstabilities: Last year we only had speculations on the nature of the dissipative mechanisms controlling the importance of these two sinks. There was theoretical evidence from *Choueiri* on the presence and importance of LHCDI in the MPD thruster plasma as well as experimental support for the existence and resilience of such microinstabilities from *Tilley* and *Choueiri* for both kW and MW level devices.

The scaling of Va with the Hall parameter : *Gallimore* undertook extensive measurements of the anode drop and re-established the strong dependence of the anode drop on the electron Hall parameter. No solid link existed at that time between the anode drop and the role of microinstabilities.

Recent developments

The scaling of anomalous resistivity with the Hall parameter: Since then, *Choueiri* added many real effects to his model of microinstabilities and carried the theory into the nonlinear phase to study the impact of such instabilities on the basic transport processes in the plasma through the induced microturbulence. One of the major findings of that study is the strong dependence of the anomalous resistivity on the electron Hall parameter. This led to the speculation that the anode drop may be due to the turbulence-induced anomalous resistivity.

The relation between anomalous resistivity and the anode drop: Shortly thereafter, *Diamant* and to a larger extent *Gallimore* inferred the local resistivity near the anode from experimental measurements and found it to be up to an order of magnitude larger than the classical value. This has considerably strengthened the link between the anode drop and plasma turbulence.

The presence of turbulence in the anode region: To further investigate this possible link, *Diamant* has undertaken a systematic probing of the plasma very near the anode looking for evidence of microturbulence. His results were positive. Prominent peaks in the fluctuating energy spectra are at and very near the frequencies (lower hybrid frequency) predicted by the wave stability and microturbulence theories. We are now relatively more confident of our earlier speculations concerning the role of microturbulence in the dissipation.

Numerical simulation with anomalous transport: In order to study the role of the above phenomena and relate them to the global flow problem *Caldo* used the anomalous transport models developed by *Choueiri* in a state-of-the-art two-D, two-fluid code to investigate *self-consistently* the effects of the turbulence on the flow and vice-versa. He found that the plasma regions near the cathode's tip and root and near the anode tip are critical from the point of view of anomalous transport.

Wunsch has developed a coordinate transformation algorithm that allows the adaptation of the MPD flow code to any axi-symetric geometry. *Choueiri* has implemented specialized compilers for the MPD code on the Cornell supercomputer that allow an order of magnitude speed up in the execution performance over that previously attainable on that machine.

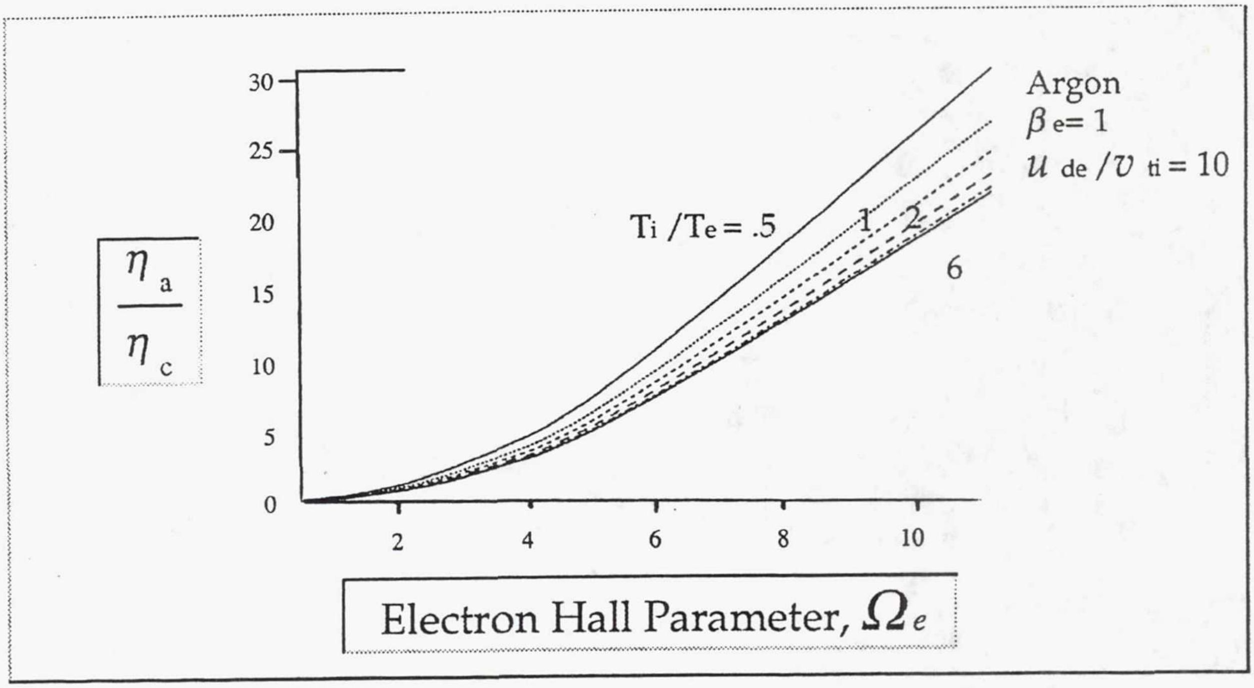
The use of magnets to decrease dissipation: Spurred by the strong scaling of the anode drop with the electron Hall parameter, *Gallimore* implanted a series of small permanent magnets in the anode that were designed to effectively annul the local magnetic field in the anode region thus hopefully decreasing the resistivity and dissipation. While the anode drop seems to have been sensibly decreased the total voltage seemed little effected.

Performance testing with the new anode: In order to follow up on the possibility of performance improvement with the magnetically annuled anode, *Kniker* and *Braugner* have just finished a relative efficiency comparison of the new and old anodes using the laboratory's thrust stand. Their experiments showed that, unfortunately, the new anode does not offer a higher thrust efficiency than the older one.

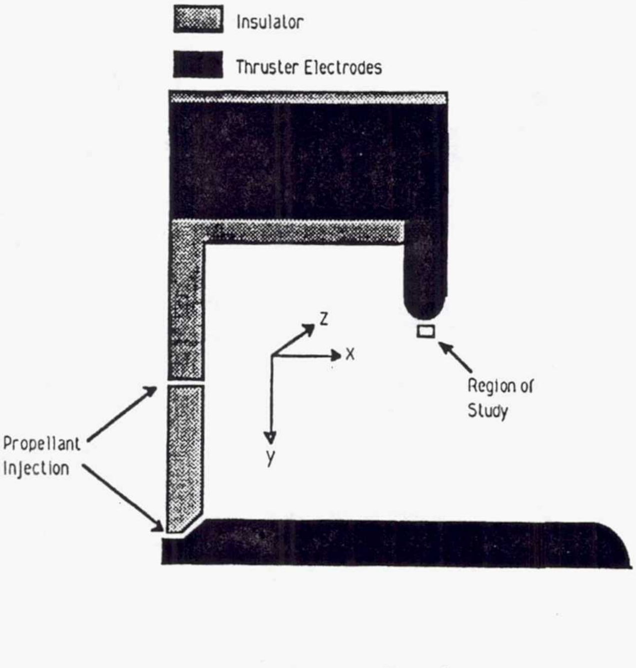
The mechanisms behind the ionization sink: The link between plasma microturbulence and excessive ionization is today as speculative as was the link between microturbulence and the anode drop last year. It is speculated from theory that electrons should benefit from the preferential heating of the unstable waves and cause a very efficient ionization through the CIV effect thus tying up a substantial fraction of unrecoverable energy in singly, doubly and triply ionized atoms. Such anomalous ionization would typically happen abruptly through spatially well defined ionization fronts. The existence of such fronts has not been properly established. *Randolph* has set out to investigate spectroscopically whether such fronts do actually exist inside the chamber of the MPD thruster. He found that a rapid ionization region possibly exists upstream of his physical viewing window and has recently succeeded in pushing this region within that window by advancing the discharge forward through the use of a partly insulated cathode.

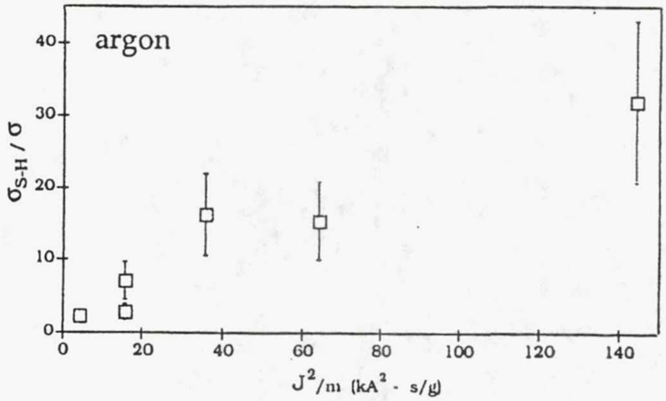
Another program aimed at the study of the fundamental aspect of the CIV effect was initiated recently. Experiments staging a CIV interaction through the injection of a neutral gas from the Russian APEX satellite have been undertaken recently and are currently being analyzed by *Choueiri*. He is currently planning more optimized gas release experiments on APEX during the upcoming months using among other tools, a kinetic stability model for CIV interactions developed at EPPDyL by *Kantsiper*.

Lithiated cathode research: *Fillmore* has finished the calibration and the preparation for his upcoming experiments on the use of a lithiated cathode for the control of cathode erosion rates. Lithiated cathodes are expected to yield orders of magnitude reduction in the erosion rate, thus eventually relegating the cathode erosion problem to the arena of development engineering as an essentially resolved fundamental problem.



Anode Power Deposition in MPD Thrusters





Inferred Electrical Conductivity

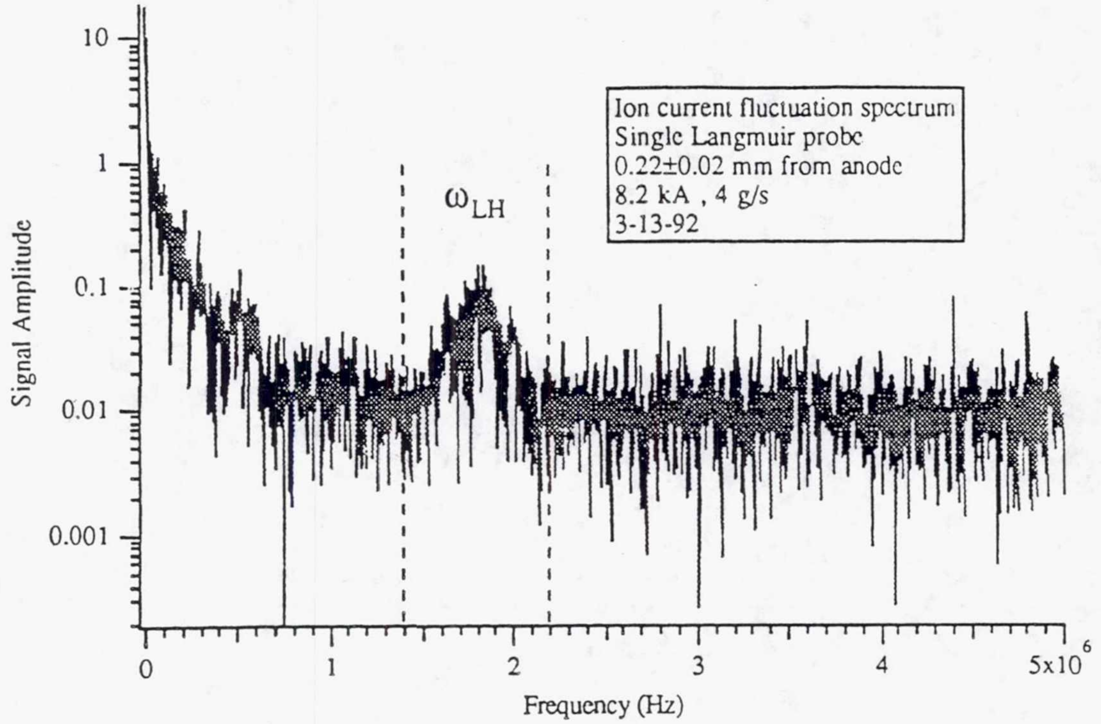


Figure 1. Spectrum recorded 0.22 mm from anode at 8.2 kA, 4 g/s.

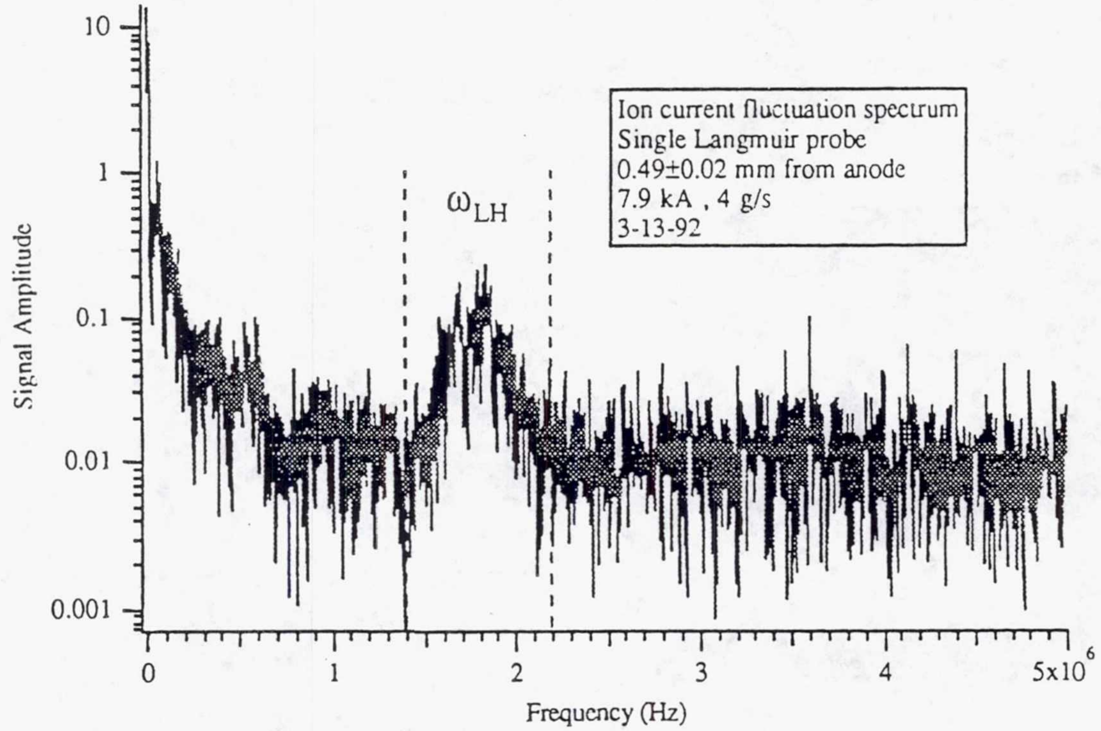


Figure 2. Spectrum recorded 0.49 mm from anode at 7.9 kA, 4 g/s.

Evidence of Lower Hybrid Turbulence Near Anode

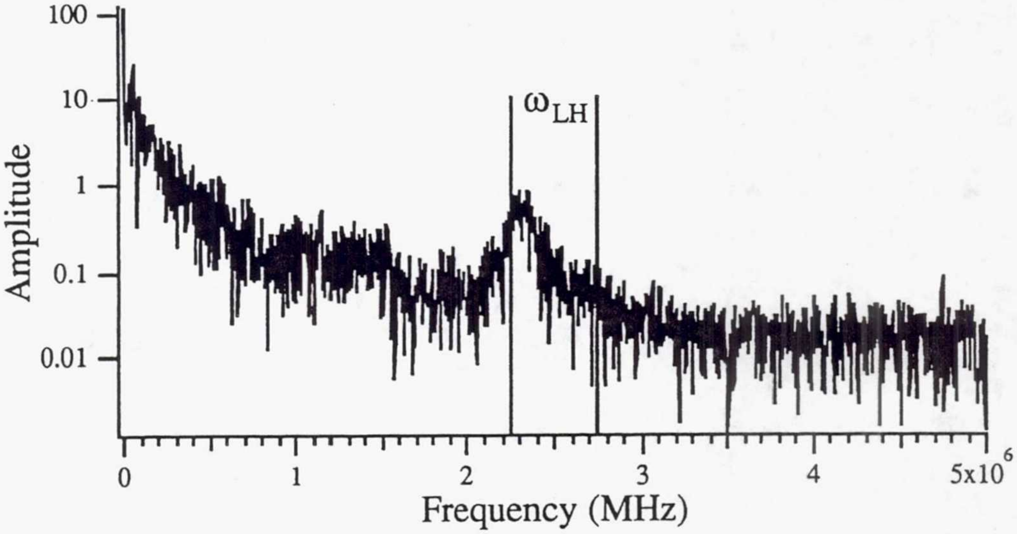


Fig. 1. Spectrum of ion saturation current fluctuations 1 mm from anode lip. From operation at 17 kA, 16 g/s argon.

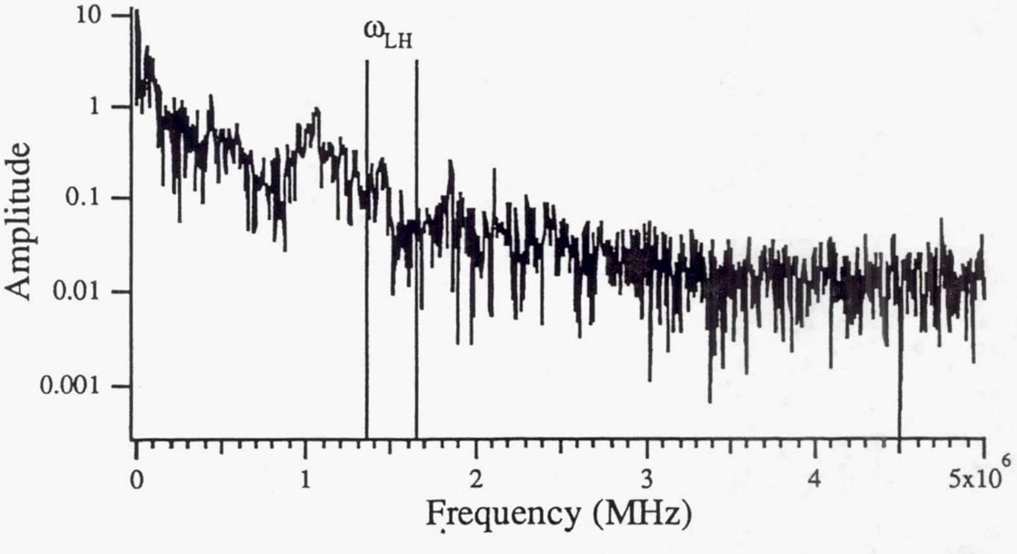


Fig. 2. Spectrum of ion saturation current fluctuations 1 mm from anode lip. From operation at 8 kA, 4 g/s argon.

Improved MPD Thruster Model

- Two-Dimensional with Axial Symmetry
- Two Temperatures
- Heat Transfer
- Nonideal Ion Equation of State (Choueiri)
- Finite Ionization Rate (Randolph)
- Variable Geometry (Wunsch)

New Numerical Method

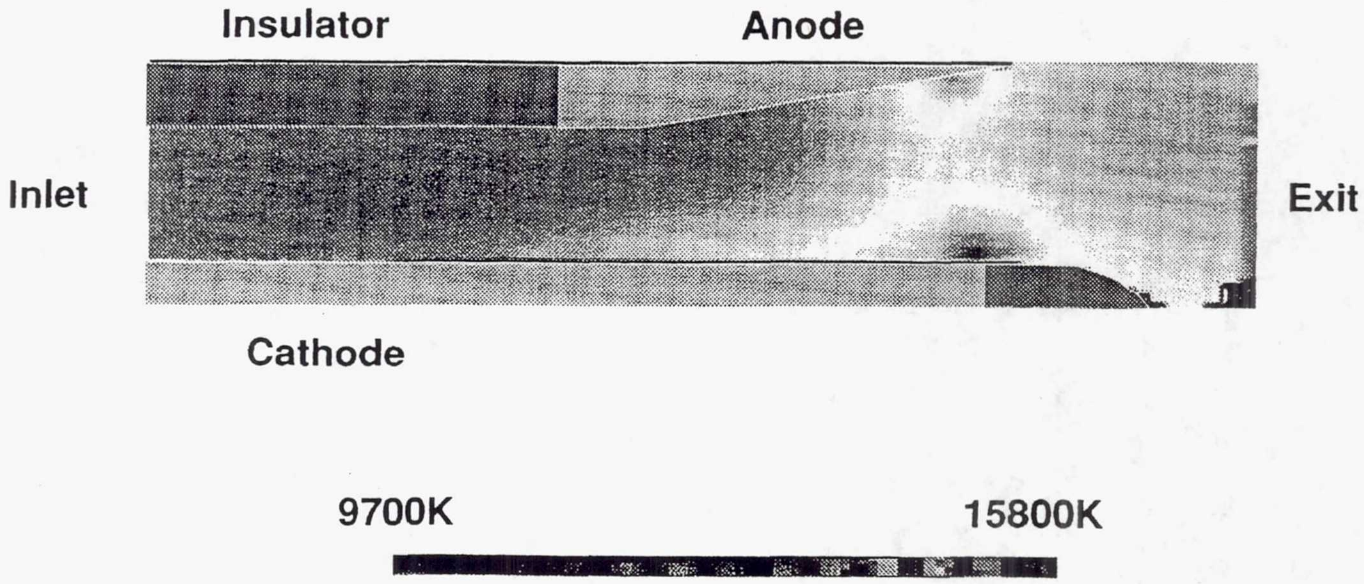
For the Conservation Equations:

- Finite-Volumes Discretization with Artificial Dissipation (Jameson)
- Euler Forward Stepping Scheme
- Multiple Grid Iteration

For the Magnetic Field Equation:

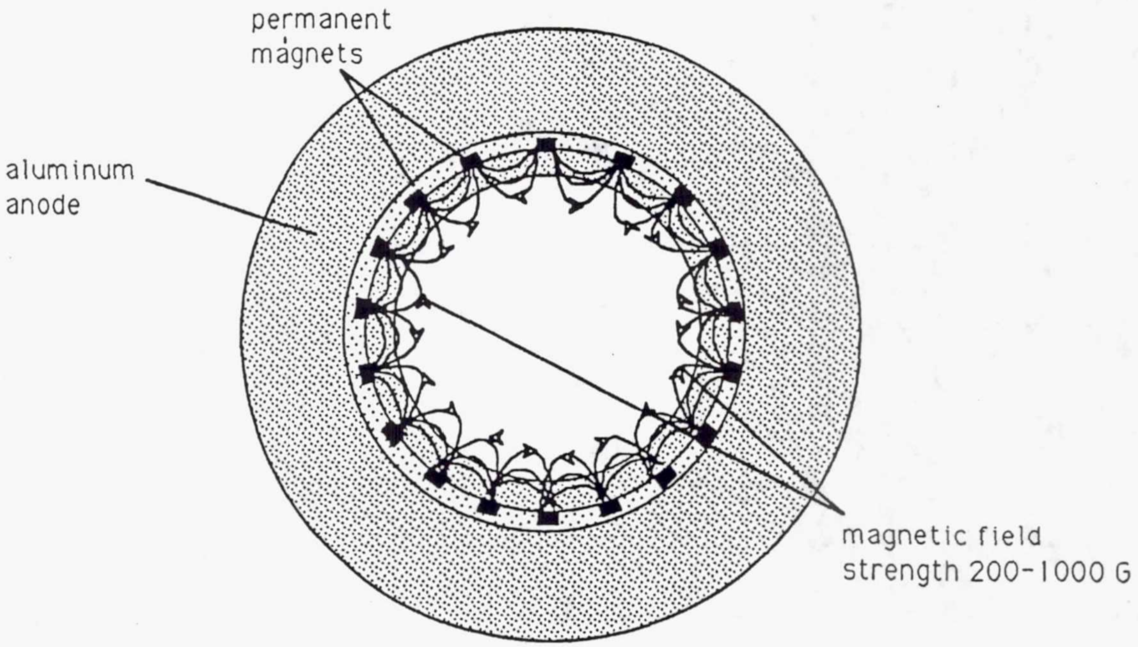
Nonlinear Jacobi Iterative Solution

Electron Temperature

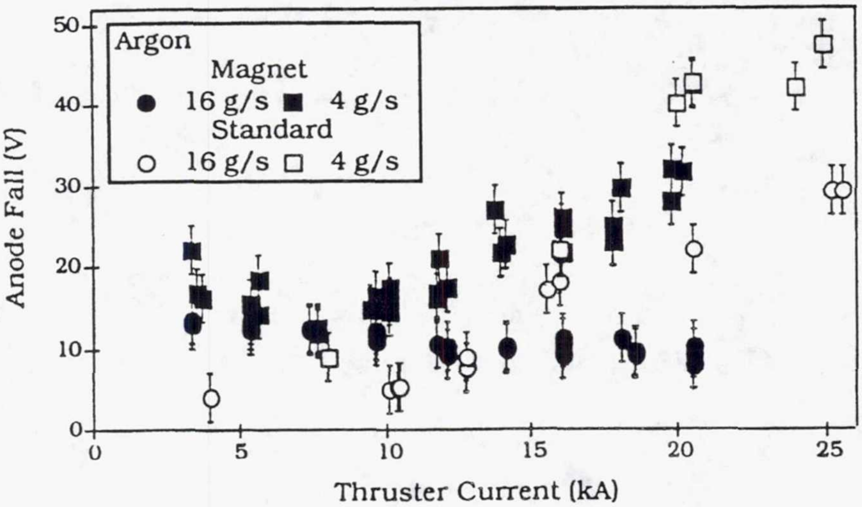


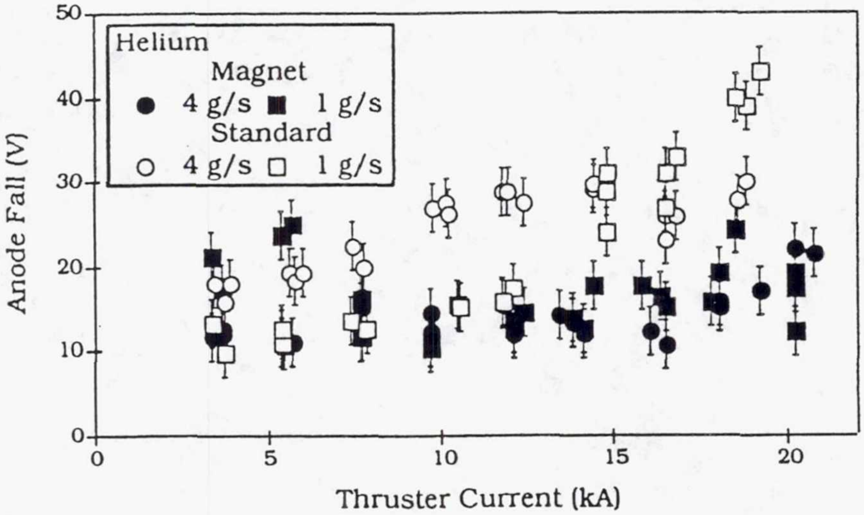
Concept

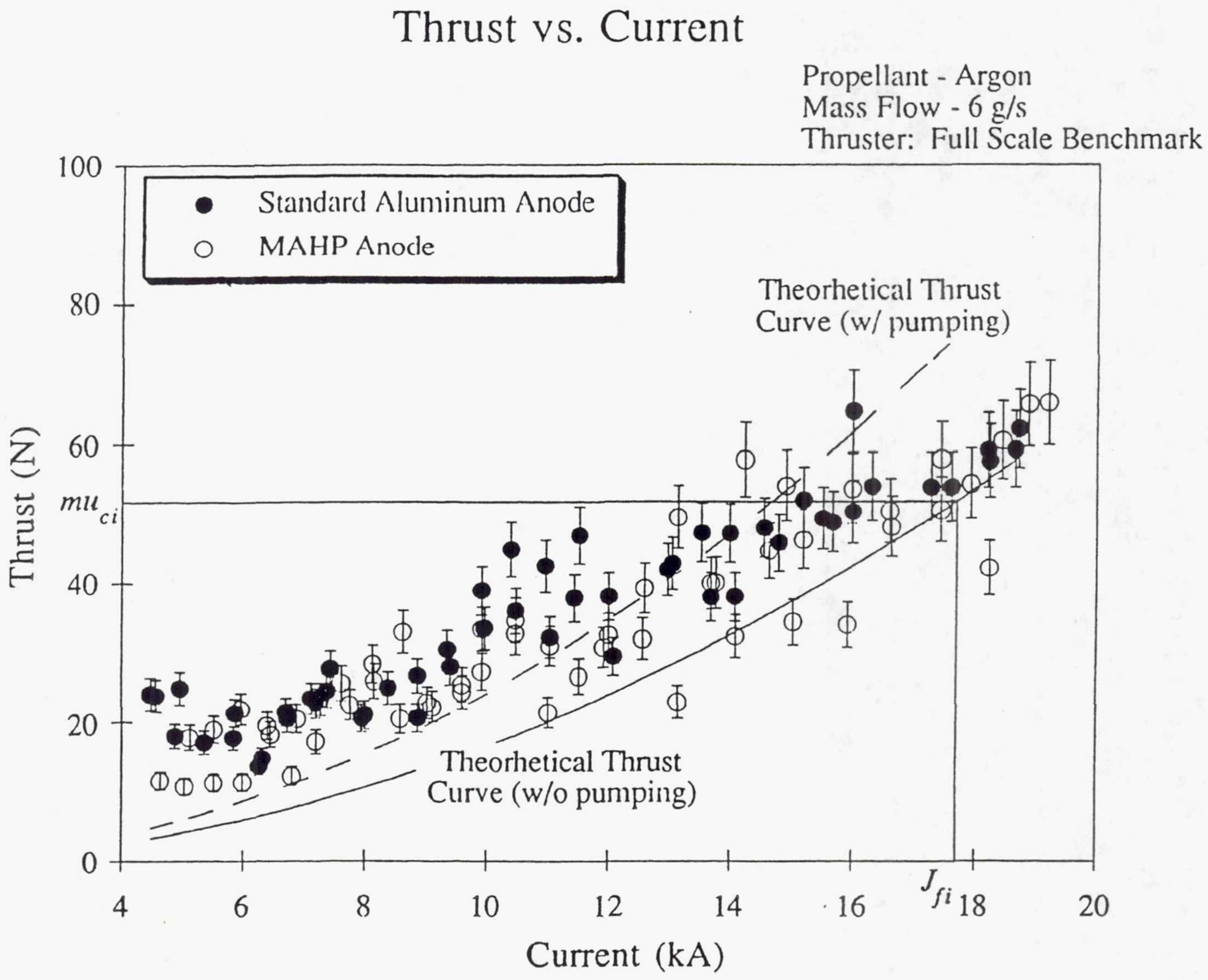
To Reduce the Induced Azimuthal Magnetic Field by Adding " Field Cancelation Zones" Near the Anode.

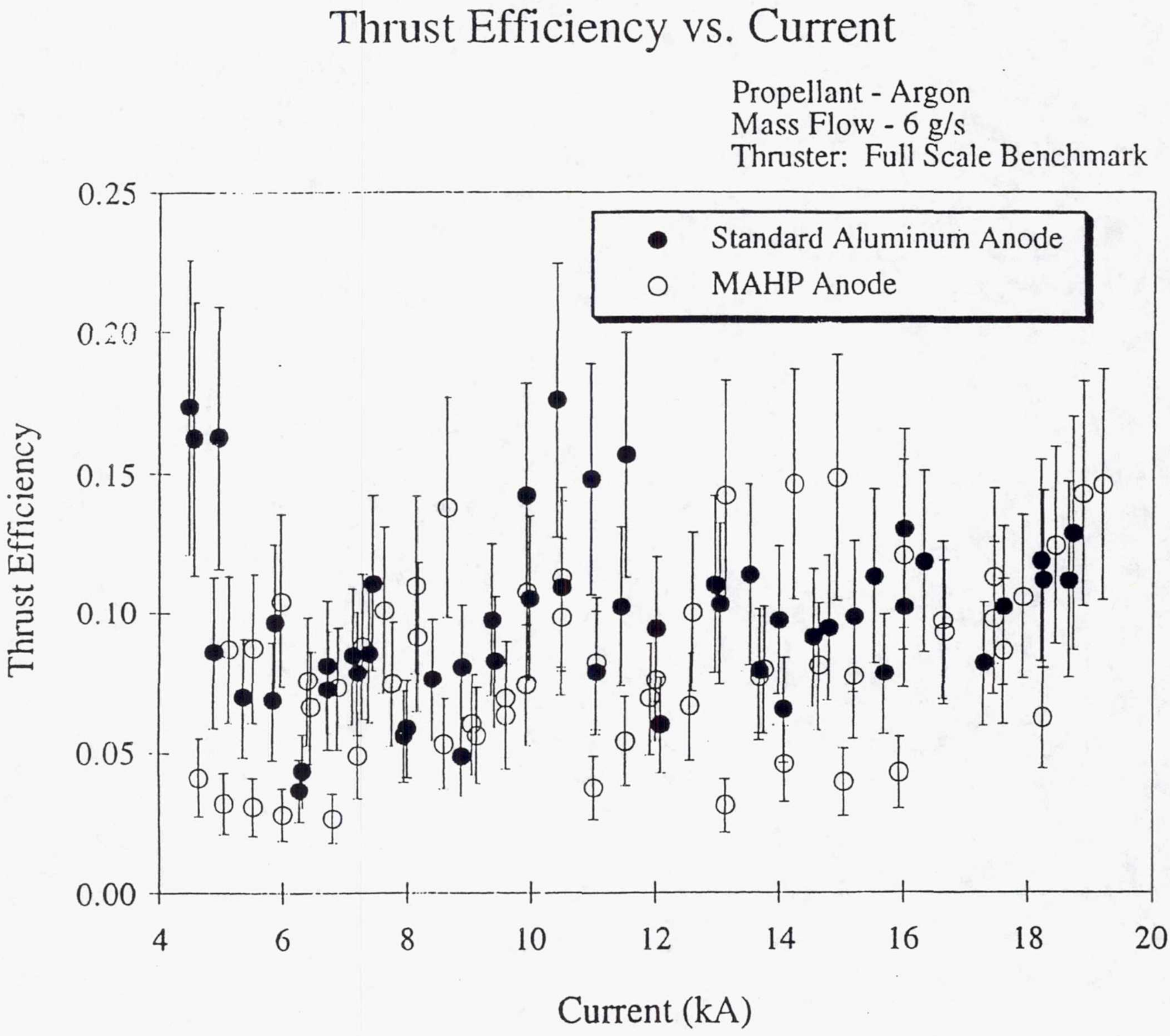


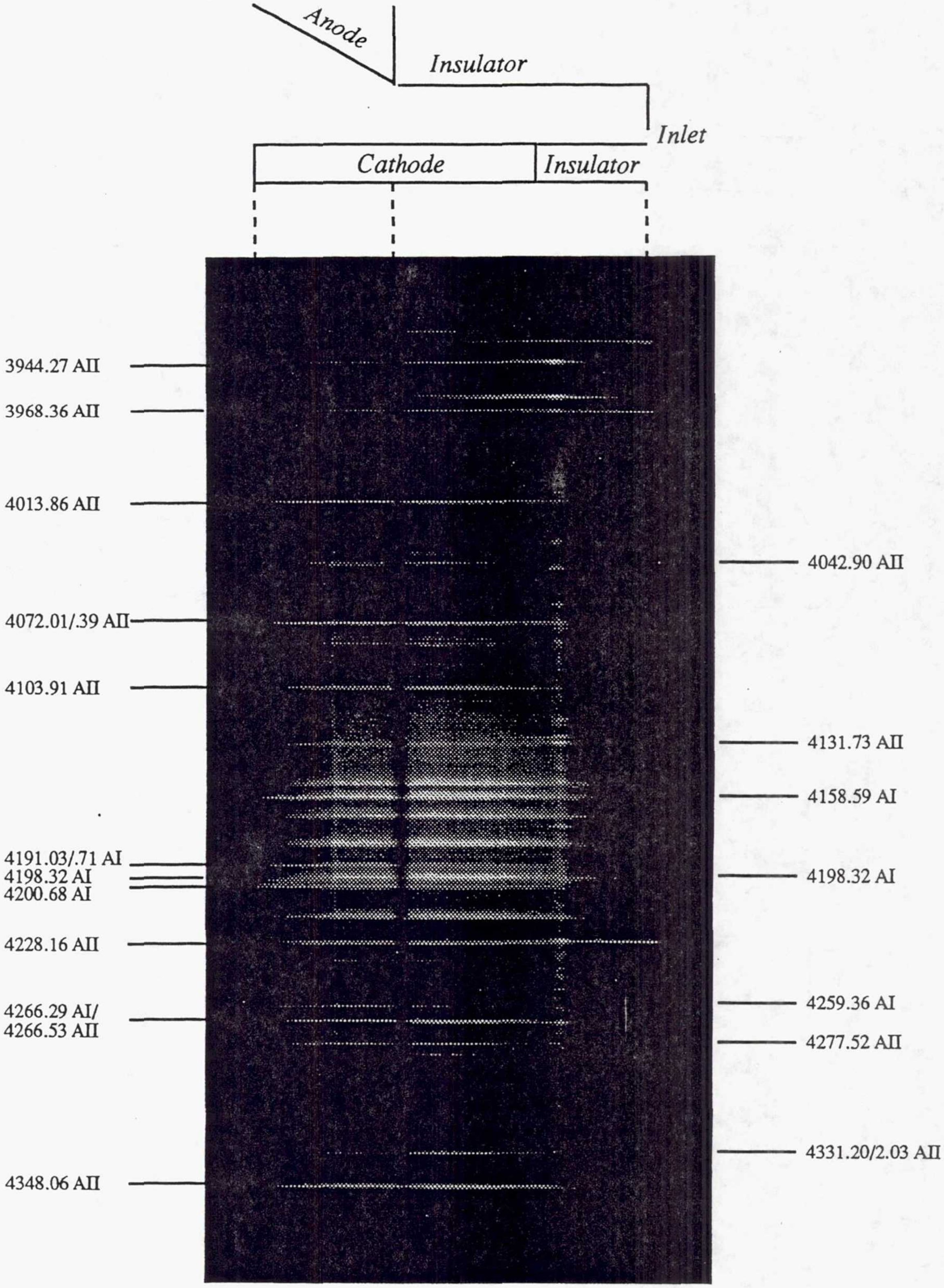
Anode Fall vs Thruster Current






Thrust vs. Current
Propellant - Argon
Mass Flow - 6 g/s
Thruster: Full Scale Benchmark
● Standard Aluminum Anode
○ MAHP Anode
Theorhetical Thrust Curve (w/ pumping)
Theorhetical Thrust Curve (w/o pumping)
Thrust (N)
Current (kA)
mu_{ci}
J_{fi}
100
80
60
40
20
0
4
6
8
10
12
14
16
18
20

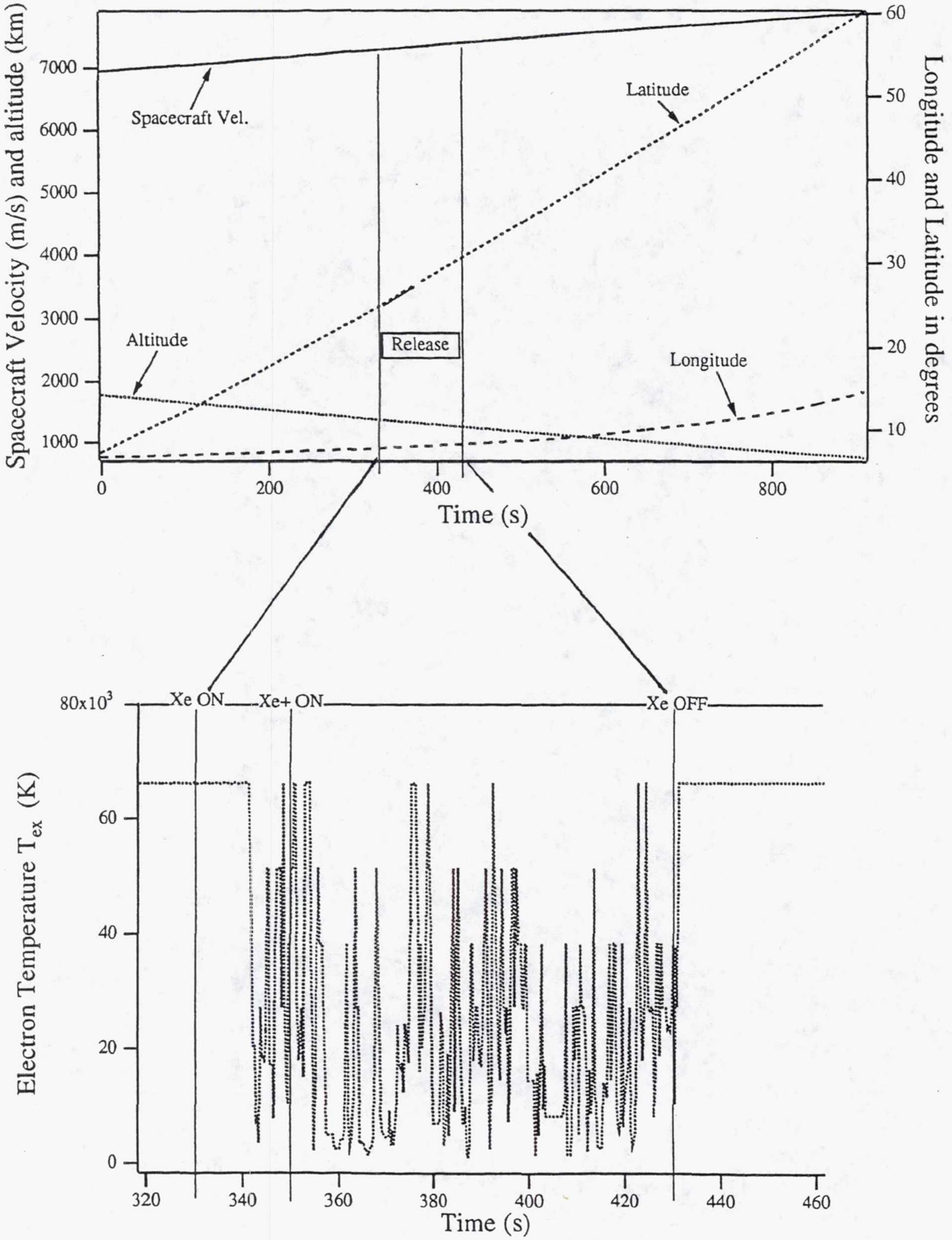

Thrust Efficiency vs. Current
Propellant - Argon
Mass Flow - 6 g/s
Thruster: Full Scale Benchmark
● Standard Aluminum Anode
○ MAHP Anode
Thrust Efficiency
0.25
0.20
0.15
0.10
0.05
0.00
4
6
8
10
12
14
16
18
20
Current (kA)



3944.27 Å to 4348.06 Å spectrum of the MPD thruster interelectrode region. Current attachment isolated downstream on the cathode to observe the initial ionization phase: Argon Mass Flow = 7 mg/s, Current = 260 A.

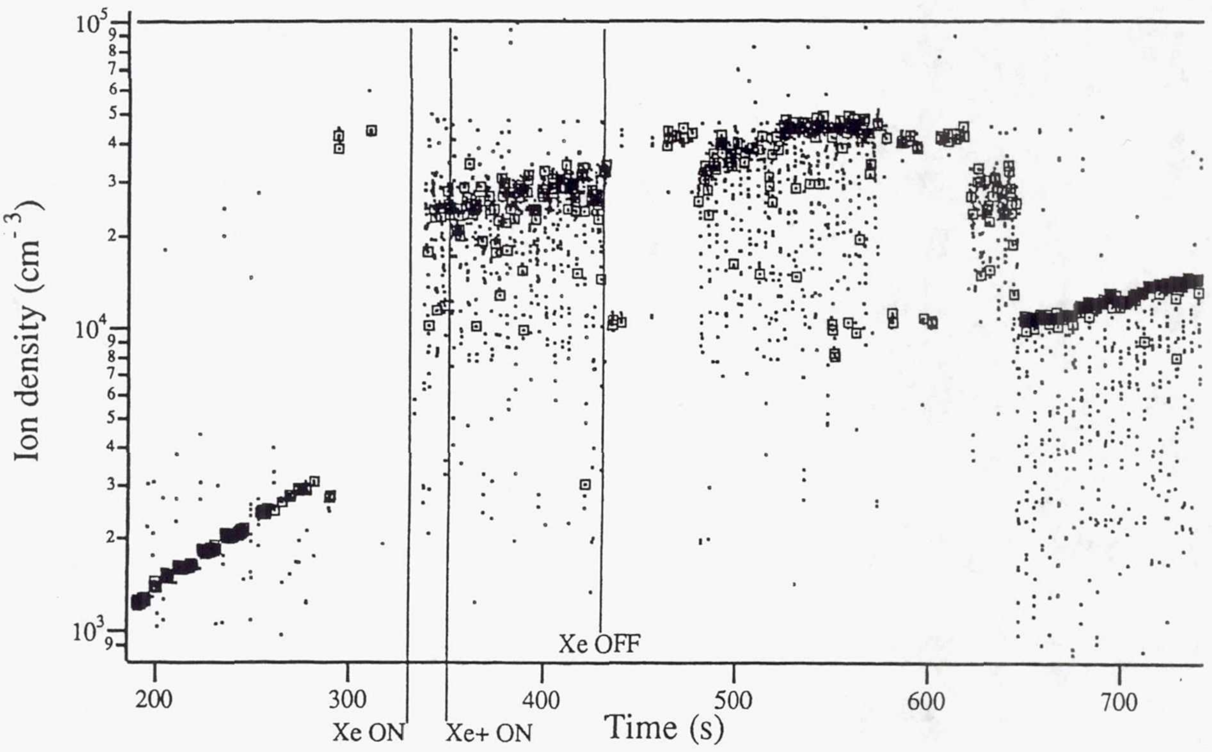
Spacecraft Orbital Parameters

During Experiment APEX/CIV-NO1



Plasma Density

During Experiment APEX/CIV-NO1



LITHIATED DISPENSER CATHODE RESEARCH

PAST RESEARCH

Polk, Myers

- Steady State erosion due primarily to sublimation
- Sublimation varies exp (T)
  T varies exp (work function)

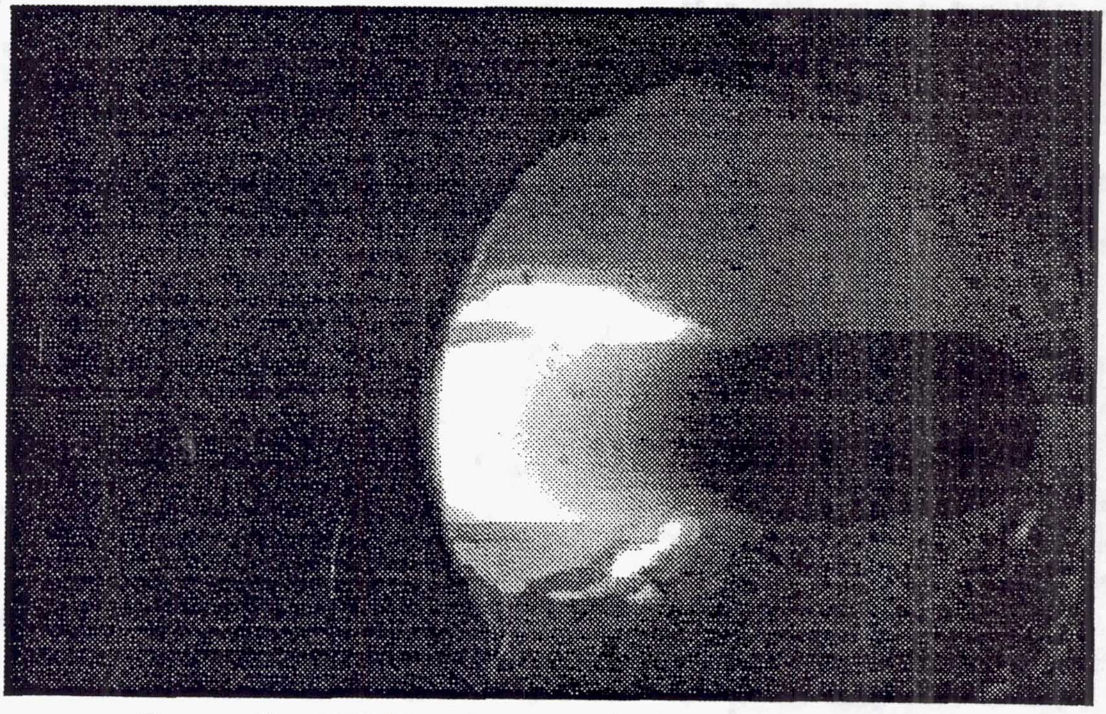
Chamberlain

- Electropositive Surface Layers improve Lifetime of Cathode
- Significant lowering of cathode temperature during steady state
- Cold cathode pitting is not observed

LITHIATED DISPENSER CATHODE RESEARCH

Objectives

1. Validate dispenser cathode design
2. Measure cathode surface temperature optically using CCD camera
3. Characterize cathode thermal behavior and correlate with thruster performance



Sample CCD picture from thruster run

Future Research Activities at EPPDyL

* **Performance characterization** of MPD thrusters with various propellants (hydrogenic propellants), various anode and cathode implementations using the laboratory's thrust stand.

* **Numerical simulations** of real MPD thrusters with various propellants, various anode and cathode implementations including non-equilibrium effects and anomalous transport.

* Further experimental and theoretical investigations of the extent of the role of **micro-turbulence** in **frozen flow** and **anode losses**.

* Feasibility study of **active turbulence suppression schemes.**

* Investigations of the nature and dependences of the dominant **ionization mechanism** through further **spectroscopic** measurements and active **space experiments.**

* Validation of the **lithiated cathode** concept.

* Synthesis, using the results of all the above activities, of practical **design criteria** for higher efficiency and longer lifetime MPD thrusters.

Appendix A. Workshop Agenda

Location

The 2nd Magnetoplasmadynamic Thruster Technology Workshop will be held in Rm 225 of the NASA Lewis Research Center Administration Building. Maps and hotel listings are attached. Visitors requiring badges must pick them up at the Main Gate.

In order to maximize the productivity of the meeting, we ask that the presenters bring 30 copies of their presentations. As was done last year, a volume will be generated incorporating the presentations and a summary of the group discussion.

Agenda

8:30: Welcome
    Dave Byers, NASA Lewis Research Center

8:35 Introduction
    Roger Myers, Sverdrup Technology, NASA Lewis Research Center

8:40 Transportation and Platforms Program Perspectives
    Gary Bennett, NASA Headquarters

8:50 Low Thrust Propulsion Program Objectives
    Frank Curran, NASA Headquarters

9:00 Mission Analysis and Systems Implications
    James Gilland, Nuclear Propulsion Office

9:30 Jet Propulsion Laboratory

10:00 Lewis Research Center

10:30 Los Alamos National Laboratory

11:00 Massachusetts Institute of Technology

11:30 Ohio State University

12:00 - 1:00 Lunch

1:00 OLAC/Phillips Laboratory

1:30 Princeton University

2:00 Break

2:30 - 5:30 Group Discussion

A. Experimental Program
  - Summary of progress made in past year
  - Suggested testing/diagnostics
  - Establish next years goals, intermediate milestones, and suggested approaches.

B. Theoretical Program
  - Summary of progress made in past year
  - Benchmark geometries and operating conditions
  - Establish next years goals, intermediate milestones, and suggested approaches.

5:30 Summary
    Roger Myers, Sverdrup Technology, NASA Lewis Research Center

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Responsible person, Dr. Roger M. Myers, (216) 977–7426.

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13. ABSTRACT *(Maximum 200 words)*

The Second Magnetoplasmadynamic (MPD) Thruster Workshop was held at the National Aeronautics and Space Administration (NASA) Lewis Research Center on May 19, 1992. There were 32 participants, including experts from NASA, the Department of Energy (DOE), the Department of Defense (DOD), and academia. Six government laboratories and six universities were represented at the workshop, the purpose of which was to review technical progress made since the last meeting held at NASA Headquarters in 1991 and discuss plans for future work. Specifically, the meeting focussed on progress made in establishing performance and lifetime expectations of MPD thrusters as functions of power, propellant, and design; models for the plasma flow and electrode components; viability and transportability of quasi-steady thruster testing; engineering requirements for high power, long life thrusters; and facilities and their requirements for performance and life testing.

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