N93-18639

MPD THRUSTER TECHNOLOGY

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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

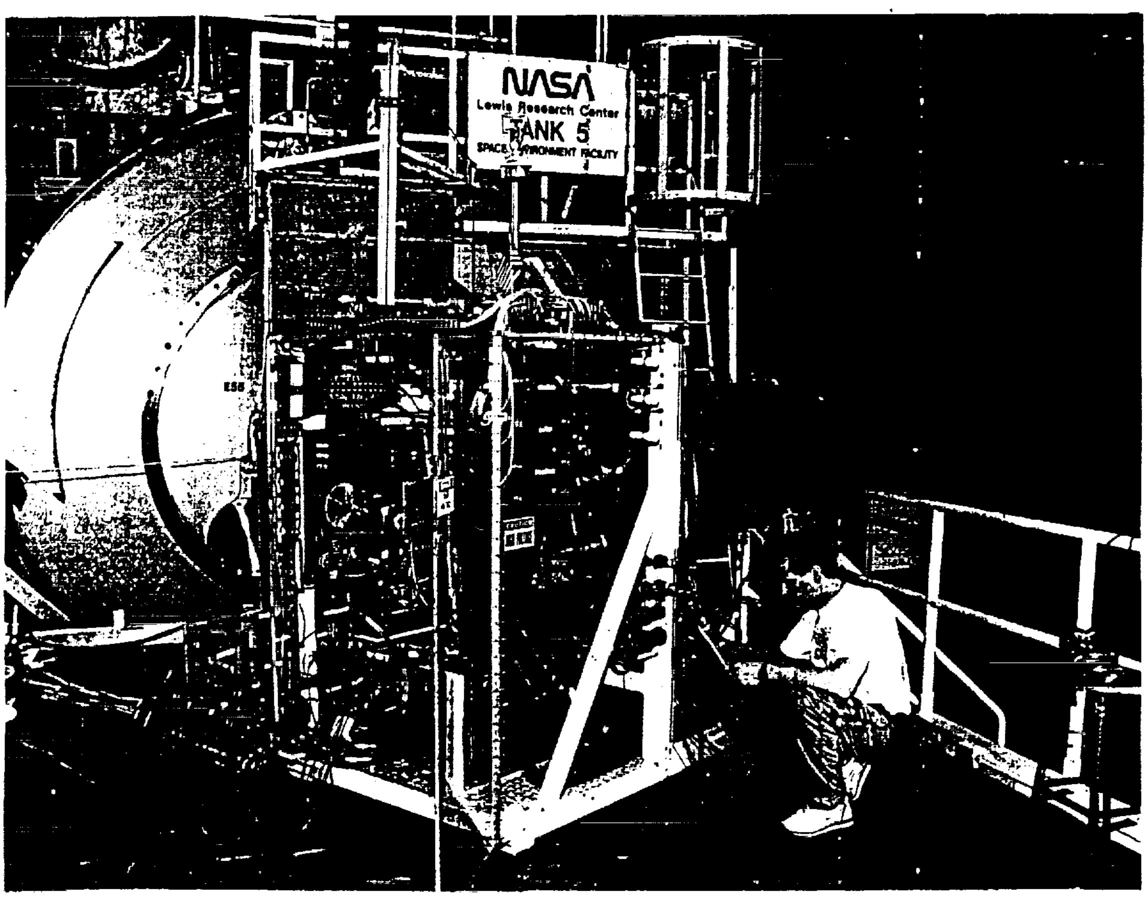
Facility Capabilities
- Cryopumping
- Beam Dumps
- Lithium facility design

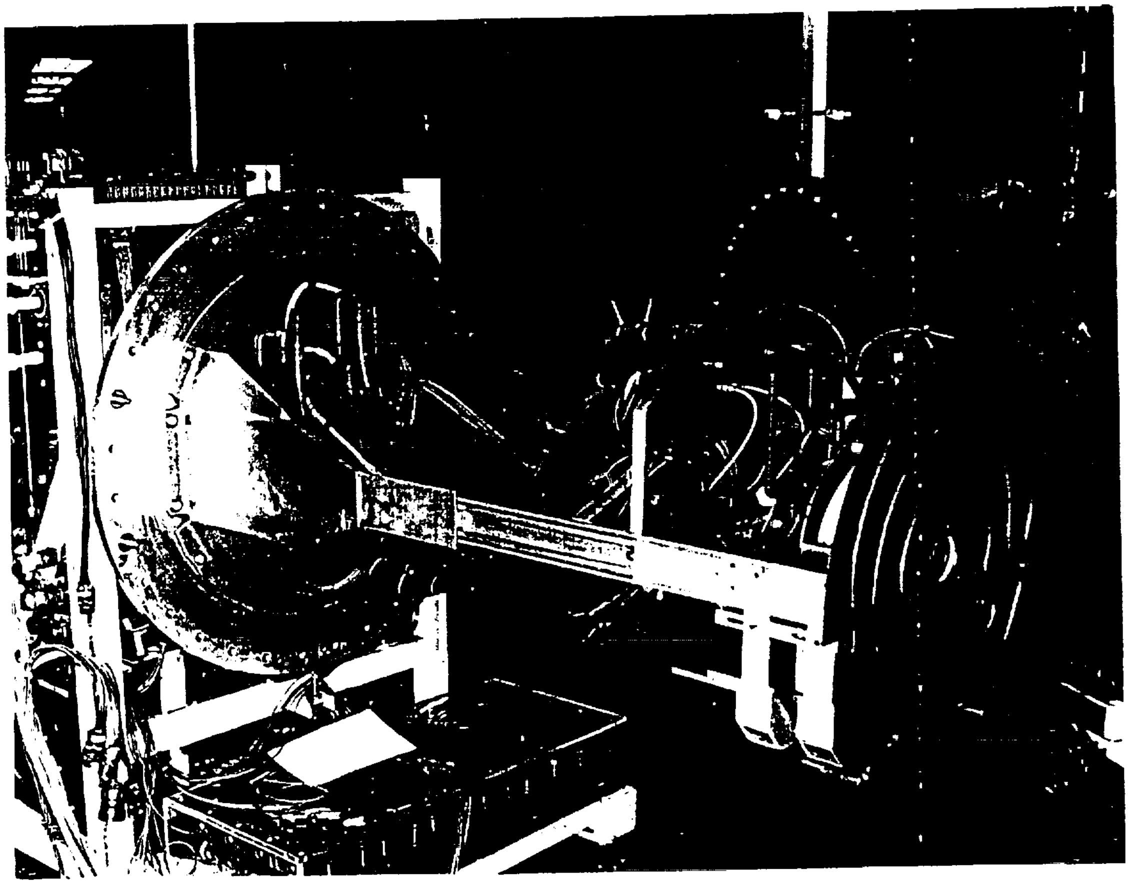
PERFORMANCE MEASUREMENTS
- Progress in Past Year -

- 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

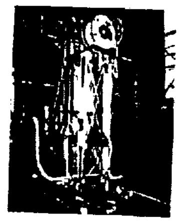
MPD Thruster Technology

High Power MPD Thruster Test Stand

Power

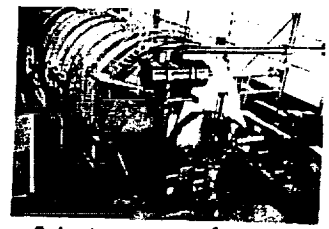
• 0.39 MW

Thrust stand

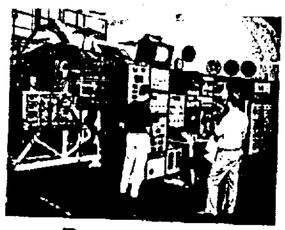


• 0.1 to 4 N

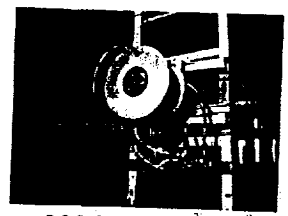
Vacuum facility



• 0.1 g/s at 3×10^{-4} TORR



Data/control

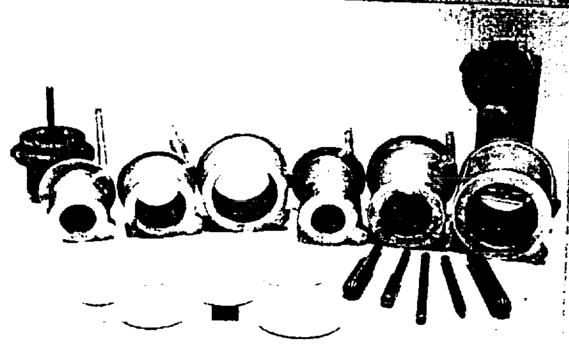


220 kW thruster

CD-91-54820

HIGH POWER ELECTRIC PROPULSION (MPD)

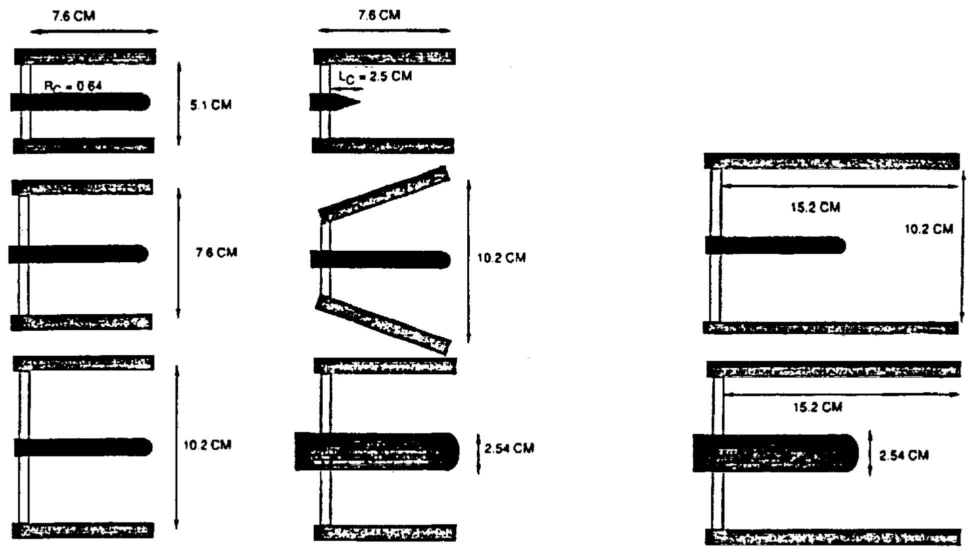
MPD THRUSTER RESEARCH AND TECHNOLOGY –THRUSTER SCALING AND MATERIALS EFFECTS–



- 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

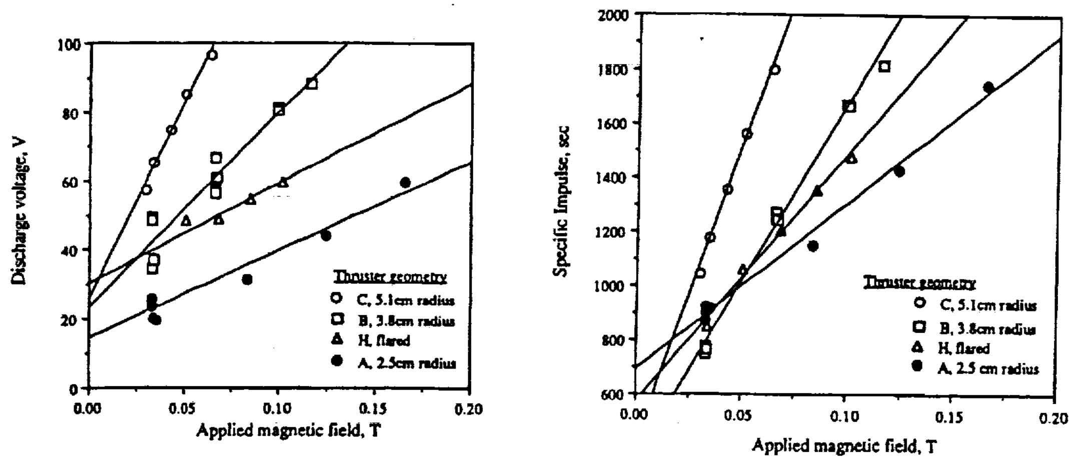
$$T = bJ_d^2 + \frac{R_a^2 J_d B_z}{k_1 L_c R_c} + f(L_a, R_a, \dot{m})$$

  - $I_{sp} \alpha\ 1/\dot{m}$ (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

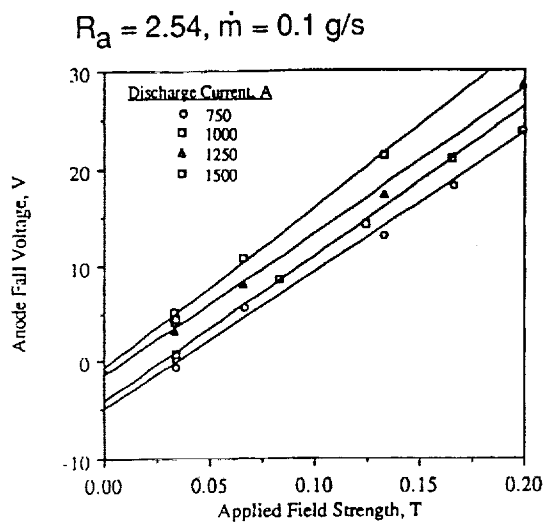
$$V_{an} = \frac{P_a - P^c_r}{J_d} - \left(\frac{5kT_e}{2e} + \Phi\right)$$

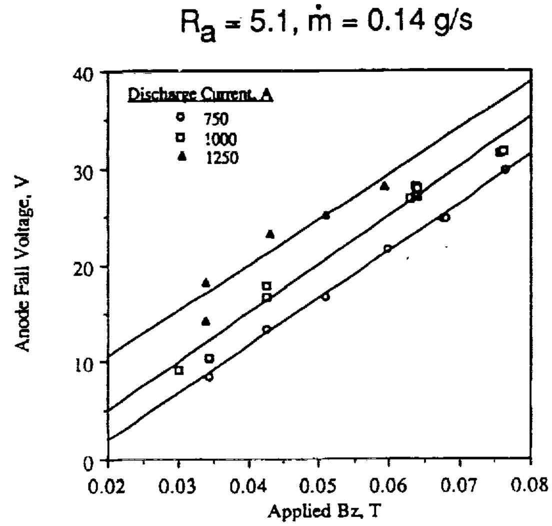
  - Cathode radiation contributed between 2 and 7 kW

- 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

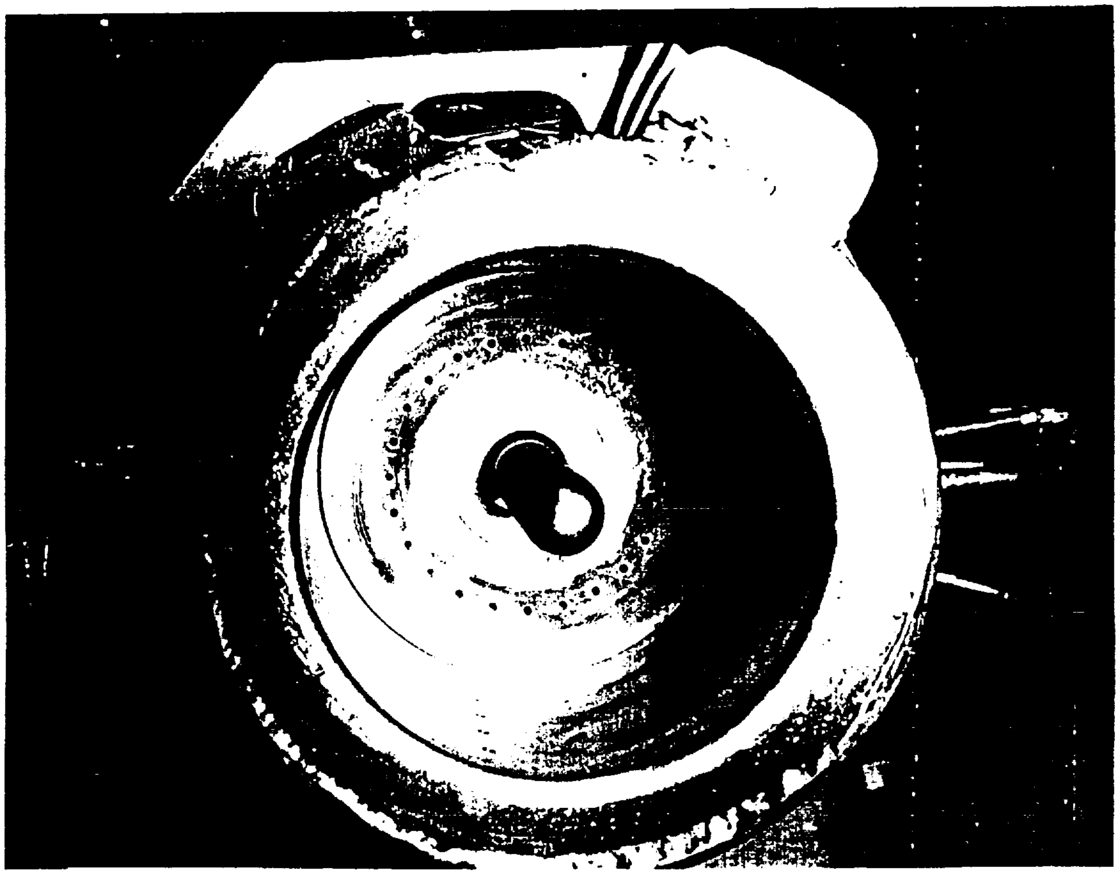


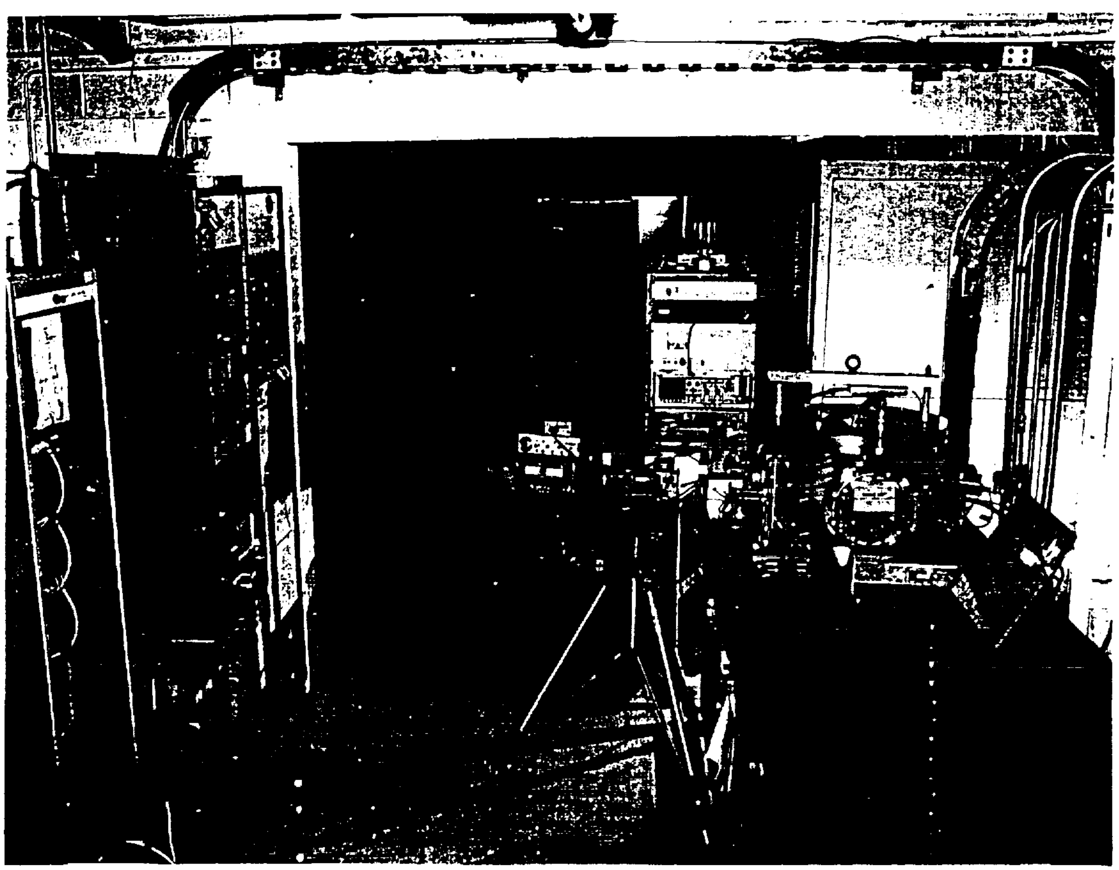


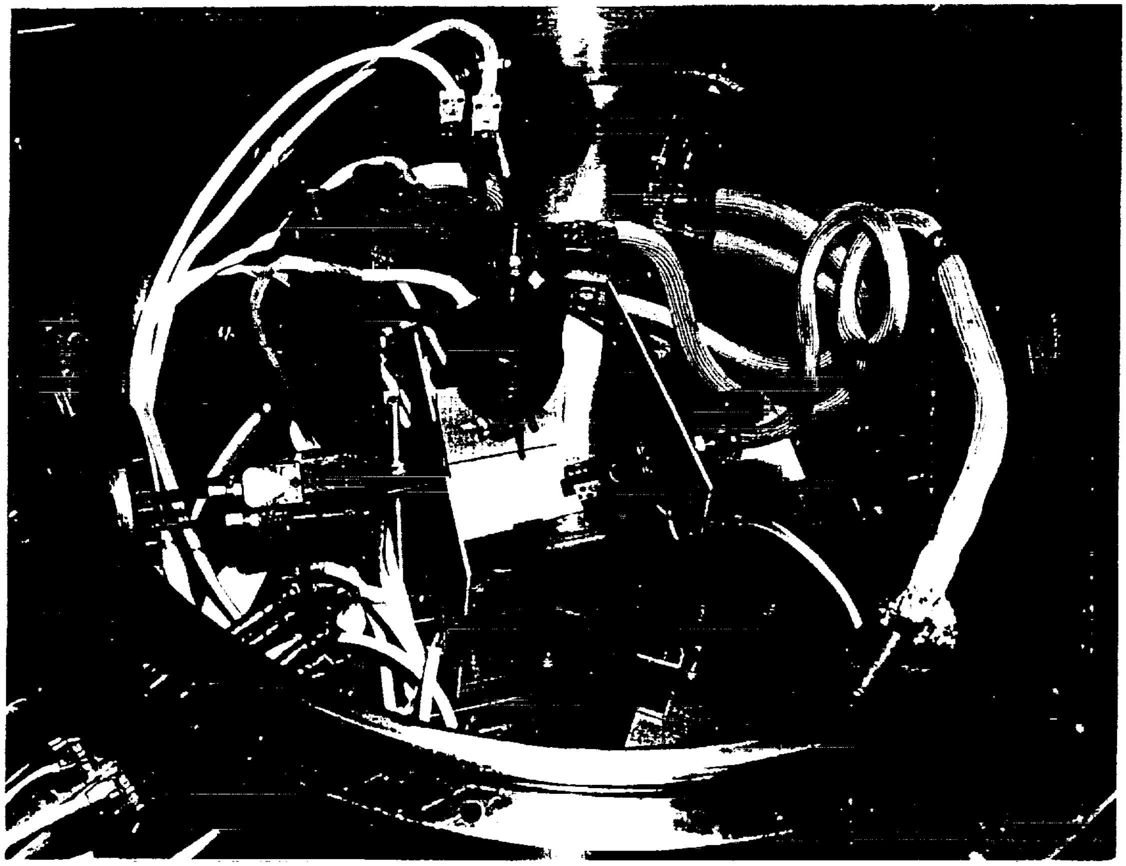
- Anode fall increases with Bz and Ra
- Anode fall decreases with increasing m

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.

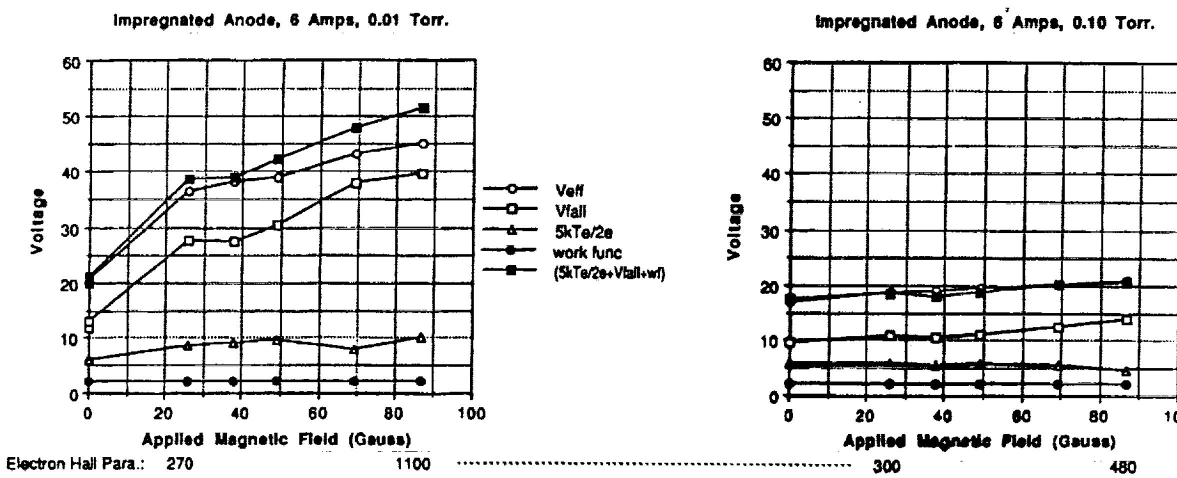






Anode Power Contributions

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

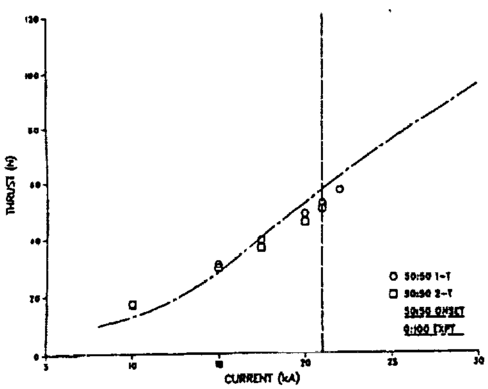
APPROACH

- 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

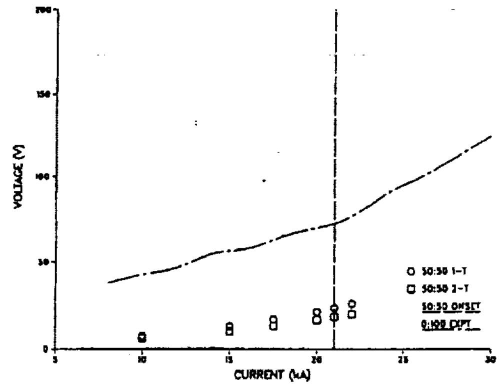
MPD THRUSTER PLASMA MODELING

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

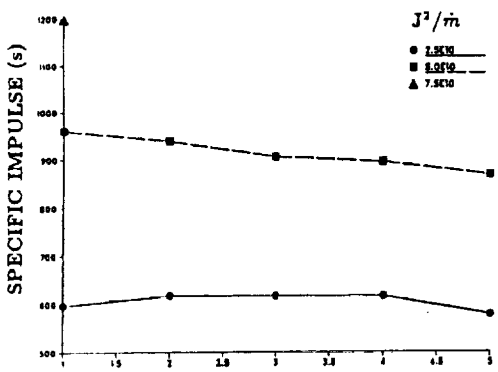
- EXTENDED ANODE MPDT: NO STEADY-STATE CODE CONVERGENCE FOR $J^2/\dot{m}$ VALUES ABOVE ONSET
  - POSSIBLE CORRELATION BETWEEN NUMERICAL STABILITY AND STABLE REGIONS OF MPD THRUSTER OPERATION
- NUMERICAL EXPERIMENTS PERFORMED TO EVALUATE GEOMETRIC SCALING EFFECTS ON MPD THRUSTER PERFORMANCE:
  - STRAIGHT 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

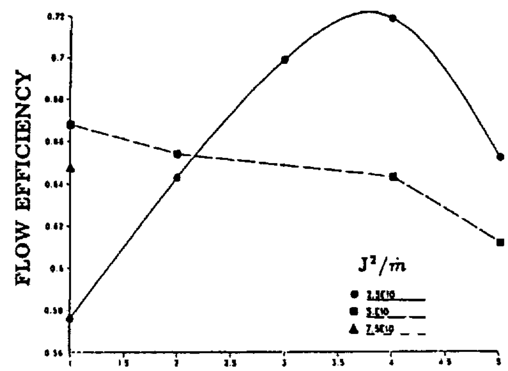
GEOMETRIC SCALING RESULTS

$R_a = 5$ 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

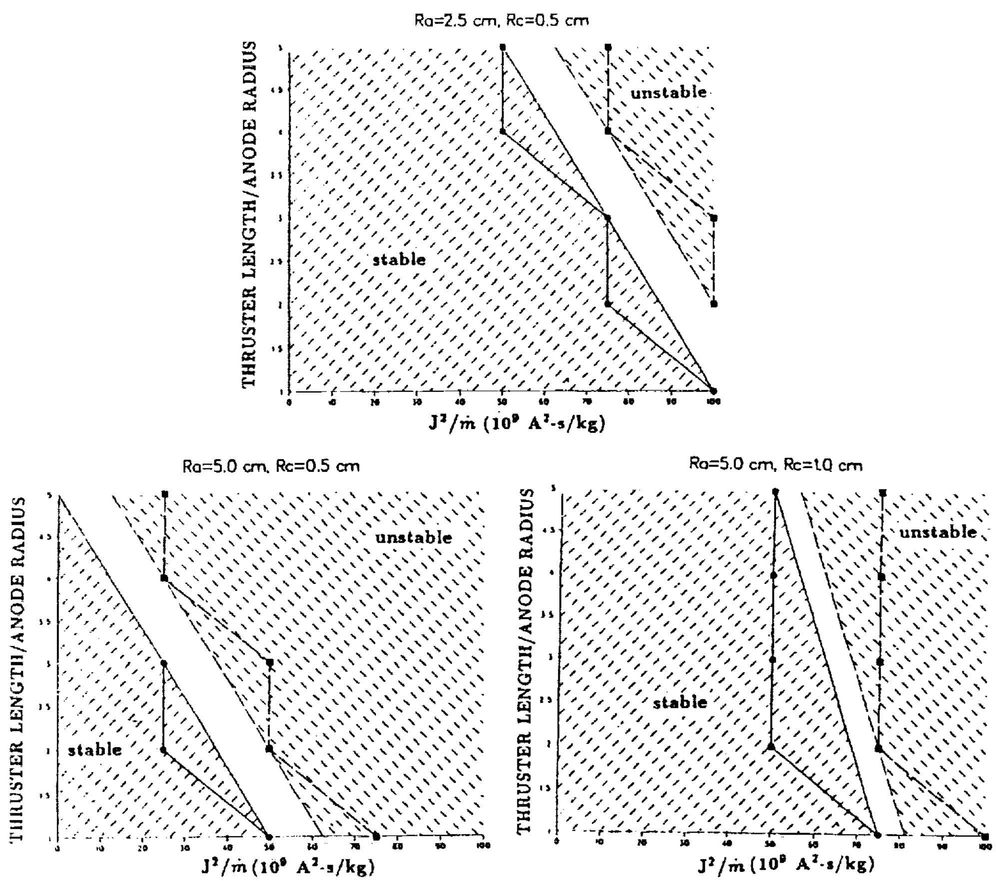
- HIGHEST I_{sp}, η_f FOR $R_a = 5$ cm, $R_c = 1$ cm, $L_a/R_a = 1$
  - $I_{sp} \approx 1400$ s, $\eta_f \approx 0.76$
  - NO STEADY-STATE CONVERGENCE FOR LARGER L_a/R_a

- 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)

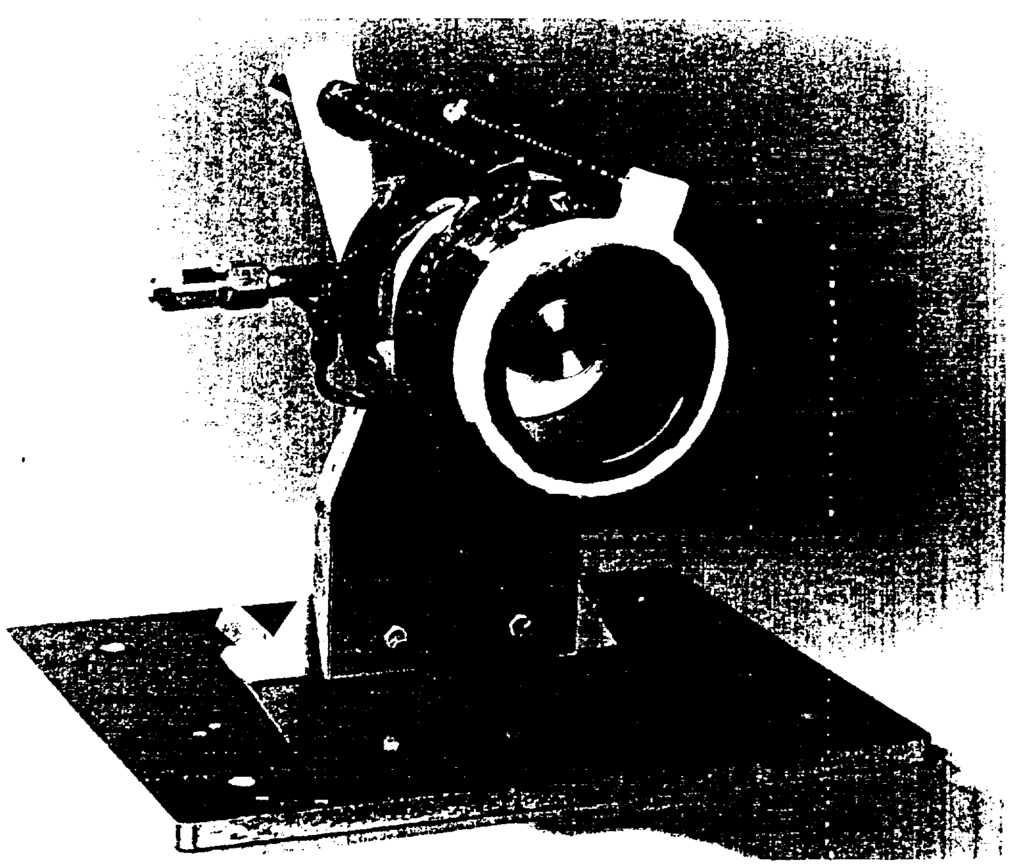


MPD Thruster Lifetime Studies
- Progress in Past Year -

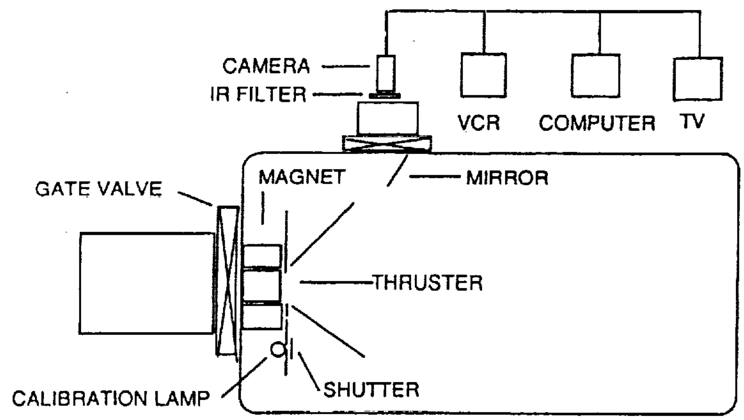
- Alternative Cathode Concepts
  - Extensive hollow cathode testing
  - Low work function rod cathode testing
  - Improved cathode cooling
  - Identified long-life pulsed cathode technology

- 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)

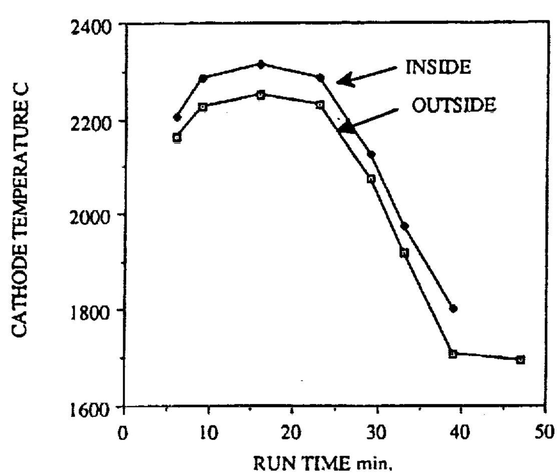


SCHEMATIC OF MPD CATHODE TEMPERATURE MEASUREMENT SYSTEM WITH IN-SITU CALIBRATION

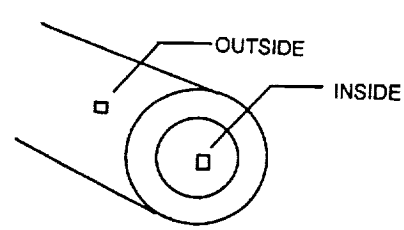


(NOT TO SCALE)

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

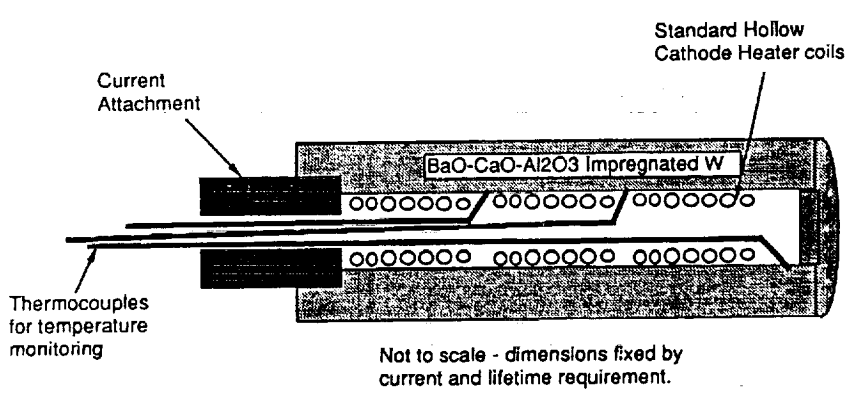
HOLLOW CATHODE TEMPERATURES INCREASE WITH:

- 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



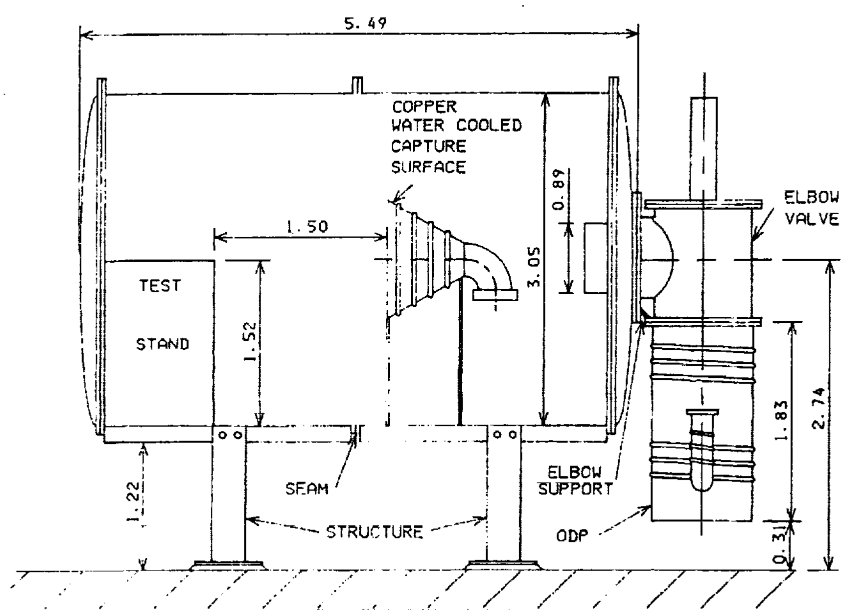
Use independent heater coils to permit axial temperature control. Monitoring temperature permits reduction in heater power as discharge power deposition increases

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 (3×10^{-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