IN-HOUSE PROGRAM OVERVIEW

- RE-ESTABLISHED IN 1987
- FOCUSED ON STEADY-STATE THRUSTERS AT POWERS < 1 MW
- DEVELOPED PERFORMANCE MEASUREMENT AND DIAGNOSTICS TECHNOLOGIES FOR HIGH POWER THRUSTERS
- DEVELOPING MHD CODE
- GOALS ARE TO ESTABLISH
  - PERFORMANCE AND LIFE LIMITATIONS
  - INFLUENCE OF APPLIED FIELDS
  - PROPELLANT EFFECTS
  - SCALING LAWS
High Power MPD Thruster Test Stand

**Power**
- 0.39 MW

**Thrust stand**
- 0.1 to 4 N

**Vacuum facility**
- 0.1 g/s at $3 \times 10^{-4}$ TORR

**Data/control**

**220 kW thruster**

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**MPD THRUSTER TEST STAND**

- In-situ Calibration Mechanism
- Displacement Transducer
- MPD Thruster
- Active Magnetic Damping
- Current Conducting Flexures
- Built-In Leveling Mechanism
- Reference Inclinometer
DEMONSTRATED MPD THRUSTER POWER INCREASING RAPIDLY

- Thruster Scaling and Materials Effects
  - 3 and 4 inch diameter anodes both 3 and 6 inches long
  - 0.5 and 1 inch diameter cathodes
  - Th and BaO impregnated tungsten cathodes
Performance Measured With Hydrogen and Argon

- Hydrogen
- Argon

Efficiency

Argon unstable above this Isp

2"D, 3"L Anode 25mg/s flow rate
750 A discharge current

Specific impulse, sec

Performance dramatically improved with hydrogen
- Efficiency increased by 2X
- $I_{SP}$ increased by 50%

Thruster Performance

Geometry and Applied Field Effects

$Jd = 1000$ A, $\dot{m} = 0.1$ g/s argon

- 2 inch diameter anode
- 3 inch diameter anode
- 4 inch diameter anode

Efficiency

Specific impulse, s

Applied Magnetic Field, T

- Efficiency increases with applied field strength
- Specific impulse increases with both anode radius and applied field strength
Anode Power Deposition
Applied Field and Geometry Effects

Increasing applied field strength and anode diameter decrease anode power fraction

Three hollow cathode assemblies fabricated and prepared for evaluation
MPD Thruster Technology

Scaling Issues

- Megawatt class operation required for missions of interest
- Cannot operate megawatt class steady-state in current facilities
- Must be able to correlate MW class pulsed thruster operation and steady state data
- Data must enable rational extrapolation to high power levels

How do we realistically study MPD thruster performance and life using currently available facilities?

Diagnostics

- X-Y probe positioning stand
  - Electrostatic probes
  - enclosed current contours
  - Axial applied B field distribution
- Plume imaging
  - Correlate ion density distribution with applied field
- Spectroscopy
  - Non-invasive temperature and density measurements
**Program Outline**

**Fluid loop**

- Conservation of mass → density ($\rho$)
- Conservation of momentum → velocity ($V_r, V_0, V_z$)
- Conservation of energy → temperature ($T$)
- Equation of state → pressure ($P$)
- Evaluate transport coeffs, hall parameters, etc...

**Field loop**

- Ohm's law and maxwell equations → induced fields ($B_0$)
- Maxwell (Ampere's) equation → current density ($I$)
- Ohm's law → electric field ($E$ → plasma potential)
- Evaluate energy source, sink terms, etc...

- Convergence on exhaust velocity $V_{new}^{ex} \leq 0.01 V_{old}^{ex}$, plasma potential: $\Phi_{new} \leq 0.01\Phi_{old}$

- No
- Yes
  - Evaluate thrust, specific impulse, efficiency,...
  - Write to data files
  - Done

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**Comparison With U. Stuttgart Model/Experiment**

(6kA, 6 g/s)

- Stuttgart-experiment
- Stuttgart-model
- NASA LeRC-model

**Current fractions into anode segments**

<table>
<thead>
<tr>
<th>Segment</th>
<th>Stuttgart</th>
<th>NASA LeRC</th>
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<td>46%</td>
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<td>3</td>
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NASA LeRC code in agreement with Stuttgart MPDT experiment/model
MPD Thruster Modeling

Comparison with Princeton University

Half-Scale Benchmark Thruster

![Graph showing thrust characteristics](image)

Enclosed current contours (measured)
12.4 kA, 1.5 g/s, quasi-steady operation

Enclosed current contours (predicted)
12.4 kA, 1.5 g/s, steady-state operation

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MPD Thruster Modeling

Comparison with Princeton University

Half-Scale Flared Anode Thruster

![Graph showing thrust characteristics](image)

Enclosed current contours (measured)
7.9 kA, 3 g/s, quasi-steady operation

Enclosed current contours (predicted)
7.9 kA, 3 g/s, steady-state operation
MPD Thruster Modeling

Status

- Self-field version of MPDT code operational
  - Modest execution times 3-5 hours VAX-CPU
  - General agreement with experimental results
  - Thruster performance evaluations underway
- Applied-field version of code under development
  - Routines for applied-B distributions incorporated
  - Preliminary testing/modification in progress

KEY TECHNICAL ISSUES
KEY SCALING ISSUES

- TWO PRIMARY CONCERNS
  - POWER LEVEL SCALING
  - QUASI-STEADY VS. STEADY STATE

- ISSUES MUST BE ADDRESSED USING
  - THEORETICAL MODELS TO ESTABLISH TRENDS AND DEPENDENCIES
  - HIGH FIDELITY PERFORMANCE MEASUREMENTS
  - DETAILED DIAGNOSTICS OF PLASMA AND ELECTRODE PROCESSES
    USED TO:
      A. ESTABLISH FUNDAMENTAL RELATIONSHIPS
      B. VERIFY MODELS

PERFORMANCE EXPECTATIONS:
MUST EVALUATE EFFECTS OF:
- PROPELLANT AND APPLIED FIELD
- ELECTRODE SIZE AND SHAPE
- PROPELLANT INJECTION

RELATION BETWEEN QUASI-STEADY AND STEADY-STATE:
- MUST ESTABLISH DATA BASE WITH CORRECT PROPELLANT IN THE APPROPRIATE OPERATING RANGE ($\frac{J^2}{\dot{m}}$?)
- MUST MEASURE PERFORMANCE, CURRENT DISTRIBUTIONS, PLASMA AND ELECTRODE PARAMETERS
PERFORMANCE EXPECTATIONS

- NOT CORRELATED WITH POWER
- STRONGLY INFLUENCED BY
  - PROPELLANT CHOICE
  - APPLIED OR SELF-FIELD

* Sovey, J. and Mantenieks, M. "Performance and Lifetime Assessment of Magnetoplasmadynamic Arc Thruster Technology", J. Propulsion and Power, Vol. 7, No. 1, Jan-Feb 1991

FACILITY REQUIREMENTS

THRUSt

DISCHARGE VOLTAGE

4" D, 3"L ANODE, 0.1 G'S ARGON, 1500 A DISCHARGE, Bz = 0.1 T
Similar anode heat xfer effect observed by Saber with self-field thrusters.

4" D, 3"L ANODE, 0.1 G/S ARGON, 1500 A DISCHARGE, Bz = .1 T

POTENTIAL MPDT FACILITIES

<table>
<thead>
<tr>
<th>FY</th>
<th>FACILITY</th>
<th>THRUSTER POWER, MW</th>
<th>OPERATION TIME, HR</th>
<th>ESTIMATED COST, $K</th>
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<tbody>
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<td>PRESENT</td>
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MATERIAL LIMITATIONS

ANODE:
- MEASURED HEAT FLUX AT HIGH POWER > 5 KW/CM²
  - LITHIUM HEAT PIPES LIMITED TO < 0.5 KW/CM²
  - OPTIMIZED BEAM DUMP (Cu) LIMITED TO ~ 5 KW/CM²
  - SSME THROAT HEAT FLUX ~ 16 KW/CM² (relevance?)

CATHODE:
- CURRENT DENSITIES AT HIGH POWER > 100 A/CM²
  - LONG LIFE CATHODES LIMITED TO CURRENT DENSITIES ≤ 20 A/CM² (LOW W.F. TWT CATHODES)

INSULATORS:
- KNOWN TO FAIL AFTER PROLONGED EXPOSURE TO UV AND HIGH TEMPERATURE

- WE MUST SELECT GEOMETRIES WHERE PERFORMANCE AND ENGINEERING LIMITS CAN BE EVALUATED

* PRINCETON UNIVERSITY

FACILITY LIMITATIONS:
- MUST MEASURE PERFORMANCE AT PRESSURES < 5 X 10⁻⁴ T
- FACILITY PRESSURE HAS LARGE EFFECT ON ANODE HEAT XFER, NOT CLEAR ON CATHODE

THRUSTER VIABILITY:
- SHOULD FOCUS ON DEVICES WHICH MATCH ENGINEERING LIMITS FOR:
  ANODE HEAT TRANSFER
  CATHODE CURRENT DENSITY
  INSULATOR LIMITS