Appendix I

MPD WORK AT MIT

by

M. Martinez-Sanchez
D.E. Hastings

PRESENTED AT THE MPD THRUSTER TECHNOLOGY WORKSHOP

NASA HEADQUARTERS, MAY 16, 1991

GOALS VS. ACHIEVEMENTS

<table>
<thead>
<tr>
<th></th>
<th>EFFICIENCY (%)</th>
<th>Iₚ (sec)</th>
<th>CATHODE EROSION (μg/C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOALS</td>
<td>50%</td>
<td>5000</td>
<td>10⁻⁴</td>
</tr>
<tr>
<td>SELF FIELD MPD</td>
<td>42% (H₂, Ref. 1)</td>
<td>6000 (H₂, Ref. 1)</td>
<td>2 x 10⁻² (H₂, Ref. 9)</td>
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<tr>
<td></td>
<td>30% (A, Ref. 2)</td>
<td>3000 (A, Ref. 2)</td>
<td>6 x 10⁻⁴ (N₂, Ref. 9)</td>
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<td></td>
<td>1.3 x 10⁻⁴ (A, Ref. 9)</td>
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<tr>
<td>APPLIED FIELD MPD</td>
<td>70% (Li, Ref. 3)</td>
<td>6800 (H₂, Ref. 5)</td>
<td>3 x 10⁻⁵ (H₂, Ref. 7)</td>
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<tr>
<td></td>
<td>70% (H₂, Ref. 4)</td>
<td>5800 (Li, Ref. 3)</td>
<td>2 x 10⁻⁴ (N₁, Ref. 8)</td>
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<tr>
<td></td>
<td>50% (N₁, Ref. 4)</td>
<td>2800 (A, Ref. 6)</td>
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</tbody>
</table>

1. Uematsu, K et al, 1984  
3. Connolly, D.J. et al 1968  
4. Tahara, H. et al. 1988  
5. Arakawa Y. et al, 1987  
6. Connolly et al, 1971  
8. Esker, D.W., 1969  
### Roadblocks

<table>
<thead>
<tr>
<th>Performance Feature</th>
<th>Limiting Effect</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust Efficiency</td>
<td>Frozen losses</td>
<td>Highest at &quot;onset&quot; limiting ionization/kinetic energy, (may depend on geometry)</td>
</tr>
<tr>
<td></td>
<td>Electrode drops</td>
<td>Force self-field MPD to MW power, less important with applied field</td>
</tr>
<tr>
<td>Specific Impulse</td>
<td>Various forms of &quot;onset&quot;</td>
<td>Highest with lightest gases</td>
</tr>
<tr>
<td>Life (Erosion)</td>
<td>Electrode evaporation, gas impurities, cathode microarcs, massive arcs at onset</td>
<td>Thermal design, impregnant dispenser, composition control, may be irrelevant for hot operation, ultimate limiter</td>
</tr>
</tbody>
</table>

### The MIT Program

- Supported by AFOSR Grants (1983 - present)
- Mainly theoretical work, with two exceptions:
  - Joint program with R & D Associates (Heimerdinger, Kilfoyle)
  - Joint program with Phillips Lab (Gaidos)
- Has concentrated on modeling fluid dynamics and physics of self-field thrusters:
  1-D Models: Dynamics of high magnetic Reynolds no. flows effects of area contouring, effects of kinetics, transport
  2-D Models: Anode depletion and other Hall effect consequences, friction, diffusion, heat loss, development of macroscopic instabilities
  Stability: Ionization, lower hybrid and electrothermal instabilities
  Kinetics: Upper level populations, inlet effects

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<table>
<thead>
<tr>
<th>WHO DID (DOES) WHAT</th>
<th>1-D Models</th>
<th>1 1/2-D Models</th>
<th>2-D Models (Numerical)</th>
<th>2-D Models (Analytical)</th>
<th>Stability Theory</th>
<th>Radiation, Kinetics</th>
<th>Experimental</th>
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<tbody>
<tr>
<td>D. Helmerdinger (Ph.D)</td>
<td>Contouring</td>
<td>Anode Depletion</td>
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<tr>
<td>Tae Wing Roa (MS)</td>
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<td>Ionization</td>
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<tr>
<td>D. Kifoye (MS)</td>
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<td>J.M. Chanty (Ph.D. cand.)</td>
<td>High $E_m$</td>
<td>Low Interaction</td>
<td>Asymptotics</td>
<td></td>
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<td>E.H. Niewood (Ph.D. cand.)</td>
<td>Physics</td>
<td>Hall, $t$-accurate</td>
<td>Lower Hybrid</td>
<td></td>
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<tr>
<td>Scott Miller (Ph.D. cand.)</td>
<td>Transport effects</td>
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<td>Jeff Preble (MS)</td>
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<td>Electro-thermal</td>
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<tr>
<td>Eric Sheppard (Ph.D. cand.)</td>
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<td></td>
<td>Radiation, Kinetics</td>
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<tr>
<td>Eric Caidos (Ph.D. cand.)</td>
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<tr>
<td>M. Martinez-Sanchez</td>
<td>High $E_m$</td>
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<td>Asymptotics</td>
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<td>D. Hastings</td>
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<td>Low</td>
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**QUASI ONE DIMENSIONAL MODELING**

- BY SACRIFICING GEOMETRICAL DETAIL, EXPLORATION OF A BROAD RANGE OF PHYSICAL EFFECTS IS POSSIBLE IN THE CONTEXT OF 1-D MODELS WITH AREA VARIATION

- SHOWN ARE EXAMPLES OF E. NIEWOOD'S RESULTS ILLUSTRATING

(a) DEGREE OF AGREEMENT WITH THRUST DATA FROM TWO PRINCETON U. THRUSTERS

(b) RELATIVE IMPORTANCE OF VARIOUS ELECTRON ENERGY SOURCES/SINKS ALONG THE LENGTH OF A THRUSTER

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TWO-DIMENSIONAL MODELING - TRANSPORT EFFECTS

- **Viscous Drag Important in Slender Thrusters**
- **Viscous Dissipation Contributes to High Ion Temperature**
- **Diffusion and Heat Conduction Important as Damping Effects**
  - Results below from S. Miller's work, for D. Heimerdinger's channel, neglecting Hall Effect.
  - Notice boundary layer development to near-fully developed flow.
  - Lack of symmetry is real, and arises from energy transport by transverse current.
Two-Dimensional Viscous MPD Flow

Magnetic Field

Max = 0.1 T
Min = 0.0 T
Inc = 0.004 T

Fluid Velocity

Max = 5000 m/s
Min = 0 m/s
Inc = 200 m/s

Gas Temperature

Max = 10000 K
Min = 0 K
Inc = 400 K

TWO-DIMENSIONAL MODELING - HALL EFFECT

- THE HALL EFFECT STRONGLY DISTORTS THE PLASMA FLOWS, AS SHOWN IN THE 2-D RESULTS SHOWN NEXT. CONDITIONS ARE

H = 2 CM. L = 10 CM B₀ = 0.1 T (I = 30 kA)
ARGON, m = 4 g/sec

- NOTICE STRONG AXIAL CURRENT ALONG ANODE. THIS PRODUCES LARGE DISSIPATION (SEE MAP) AND HIGH IONIZATION FRACTION. PLASMA IS KEPT ELECTROTERMALLY STABLE BY ELECTRON HEAT CONDUCTION

- VERY STEEP VOLTAGE DROP NEAR ANODE FROM LOCALLY HIGH HALL FIELD. SEE POTENTIAL CUT IN NEXT GRAPH. THIS WAS SEEN IN OUR TESTS UNDER SIMILAR CONDITIONS (SEE BELOW)
Two Dimensional MPD with Hall Effect

Current Lines

Max = 0.1 T
Min = 0.0 T
Inc = 0.002 T

Electron Temperature

Max = 34000 K
Min = 10000 K
Inc = 500 K

Ionization Fraction

Max = 1.0
Min = 0.0
Inc = 0.02

2-D MPD EQUATIONS
POT

\[ \begin{array}{c}
\text{POT} \\
\text{I-6}
\end{array} \]
Microscopic Instabilities in MPD Flows

- Microscopic plasma instabilities have been shown to be common in many plasma regimes, eg. fusion plasmas, ionospheric plasmas.
- In MPD thrusters, current represents a large source of free energy, which may drive instabilities.
- Modified Two Stream instability was chosen as a likely candidate for importance in MPD.

Modified Two Stream Instability

Significant increases in heavy species temperature due to anomalous heating

Significant increase in ionization fraction due to increased dissipation

Increase in plasma resistivity but no macroscopic plasma instability
Conclusions

- Plasma can evolve to new equilibrium in presence of Modified Two Stream Instability, with increased ionization fraction and heavy species temperature.
- Microscopic plasma instabilities could lead to large variations in operating voltage and, therefore, efficiency.
- Plasma instabilities are important in modelling MPD flows.
- Experiments, both existing and, when required, new, should be used to ascertain what types of instabilities may be excited in MPD flows.

ELECTROTHERMAL STABILITY THEORY

- UNBOUNDED PLASMA BECOMES STATICALLY UNSTABLE NEAR FULL IONIZATION. CONDUCTIVITY = $T_e^{-3/2} \alpha_0$, SO REGIONS OF HIGHER $T_e$ TEND TO CHANNEL CURRENT, FURTHER RAISING $T_e$.
- EFFECT IS MASKED AT PARTIAL IONIZATION BY ENERGY ABSORPTION IN IONIZATION PROCESS. SIMILARLY, HEAT DIFFUSION OR ELECTRON-ION PAIR DIFFUSION DAMPEN IT FOR SMALL (LESS THAN $\sim 2-4$ CM) LENGTHS.
- WE COUPLED A STANDARD STABILITY ANALYSIS WITH A 1-D MPD MODEL TO PREDICT CONDITIONS WHEN
  (a) INSTABILITY WOULD DEVELOP SOMEWHERE (USUALLY AT EXIT)
  (b) GROWTH RATE WOULD EXCEED SOME THRESHOLD
- RESULTS SHOW GOOD AGREEMENT WITH ONSET TRENDS VERSUS
  (a) LENGTH
  (b) WIDTH
  (c) MASS FLOW RATE (THIS DEVIATION FROM $1/m$ SCALING WAS UNEXPLAINED BEFORE)
FROM OUR COOPERATIVE WORK WITH R&D ASSOCIATES (HEIMERDINGER, 1988)

USING QUASI-2D CHANNEL AND 4g/sec. ARGON

PROBE AT = 2 mm FROM ANODE DETECTS LARGE ΔV, AT = 30 KA (CLOSE TO THEORY PREDICTION), BUT PLASMA REMAINS "QUIET"

AT 60 KA, LARGE, QUASI-PERIODIC VOLTAGE FLUCTUATIONS OCCUR

VERY CLEAR SEPARATION OF EFFECTS

SEPARATION OF 'ONSET' AND ANODE DEPLETION
**Exit Plane Spectroscopic Measurements**

- **DURING THE SAME TEST SERIES, D. KILFOYLE USED A 1.26 m. SPECTROSCOPE TO MEASURE LINE WIDTHS AND LINE INTENSITY RATIOS OF ARGON II AND II LINES (H₂ USED AS A DIAGNOSTIC ADDITIVE)**

- **DATA SHOW HIGH ARGON ION TEMPERATURES (HIGHER THAN Tₑ IN THE ANODE REGION), WHICH COULD IMPLY THE PRESENCE OF MICRO-INSTABILITIES**

- **DATA ALSO SHOW STRONG ANODE DEPLETION (AT I = 60 kA), IN AGREEMENT WITH ΔVₐ DATA**
ONSET AS PERFORMANCE LIMITER. PHENOMENA

AT HIGH CURRENT/LOW MASt FLOW SEVERAL PHENOMENA OCCUR (NOT ALWAYS SIMULTANEOUSLY WHICH LIMIT I, I-p RANGE.

<table>
<thead>
<tr>
<th>PHENOMENON</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) SHARP RISE IN UNSTABILITY</td>
<td>MOST COMMON DEFINITION, PLASMA INSTABILITY LOCALIZED DOWNSTREAM</td>
</tr>
<tr>
<td>(b) INCREASED WALL EROSION</td>
<td>CLOSELY ASSOCIATED TO (a) CURRENT CONCENTRATIONS</td>
</tr>
<tr>
<td>(c) DEVELOPMENT OF LARGE ANODE DROP</td>
<td>NOT ALWAYS PRESENT, ALLEVIATED BY ANODE GAS INJECTION</td>
</tr>
<tr>
<td>(d) TRANSITION V = ITO V = I^p</td>
<td>PROBABLY UNRELATED, BUT HAS BEEN ASSOCIATED WITH (ONSET)</td>
</tr>
</tbody>
</table>

APPROXIMATE EMPIRICAL CORRELATION:

\[ \frac{I^2}{m} \propto K \frac{I}{H} \]

- \( I \) = CURRENT
- \( m \) = FLOW RATE
- \( M \) = MOLEULAR MASS
- \( L \) = ACCELERATOR LENGTH
- \( H \) = INTER-ELECTRODE DISTANCE
- \( k \) = CONSTANT
<table>
<thead>
<tr>
<th>DESIGNATION</th>
<th>BASIC ASSUMPTIONS</th>
<th>PREDICTIONS</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) EQUIPARTITION, OR CRITICAL IONIZ. VELOCITY</td>
<td>'ONSET' OCCURS WHEN</td>
<td>[ \eta_{\text{frozen}} = \frac{1}{2} ]</td>
<td>PROVIDES ROUGH CORRELATION OF MOST DATA</td>
</tr>
<tr>
<td></td>
<td>[ eV_1 = \frac{1}{2} m_1 c^2 ]</td>
<td>[ \frac{1}{2} = \frac{2eV_1}{m_1} \sqrt{\frac{2eV_1}{m_1} W} ]</td>
<td>(W = CHANNEL DEPTH)</td>
</tr>
<tr>
<td></td>
<td>(H = INTERELECTRODE DISTANCE)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b) ANODE DEPLETION</td>
<td>HALL AXIAL CURRENT FORCES PLASMA AWAY FROM ANODE.</td>
<td>[ \frac{m_1^2}{m} = \frac{945 c k \left( T_e + T_i \right)}{16 \sigma \mu_a^2 \Pi^2} ]</td>
<td>APPEARENTLY SAME EFFICIENCIES AS DATA</td>
</tr>
<tr>
<td></td>
<td>'ONSET' WHEN</td>
<td></td>
<td>PRESCRIPTION</td>
</tr>
<tr>
<td></td>
<td>[ (\eta_0)_{\text{anode}} = 0 ]</td>
<td></td>
<td>IS THAT ANODE SHEATH WILL BREAK DOWN</td>
</tr>
<tr>
<td>(c) FULL IONIZATION</td>
<td>ONE OF SEVERAL ANOMALOUS EVENTS OCCURS AS IONIZATION ENERGY SINK DISAPPEARS</td>
<td>[ \eta_{\text{frozen}} = \eta_{\text{geometry}} ]</td>
<td>A VARIATION ON (a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[ \frac{V_1^2}{m} = \frac{2eV_1}{m_1} \sqrt{\frac{2eV_1}{m_1} W} ]</td>
<td>PROVIDES MORE DETAIL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[ \frac{1}{A^*} = \frac{1}{W_0} ]</td>
<td>STILL NO MECHANISM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[ \mu_a = \frac{m}{v_0} ]</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>[ \eta_{\text{th}} = \text{VELOCITY FOR MOMENTUM = MAGNETIC FORCE} ]</td>
<td></td>
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<tr>
<td>(d) INSTABILITIES</td>
<td>SEVERAL PROPOSED: IONIZATION INSTAB.</td>
<td>INSTABILITY THRESHOLD</td>
<td>ELECTRO THERMAL INSTAB.</td>
</tr>
<tr>
<td></td>
<td>MICROINSTABILITIES OF TWO-STREAM TYPE</td>
<td>(DEPENDS ON TYPE)</td>
<td>PROVIDES MECHANISM FOR (c)</td>
</tr>
<tr>
<td></td>
<td>STATIC ELECTROTHERMAL</td>
<td></td>
<td>MICRO INSTABILITIES MAY EXPLAIN HIGH T_e</td>
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<td></td>
<td></td>
<td></td>
<td>ALL VERIFIABLE BY DELAYED PROBING</td>
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</tbody>
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ORIGINAL PAGE IS OF POOR QUALITY
GEOMETRY EFFECTS ON ONSET

• Based on 1-D, variable area model with P neglected. "Onset" assumed when
  \[ V - \frac{1}{2} \ln u = m \frac{e V}{m} \]

• Two contours:
  (a) Constant area
  (b) Conv. - Div. (Spacing chosen for constant current density)

• Length measured by magnetic Reynolds no. based on Alfvén critical speed:
  \[ R_m = \frac{\mu_0 \sigma}{V_A} I \]
  \[ V_A = \sqrt{\frac{2 \pi e m}{m_i}} \]

• Two measures of "onset"
  (1) Normalized \( I^2/m \)
    \[ Y = \frac{U_{ref}}{V_A^*} \]
    \[ U_{ref} = \left[ \frac{I}{2 \pi \mu_0 A} \right] \]
  (2) Normalized exit velocity:
    \[ Z = \frac{U_e}{V_A^*} \]

- Results show significant gains in \( \eta_F \) and \( I_p \) by contouring
- But no gains of \( I^2/m \) - showing limitations of \( I^2/m \) parameter
- Gains highest at large \( R_{m_A} \)

ONSET AT FULL IONIZATION - CONSEQUENCES

• Preble's work on electrothermal instability predicts correctly several trends, including deviations from \( I^2/m \) rule.

• Electrothermal instability seen to occur at \( \alpha \approx 0.9 \) only. However, 'full ionization' is necessary for instability, not sufficient.
  (a) Growth may be weak in passage time
  (b) In small channels or at low pressures, diffusive effects provide stability

• Theory still too crude (linear, constant background, no ion dynamics...)

However, given its success, it is interesting to explore consequences of 'full ionization' model.

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ANODE DEPLETION LIMIT INCREASES ONLY WEAKLY WITH LENGTH ($R_{MA}$). HENCE, IF $R_{MA}$ IS INCREASED IN ORDER TO GAIN EFFICIENCY AND $I_E$, DEPLETION MAY HAPPEN BEFORE ONSET.

THIS WAS CLEARLY OBSERVED IN OUR OWN TESTS. ALSO SEEN BY KURIKI ET AL. (AIAA-81-0683) IN KIII THRUSTER. HERE, $\Delta V_A$ FIRST INCREASED GREATLY WITH CURRENT, THEN COLLAPSED AS ONSET FLUCTUATIONS OCCURRED.

THE GRAPH ALSO SHOWS A BAND OF PREDICTED DEPLETION NORMALIZED $I^2$/IN PARAMETER ($Y$) FOR ARGON. FOR $H_2$, THRUSTERS MAY ENCOUNTER DEPLETION FIRST.

NOTICE THAT (PARTICULARLY FOR CONSTANT AREA), DEPLETION AND FULL IONIZATION HAPPEN (IN ARGON) AT ABOUT THE SAME TIME FOR THE IMPORTANT $R_{MA}$ RANGE. THIS HAS BEEN NOTED REPEATEDLY, AND HAS BEEN A SOURCE OF CONFUSION.
SUMMARY ON SELF-FIELD MPD

- Efficient only at high power due to low voltage, large electrode losses.
- High power operation limited by "onset".
- Physics of onset not yet clear, but it appears to dictate ratio of frozen loss to kinetic energy. However, this ratio may be controlled by design.
- Anode depletion is separate limiter, especially for long channels. Should design for coincident onset and depletion (or find ways to reduce \( \Delta V_{\text{anode}} \)).
- Life issues difficult, but progress is encouraging.
- Specific impulse appears sufficient if using \( \text{H}_2 \) or \( \text{Li} \).

APPLIED FIELD MPD - THE LOGICAL GROWTH PATH

- No technology for high \( I_{sp} \), compact thrusters in the 50 - 100 kW range.
- AF - MPD poorly understood, but has shown potential to fill this role. In addition, no apparent high power limit (may become SF at high power).
THE CASE FOR AF

A-PRIORI ARGUMENTS:

(a) INCREASED IMPEDANCE DUE TO $U_B B_z$ VOLTAGE LESSEN IMPACT OF ELECTRODE $\Delta V$'s - SHOULD ALLOW FOR POWER OPERATION.

(b) PLASMA ROTATION REDUCES ELECTRODE DAMAGE BY ARCS OR OTHER FAULTS - MAY ALLOW POST-ONSET OPERATION.

(c) MAGNETIC CONFINEMENT SHOULD HELP PROTECT WALLS - REDUCE WALL LOSSES, LENGTHEN LIFE.

(d) MAGNETIC NOZZLE SHOULD ALLOW SOME FROZEN LOSS RECOVERY BY EXTERNAL EXPANSION.

THE CHALLENGES OF AF MPD

(a) ADDED OPERATIONAL COMPLEXITY. BUT SEE RECENT WORK (TAHARA ET AL., ARAKAWA ET AL.) SHOWING POTENTIAL FOR SERIES LOOPS OR PERMANENT MAGNETS.

(b) INCREASED TESTING DIFFICULTIES (LONG MAGNETIZED PLUME). BUT LOW POWER OPERATION TO COUNTER.

(c) GREAT PHYSICAL COMPLEXITY THRUST - PRODUCING MECHANISMS STILL DEBATED. SPATIAL-TEMPORAL UNIFORMITY NOT GUARANTEED. REGIMES OF OPERATION UNCHARTED.
RECOMMENDATIONS

- Reproduce and verify selected applied field MPD experiments from early literature and/or from abroad.
- Support theory/modeling work on AF thrusters to exploit existing computational capabilities.
- Continue quasi-steady SF and AF testing to study detailed plasma mechanisms responsible for "onset" and other bulk effects.
- Use 100 - 500 kW steady state facilities for
  (a) Studies of electrode life and thermal design for both, AF and SF thrusters.
  (b) Performance mapping and system integration for AF thrusters.