THE MHD-CONTROLLED TURBOJET ENGINE: AN ALTERNATE POWERPLANT FOR ACCESS TO SPACE

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OUTLINE OF PRESENTATION

- TITLE. Introduce Plasma/MHD Team
- Introduction: Access-to-Space, the NASA HYP TSTO Program (TBCC, Alternate Airbreathing engines). Why airbreathing engines? (case for external oxidizer)
- MHD Applications in Aeronautics and Space.
- Plasmas/MHD in Aeronautics: A new role for “Non-equilibrium plasma aerodynamics/MHD” (energy bypass, flow control, ignition, fuel reforming etc)
- Rationale and Potential Advantages for MHD-CT
- MHD Energy Bypass Engine
- Full governing Equations
  - The governing similarity parameters (Stuart number, Magnetic Reynolds number, etc)
  - The Annular Hall Generator: A few results (importance of Hall and ion-slip in WIG)
- Summary and Conclusions
- Challenges and Future work (Sustaining conductivity, magnets, control, etc)
- END
ADVANCED A/B ENGINES FOR SPACE ACCESS.  
(Must Provide Significant Improvements in System Performance or Significant Reductions in Launch Costs)

• Rocket Engines have traditionally been used for accessing Space.

• The Quest for use of free oxidizer

(1) AIRBREATHING ENGINES (Reusable): Using Atmospheric Oxygen as Oxidizer can potentially yield a revolutionary increase in Payload Mass Fraction compared to rockets. However, no single airbreathing technology can operate over the entire Mach number range (Mach 0 to 25) required to reach orbit. Thus ramjets, scramjets, TBCC, RBCC, Pulse Detonation Engines, etc.

(2) AIR Liquefaction Engines: LACE, KLIN (US & WORLD).

(3) PRECOOLED Engines: ATREX(Japan), SABRE (UK) (in the news recently)

(4) RBCC: GRC’s Trailblazer

(5) TBCC: NASA ARMD TSTO Configuration and Mode-Transition Experiment (GRC)

(6) Magneto-Plasma-Chemical Engine: AJAX Scramjet (Russia)

(7) MHD-Controlled Turbomachine: GRC’s Energy-Bypass engine

ENGINES FOR SPACE ACCESS: EXAMPLES

SABRE (UK)

ATREX (Japan)

AJAX (Russia)
“AJAX” KEY HYPERSONIC VEHICLE TECHNOLOGIES

• **MHD Power Generation**
  
  - power on-board systems for plasma drag reduction. Use weakly-ionized gases (WIG) ahead of aircraft for shock-wave modification, modify flow around aircraft, ....

• **MHD control of inlet** ("magnetic contraction") flow-field at off-design conditions, minimize recovery losses, etc.

• **MHD Acceleration** in nozzle

• **Increase range of Scramjet Operation**

• **In-flight Reforming of kerosene and water fuel mixture** to produce Hydrogen
PLASMA/MHD

Applications of interest to NASA
This concept includes an E-beam pre-ionizer, an MHD power generator, an MHD compressor, a combustor, and an MHD accelerator.
Applications of MHD Technology - Aeronautics and Space Research (II)

Plasma/MHD Flow Control in Inlets

Artist Concept of a Regenerative Aerobraking Capsule during Martian Entry. Collection ports are located aft of nose region to maximize MHD power generation.
NASA GRC Hypersonics Project:

Enable Airbreathing Access to Space: Focus on Turbine-Based Propulsion Systems, Also Consider Other Propulsion Systems (RBCC, PLASMA/MHD, etc).

Rocket Powered

2nd Stage: Orbital Vehicle

AIRBREATHING 1st STAGE
FUEL: LH2
**TBCC Propulsion Benefits: Efficiency, Safety, Reliability**

- **ISP** = Thrust/Pound per second of propellant (fuel) flow rate

**Airbreathing Propulsion Significantly Increases Propulsion Efficiency**

- Turbojets
- Scramjets
- Ramjets

**Isp**

- Hydrogen Fuel
- Hydrocarbon Fuels

**Gross Weight**

- First Stage
- Second Stage

**Reduced Cost & Increased Safety**

- 14%
- 10%
- 28%
- 46%
Turbine-Based Combined-Cycle (TBCC) Engine Mode Transition Challenge

- TBCC engines comprised of turbines mounted over ramjets/scramjets are promising propulsion systems for hypersonic cruise aircraft and reusable launch vehicles.
- Feasibility of mode transition between engines has not yet been fully established. (1957 Experiment at AEDC, NASA GRC Experiment currently in 10X10)
  - Aerodynamic, mechanical and thermal interactions must be understood and managed
  - Thrust margin must remain adequate with little or no operability risk
  - Airframe-engine system must be able to tolerate and control events that could cause mission failure or vehicle loss (e.g., inlet unstart, engine flameout, thermal transients, etc.)
CCE LIMX Installed in NASA 10X10 SWT
Motivation Behind Concept: Sustained Hypersonic Flight (I)

• **MHD Engine is proposed as a single-flowpath alternative to current Turboramjet Architectures.**
  The ‘Over-Under’ and ‘Wrap Around’ flow-paths are heavy, require **mode transition** during acceleration and deceleration, have high design sensitivity, and are prone to ‘unstart’. Also “deadweights” are carried along.

• **GOAL: Extend Operating Range of Turbojets to Mach 7 for Sustained Hypersonic Flight**
  Address Off-design performance of airbreathers and greatly **reduce sensitivities.** Exploit Thrust Capabilities and Reliability of Turbomachinery. **No “mode-transition” and no dead weights carried aloft!**

• **MHD Power Generation** - power on-board systems for plasma drag reduction. Use weakly-ionized gases (WIG) ahead of aircraft for shock-wave modification, modify flow around aircraft, ....

• **MHD control of inlet (“magnetic contraction”) flow-field at off-design conditions, minimize recovery losses, etc.**

• **ADDRESS MAJOR ISSUE: AIRFRAME-PROPULSION-CONTROLS INTEGRATION (PAI):** The development of an airbreathing hypersonic vehicle requires the demonstration of an **integrated design.** Integrate MHD with High Mach/High L/D Waverider Configuration for space access vehicle.

• **Address vehicle design issues that are sufficiently complex and dependent in some unknown way on scale**, such that they may not be reliably resolved even by combining test results from a number of separate facilities.
MHD ENGINE
A NEW ROLE FOR NON-EQUILIBRIUM PLASMA
AND MHD (MAGNETOHYDRODYNAMICS)
FOR A FLIGHT-WEIGHT ENGINE
SPACE LAUNCH MISSION: TWO-STAGE TO ORBIT LAUNCH VEHICLE (TSTO)

Airbreathing 1st stage (Accelerator) uses Liquid Hydrogen (LH2) fuel. (On-board cryogenics). Oxygen (O2) from atmosphere.

Horizontal take-off to Mach 7.

Cryostats, etc capable of supporting Hi-Temp Superconducting Magnets.
Objectives/Program and Project Goals

• Establish the **feasibility** and **demonstrability** of **kinetic energy bypass** from the inlet air stream of a jet engine. This energy bypass is accomplished using weak ionization of the inlet stream by an external means and MHD interaction with the ionized gas.

The engine will consist of an existing commercial or military jet engine preceded by an MHD power extractor. The jet engine may be a turbojet (e.g. Allison J-102), turbofan, or a ramjet, individually, or in various combined configurations.

The MHD power generator is a novel GRC invention (Patent issued). **The resulting engine is a revolutionary power-plant capable of flight to Mach 7.**

• Provide a physics based tool to conduct a 1-D axi-symmetric analysis of an annular MHD Hall generator/accelerator for:
  - Turbojet cycle analysis
  - Preliminary generator/accelerator design

• Predict whether **nonequilibrium** \(^*\) ionization (a key enabling technology) using **pulsed nanosecond discharges** (FIW) can be used to produce a Lorentz body force in the flow with a magnitude sufficient to:
  - Generate/deliver substantial amounts of electrical power in supersonic flow
  - Considerably reduce/increase the kinetic energy of supersonic flow without shock/expansion waves.

\(^*\)
Annular MHD Hall Generator Concept

- Geometrically compatible with a turbojet
- Current spirals down the flow path setting up an axial Hall electric field tapped for power extraction/addition
- Conductivity established by non-equilibrium ionization (not alkali metal addition)
- Geometry already used on the Russian Stationary Plasma Thruster for space propulsion
- Geometry explored for combustion-driven MHD power generation in the 1930s to 1950s (K and H generator)
- Concept offers the potential for a single flow path to Mach 7+ without mechanical mode transitions
  - Electrically maintained enthalpy
The K (Karlovitz) and H (Halasz) Hall Generator circa 1933. (Westinghouse)

Fig. 1. Scheme of the generator.

Fig. 5. Experimental generator.
GOAL: Extend the operating range of a jet engine to Mach 7+

MHD/PLASMA equations with nonequilibrium air chemistry.

Continuity of Mass
\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \]

Conservation of Momentum
\[ \rho \frac{D\vec{V}}{Dt} = -\nabla p + \nabla \cdot \vec{\tau} + \frac{1}{\mu_0} (\nabla \times \vec{B}) \times \vec{B} \]

Conservation of Energy:
\[ \rho \frac{D\vec{e}}{Dt} = -p \nabla \cdot \vec{V} - \Phi + \nabla \cdot (K \nabla T) + \frac{\eta}{\mu_0^2} (\nabla \times \vec{B})^2 + \sum_{i=1}^{11} \nabla (\rho D_{im} c_i \nabla c_i) \]

Magnetic Induction:
\[ \frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{V} \times \vec{B}) - \frac{1}{\mu_0} \nabla \times (\eta \nabla \times \vec{B}) - \nabla \left[ \frac{1}{n_e \mu_0} (\nabla \times \vec{B}) \times \vec{B} \right] \]

Conservation of species:
\[ \frac{Dc_i}{Dt} = \frac{\dot{w}_i}{\rho} + \nabla \cdot (\rho D_{im} \nabla c_i) \]

Conservation of Vibrational Energy:
\[ \frac{D_{\text{vib}}}{Dt} = \sum_{\text{molecules}} \frac{1}{T_i} (e_{\text{vib},i}^{\text{eq}} - e_{\text{vib},i}) + \nabla \cdot (\rho D_{im} e_{\text{vib}} \nabla c_i) + G \frac{d(c_i \rho)}{dt} \]

Equation of State:
\[ P = \sum c_i \rho^\gamma T / M_i \]

(Maxwell’s Equations, Navier-Stokes Equations, and Nonequilibrium Chemical Kinetics)
A weakly-ionized gas (WIG) implies that Hall effect and ion-slip terms will contribute to the current: 

**OHM's LAW for WIG**

\[ \mathbf{j} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - \frac{\Omega_e}{B} (\mathbf{j} \times \mathbf{B} - \nabla p_e) + (1 - \alpha)^2 \frac{\Omega_e \Omega_+}{B^2} [ (\mathbf{j} \times \mathbf{B}) \times \mathbf{B} ] \]

- **Hall Effect**

\[ \frac{\partial \mathbf{B}}{\partial t}_{\text{hall}} = -\nabla \times \frac{\beta}{\mu_0} [ (\nabla \times \mathbf{B}) \times \mathbf{B} ] \]

\[ \mathbf{B}^{n+1,k+1}_{i,j} = \mathbf{B}^{n+1,k}_{i,j} - \alpha \cdot \mathbf{P} \cdot \mathbf{F}_{i,j} \left( \mathbf{B}^{n+1,k}, \mathbf{B}^{n,k} \right) \]

\[ \mathbf{F}(\mathbf{B}^{n+1,k}, \mathbf{B}^{n,k}) = \mathbf{B}^{n+1} - \mathbf{B}^{n} + \Delta t \nabla \times \left[ \frac{1}{\mu_0 n_e e} (\nabla \times \mathbf{B}^* ) \times \mathbf{B}^* \right] \]

\[ \mathbf{B}^* = 0.5 \cdot (\mathbf{B}^{n+1} + \mathbf{B}^{n}) \]

- The Ion Slip term is solved with an iterative, implicit method.

\[ \frac{\partial \mathbf{B}}{\partial t}_{\text{ionslip}} = \nabla \times \left[ \frac{(1 - \alpha)^2}{n_e m_+ v_{o+}} \left\{ \frac{\nabla \times \mathbf{B}}{\mu_0} \times \mathbf{B} \right\} \times \mathbf{B} \right] \]

- incorporates Ohm's law through the magnetic induction equation.

\[ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\nabla \times \mathbf{B}) - \frac{1}{\mu_0} \nabla \times (\eta \nabla \times \mathbf{B}) \]

- The Hall Effect term is solved with an iterative, semi-implicit method based on a Crank-Nicolson discretization.

- The Ion Slip term is solved with an iterative, implicit method.
COMPUTER SIMULATION: AVAILABLE CODES USED

• **(1) MACH2 Code Simulation: For Weakly-Ionized Gas. (2.5-D)**
  - Resistive-Hall-MHD with Braginskii Transport, Multi-ported Circuit Solver (e.g. LRC, PFN), Various Models For Anomalous Resistivity and Electron-Neutral Contributions
  - Analytic or Real Semi-empirical (SESAME) Equations of State, LTE Ionization State

• **(2) OSU NON-EQUILIBRIUM FLOW CODE (1-D)**
  - Master equation for vibrational populations of N₂ and O₂. Boltzmann equation for electrons.
  - Nonequilibrium air chemistry including ion-molecule reactions
  - Nonequilibrium electron kinetics (ionization, recombination, and attachment)
  - 1 – D Gas dynamics. Generalized Ohm’s law
  - Validated by comparing with electric discharge, shock tube, and MHD experiments

• **(3) IN-HOUSE ENGINEERING CODE: 1 - D Axisymmetric** (equations with large radius approximation/small gap gives a meanline generator/accelerator design.)
  - “MHD approximation “to fundamental equations of plasma dynamics (Low Magnetic Reynolds Number, Maxwell’s Equations unaffected by gasdynamic motion, magnetic field induced by fluid motion negligible compared to applied Magnetic Field).
  - Approach from DOE MHD generator program: Assumes steady state “Plasma Dynamics” using the conservation laws and conductivity. No detailed plasma kinetics!
Preliminary Results

MHD Bypass Engine Application – OSU Evaluation

- OSU quasi-1D, nonequilibrium MHD air flow code used
- Ionization by uniformly distributed e-beam (need simulation with pulsed ionizer)
- Realistic E-beam power 0.11 MW (20 keV electron beam, 0.2 mA/cm²)
- 10 Tesla magnetic field

- Substantial reduction in the kinetic energy of supersonic flow is possible
- 50% Conversion of kinetic energy to electrical power predicted
3-D MHD Equations in Low Reₘ Approximation

- Analytical approach (from DOE MHD generator program): Assumes steady state “Plasma Dynamics” using the conservation laws and conductivity
  - induced magnetic field << applied magnetic field (Small Magnetic Reynolds Number)

Momentum: \[ \rho (v \cdot \nabla) v = j \times B - \nabla p \]

Mass: \[ \nabla \cdot (\rho v) = 0 \]

Energy: \[ \rho v \cdot \nabla \left( \frac{|v|^2}{2} + U \right) = -\nabla \cdot (vp) + j \cdot E \]

Current: \[ \nabla \cdot j = 0 \]

Ohm’s Law: \[ j = \sigma (E + v \times B) - \frac{\omega \tau}{|B|} j \times B \]

Axisymmetric 1-D MHD Assumptions

- Azimuthal symmetry
- Large radius approximation, with functions of $z$ only: $p(z)$, $v_\theta(z)$, $v_z(z)$, $j_\theta(z)$, $j_z(z)$, $T(z)$, $\rho(z)$, $E_z(z)$
- Constant terms: $B_r$, $\sigma$
- Zero terms: $B_\theta$, $B_z$, $v_r$, $j_r$, $E_\theta$, $E_r$
- Ideal, calorically perfect gas
- **Pure Hall device**: Applied tangential $E_\theta$ is zero by short circuit around the annulus.
**Engineering Model: Axisymmetric 1-D MHD Equations**

**Axial Momentum:**
\[ \rho v_z \frac{dv_z}{dz} = -j_\theta B_r - \frac{dp}{dz} \]

**Angular Momentum:**
\[ \rho v_z \frac{dv_\theta}{dz} = j_z B_r \]

**Continuity:**
\[ \rho v_z A = \dot{m} \]

**Energy:**
\[ \rho v_z \frac{d}{dz} \left( \frac{v_\theta^2 + v_z^2}{2} + h \right) = j_z E_z \]

**Current:**
\[ j_z A = I \]

**Axial Ohm’s Law:**
\[ j_z = \frac{\sigma B_r}{1 + (\omega \tau)^2} \left[ \frac{E_z}{B_r} - v_\theta + \frac{\omega \tau B_r}{|B|} v_z \right] \]

**Azimuthal Ohm’s Law:**
\[ j_\theta = \frac{\sigma B_r}{1 + (\omega \tau)^2} \left[ v_z - \omega \tau \frac{E_z}{|B|} + \frac{\omega \tau B_r}{|B|} v_\theta \right] \]
Basic scaling parameters (I)

Reynolds Number

\[
\text{Re} = \frac{\text{Inertia Forces}}{\text{Viscous Forces}} = \frac{U_0 L}{\nu}
\]

Magnetic Reynolds Number

\[
\text{Re}_m = \frac{\text{Convection of } \vec{B}}{\text{Diffusion of } \vec{B}} = \frac{\text{Induced Field}}{\text{Applied Field}} = \frac{U_0 L}{\nu_m} = \mu_0 \sigma U_0 L
\]

\[
\text{Re}_m \ll 1
\]
Induced magnetic field is small compared to applied field, \( B = B_{\text{Applied}} \)

AND

Electric field can be expressed as
\[
\text{Gradient of a potential, } E = -\text{grad}\Phi
\]

Stuart Number (Magnetic Interaction parameter)

\[
N \equiv St = \frac{\text{Electromagnetic Forces}}{\text{Inertia Forces}} = \frac{\sigma B_0^2 L}{\rho U_0} = \frac{\sigma U_0 B_0^2}{\rho U_0^2 / L}
\]
1-D Annular MHD Solution Procedure

• Given inlet plasma dynamic conditions
• Equations numerically integrated wrt \( \ell /z \) with inputs – \( B_r, \sigma, L \)
• Two temperature plasma model of \textit{nonequilibrium} ionization
  - \( T_s \) – bulk gas static temperature
  - \( T_e \) – constant electron temperature (1 ev, 11605\(^\circ\)K)

• Hall parameter

\[
\omega \tau = \frac{e|B|}{m_e n Q c_e}
\]

- Electron cyclotron frequency
- \( \tau \) mean free time between collisions

• Hall loading parameter

\[
K_h = \frac{\alpha E_z}{\omega \tau v_z B_r}
\]

• Geometry specification

\[
\frac{d(\rho v_z)}{dz} = \text{constant}
\]
Annular MHD Hall Generator Design

Inlet conditions:

M = 5.02
Ps = 32.7 Torr
Ts = 420°K

Generator parameters:

Br = 5 Tesla
σ = 5 mho/m
L = 3 m
Kh = -0.09
d(ρvz)/dz = -21 kg/m³-s
ηNg = 0.63
ηs = 0.84
V = 55.8 kV
I = 28.7 Amp/kg/s
Pe = 1.60 MW/kg/s
MHD Energy Bypass Demonstration in Turbojet-Based Engines: Preliminary findings – Simulation using Allison J-102 Engine

- Mach 0.9 – 2.0: Aerodynamic Drag Control with WIG
- Mach 2.0 – 3.0: Power Generation and Bypass in Question
- Mach 3.0 – 7.0: Power Generation and Bypass Feasible

**NOTE:** In the Mach 2.0 – 3.0 regime, a SIMULTANEOUS MASS BYPASS may be desirable / advantageous.
Activities in Plasma Laboratory (VF69)

Understand the physics of the cold, non-equilibrium plasma generation in air and provide data for a multi-temperature model development to be used for evaluating its effectiveness in hypersonic flow control, heat transfer reduction, power generation, and noise suppression.

"PULSER-SUSTAINER" TECHNIQUE CHOSEN FOR PLASMA GENERATION.

- Sub-atmospheric conditions set by Mach 7 flight at 30 km
- Bell jar with mechanical pump and dry air source assembled for 10 to 80 Torr

High Voltage Pulsed Power Supplies (FIW):
- High voltage pulser power supply with 10 to 100 kV amplitude, 2 ns rise, 2 to 5 ns width, 3 ns fall, and 6 to 100 kHz repetition rate.
- 2nd pulser power supply: 10 to 40 kV amplitude, 2 ns rise, 20 ns width, 3 ns fall, and 6 to 100 kHz repetition rate.
- Sustainer floating power supply with 2 kV and 3 A
Non-equilibrium Ionization Assessment

• Pulser-sustainer discharge\(^1\) ionization process using nanosecond pulses is proposed as the means for the non-thermal ionization
  – Energizes and sustains electrons at a high \(T_e\) while maintaining a low nearly constant ion/neutral temperature \(T_s\)
  – \(\sigma=1.0 - 5.0\) mho/m requires an \(n_e/n=1.90\times10^{-6}-9.52\times10^{-6}\) for \(T_e=1\text{ev}\)^\(^1\)
  – Initial belljar tests\(^2\) indicate an ionization fraction \(1.1\times10^{-8}\) at 50 Torr

• Annular Hall type MHD Generator/Accelerator operation
  – Azimuthal current could act like a sustainer current to keep \(T_e\) elevated
  – Non-thermal ionization facilitates MHD interaction with the core flow since the boundary layers won’t have a higher conductivity


PLANNED PLASMA/MHD EXPERIMENT
MHD/Turbojet Engine Concept: Planned Future Experiment in NASA 10X10 Wind-Tunnel using Allison J-102

Mach 7 Inlet  MHD Generator (Axisymmetric Hall Type)  Variable geometry Mach 3 Inter-stage region  Turbojet Engine Allison J-102 Class

FIW Plasma guns  Superconducting Magnet  Bypass doors

MHD Power Extraction Patent

FIG.-1

Annular Hall –Type MHD Generator: Based on Hall thruster Design for Space and Fast Ionization Wave non-equilibrium plasma generation. US Patent (6,696,774 B1; 2004)
Experimental Method for Conducting Engine Test

(1X1 for small-scale engine, HTF for large-scale. Turbomachine may sit outside tunnel stream.)

Figure 3. Demonstration Test Scheme.
MHD–CONTROLLED TURBOJET: Summary: Initial Analysis and Findings

This Mach 7+ (projected) is based on the combination of two proven technologies (each over 50 years old):

1. Deceleration of an artificially-ionized supersonic/hypersonic stream by applied magnetic fields (MHD) and,
2. Turbomachinery.

- MHD Engine Bypass Concept has 2 Major Advantages:
  1. Turbomachinery operates continuously over entire Mach range from 0 – 7. No mode transition.
  2. No deadweight engines carried aloft.
  3. Hydrocarbon Fuel reforming technology using plasmas is available so conversion to Hydrogen in-situ may be exploited.

- CRITICAL ENABLING TECHNOLOGIES in: Ionizers (electron beam, microwave, high-voltage pulsed power, etc devices) for sustained conductivity along Hall Generator,
  - design of the “Interstage region” between Generator Exit and Turboengine. -- Approaches to reduce total pressure loss via ejectors must be explored

  - Lightweight magnets of nanotube construction, or superconducting magnets. Issues lie in magnet weight if hydrocarbon fuels are used. Superconducting magnets if liquid hydrogen is the fuel.
EPILOGUE: Why pursue this science?

- A dedicated NASA effort in plasma and magneto-aerodynamics will:
  
  (1) Sustain the science in the face of increasing world-wide activity
  
  (2) Developing efforts for light-weight magnets
  
  (3) High pressure ion-beam technologies
  
  (4) Lay ground work for plasma/MHD-integrated flight vehicle design: projected improvements in performance can truly enhance the feasibility of hypersonic flight and space access.
  
  (5) Hypersonic MHD is a truly multidisciplinary subject: The ability to model it in a realistic manner will be a triumph for applied math methods in fluids, electromagnetics (gaseous and solid), and in the non-equilibrium kinetic modeling of plasmas.

- MHD body force offers an inherently variable geometry and means of shockless interaction with high speed inlet flows. “Shockless” supersonic flow is possible!
THANKS to my PLASMA/MHD Colleagues

- Dr. Steve Schneider (NASA GRC)

- Dr. Theresa Benyo (GRC) (PhD June, 2013, Kent State University). Thesis title is “Computational Investigation of MHD Energy-Bypass System for Supersonic Gas Turbine Engines”.

- Dr. Eric Gillman (PhD 2012, University of Michigan) Thesis title is “Cathode Spot Injection of Dielectric Particles with Applications to Radio Communications Blackout Plasma Depletion”, NASA GSRP. Currently at Naval Research Laboratory

- Mr. Benjamin Yee (PhD, University of Michigan) (September, 2013) Thesis title is “The Energetics of a Pulsed-Nanosecond Discharge with Application to Plasma-Aided Combustion.” NASA GSRP Currently at SANDIA.

- Dr. John Foster (Professor, University of Michigan, Ann Arbor)

- Plasmas/MHD for Flow Control of and Energy Extraction from Weakly and Fully Ionized Hypersonic flows: (Understand the physics of the plasma mechanism for practical aerospace applications. The critical science issue is the nature of the coupling that can arise between a weakly-ionized gas and a gas dynamic flow-field, and its possible control for favorable effects).

- MHD-Energy Bypass Engine Concept.

- Sonic Boom Reduction by Plasma

- Injection of Repetitive High-Voltage Nanosecond Plasma in dielectric liquids (water, hydrocarbon fuels, etc).

- Reentry plasmas and antenna breakdown: Mitigation of Reentry Communications Blackout using “Magnetic Windows”. Communications and GPS issues.