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

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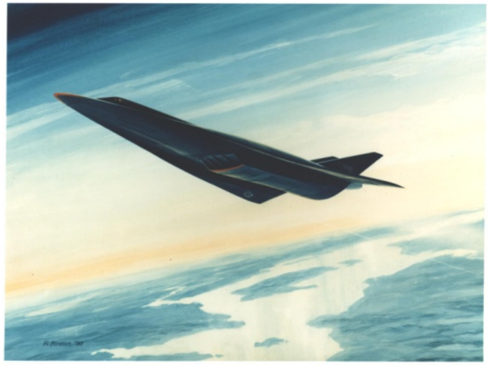
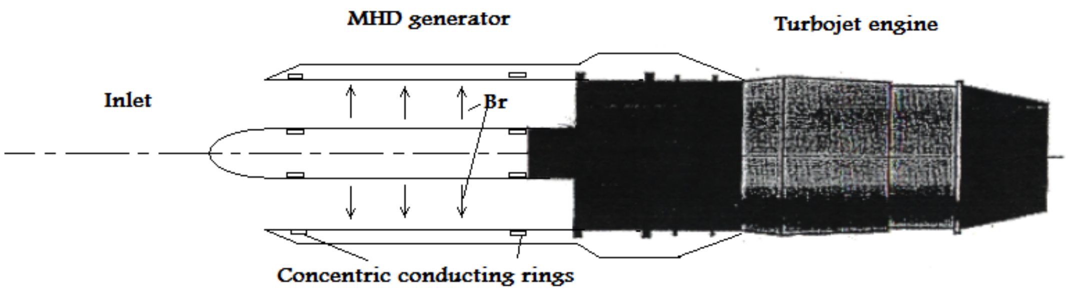


DOE/NETL MHD Workshop
October 2014



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)

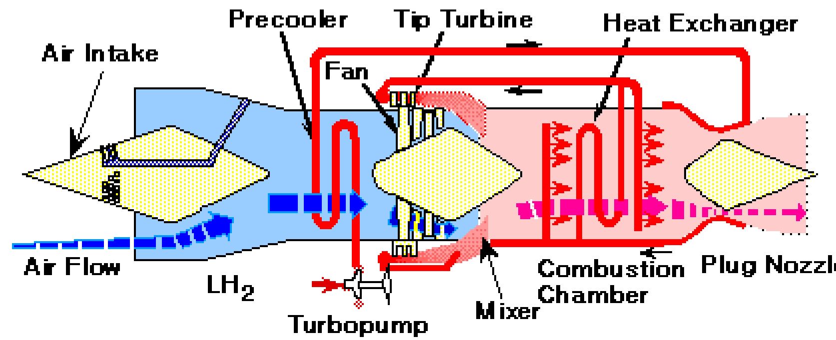
(7) MHD-Controlled Turbomachine: GRC's Energy-Bypass engine

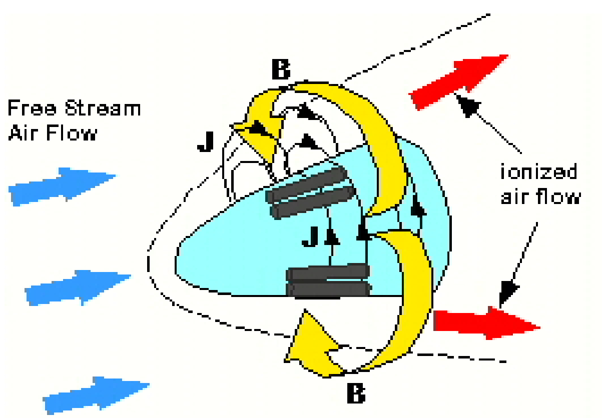
Further Reading: "Emerging Air-Breathing Propulsion Technologies" - a Book Chapter in Wylie Encyclopedia of Aerospace Engineering, pp1051-1062), October, 2010. (D. R. Reddy and I. Blankson /NASA Glenn Research Center).

ENGINES FOR SPACE ACCESS: EXAMPLES

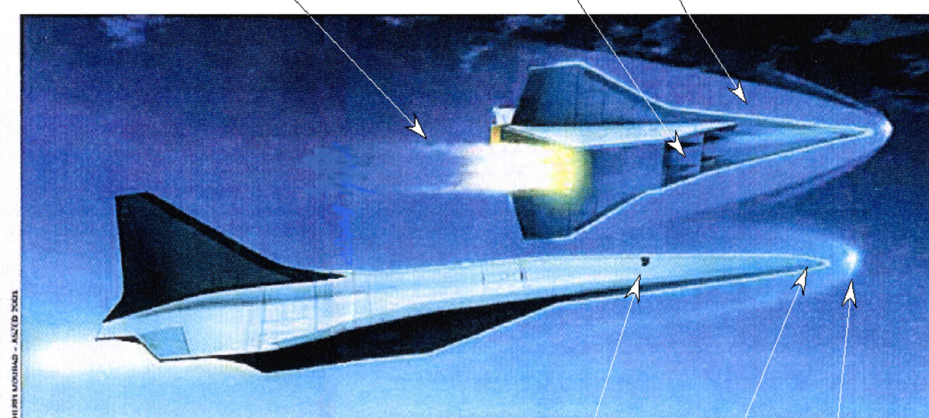
SABRE (UK)

ATREX (Japan)





Schematic of the Multipole Magnetic
System Intalled on a Hypersonic Aircraft
Figure 11, IAF-97-V.5.10



Alexandre Szames, Air & Cosmos Dec 2001

AJAX (Russia)

“AJAX” KEY HYPERSONIC VEHICLE TECHNOLOGIES

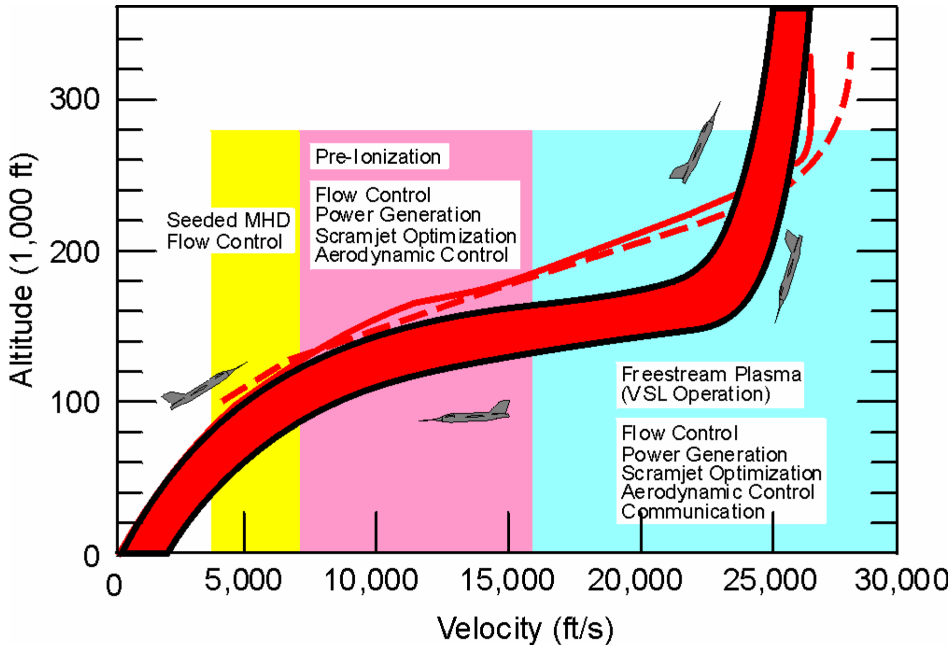
- MHD Power Generation - power on-board systems for plasma drag reduction. Use weakly-ionized gases (WIG) ahead of aircraft for shock-wave modification, modify flow around aircraft, ….
- MHD control of inlet (“magnetic contraction”) flow-field at off-design conditions, minimize recovery losses, etc.
- MHD Acceleration in nozzle
- Increase range of Scramjet Operation
- In-flight Reforming of kerosene and water fuel mixture to produce Hydrogen

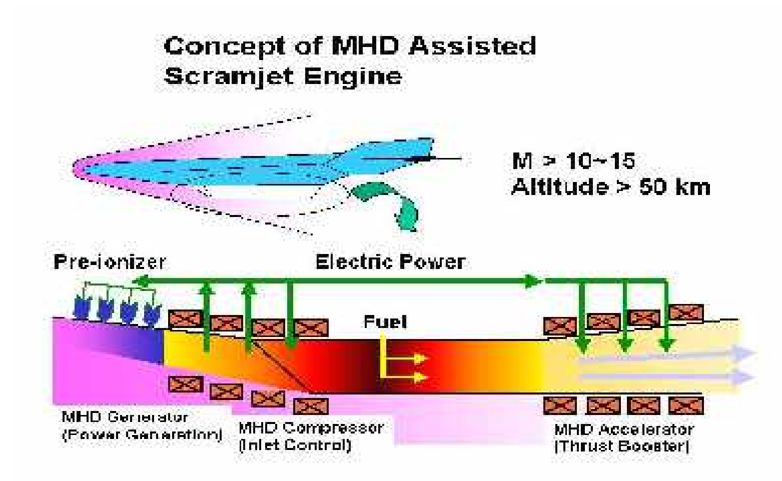
PLASMA/MHD

Applications of interest to NASA

Applications of MHD Technology- Aeronautics and Space Research (I)

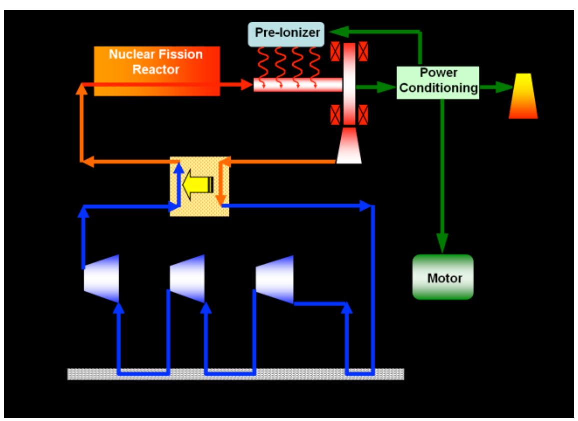
MHD Application Map



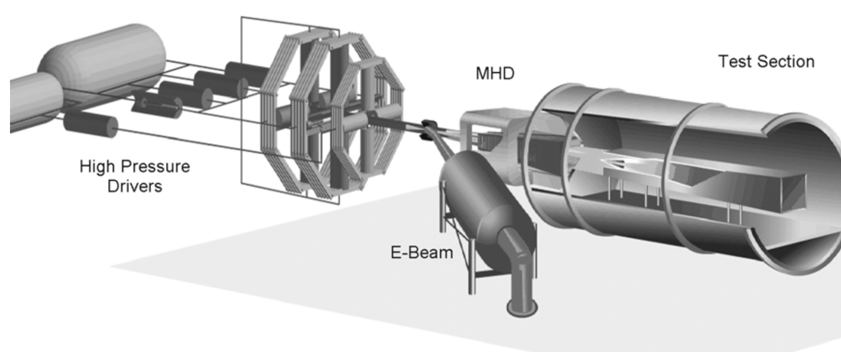


CONCEPT OF AN MHD ASSISTED SCRAMJET ENGINE

This concept includes an E-beam pre-ionizer, an MHD power generator, an MHD compressor, a combustor, and an MHD accelerator



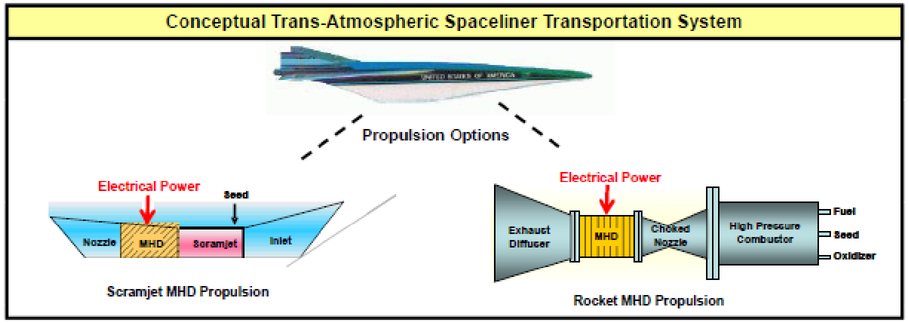
MHD /Nuclear Space Power for Space Vehicle



MARIAH: Hypersonic Wind-tunnel – MHD Acceleration

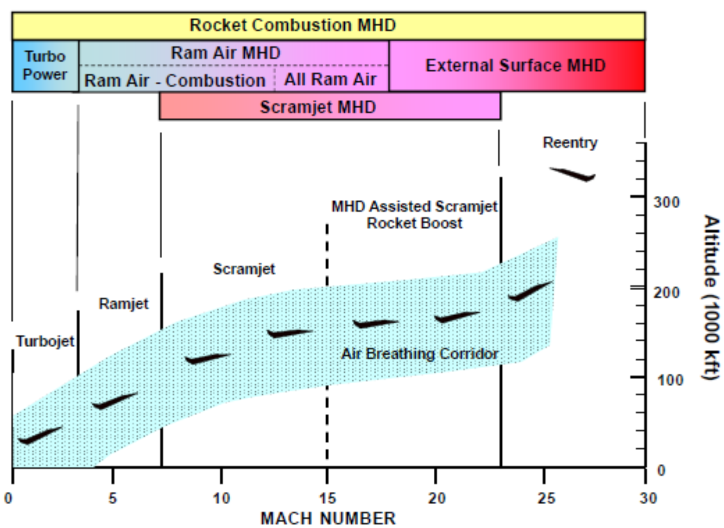
Conceptual MHD Propulsion Systems

- Magnetohydrodynamic Augmented Propulsion
  - Electrical Augmentation of Thermal Propulsion Systems
    - MHD cross-field accelerator (electromagnetic effects >> electrothermal effects)
    - Increased P_{jet} – conceivably enough for ETO application
    - Isp > 1000 sec – conceivably 2000–3000 sec
    - Hybrid chemical/electric architecture provides redundancy & *"assured propulsive capability"*
    - Applicable to airbreathing , rocket ,or combined-cycle propulsion modes



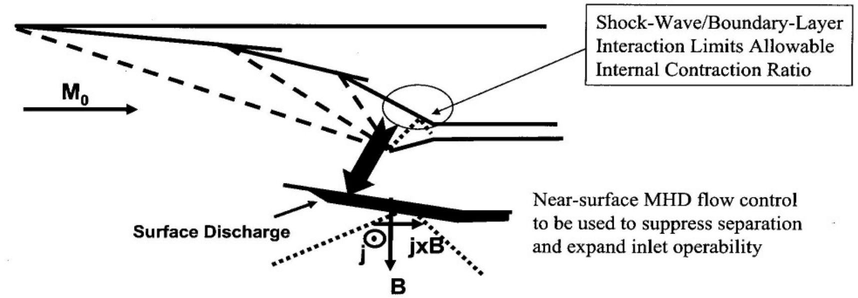
The Big Question: What is the source of electrical power? On-board or off-board?

MHD Flight Regimes



Applications of MHD Technology- Aeronautics and Space Research (II)

Plasma/MHD Flow Control in Inlets



Advantages of Technique	Disadvantage of Technique
Limited ionization region	Power input required
Small volume required with high B-field	Mass penalty due to magnet
Near wall velocities low, $St = \sigma B^2 L/\rho U$	
Phenomenon is controllable	

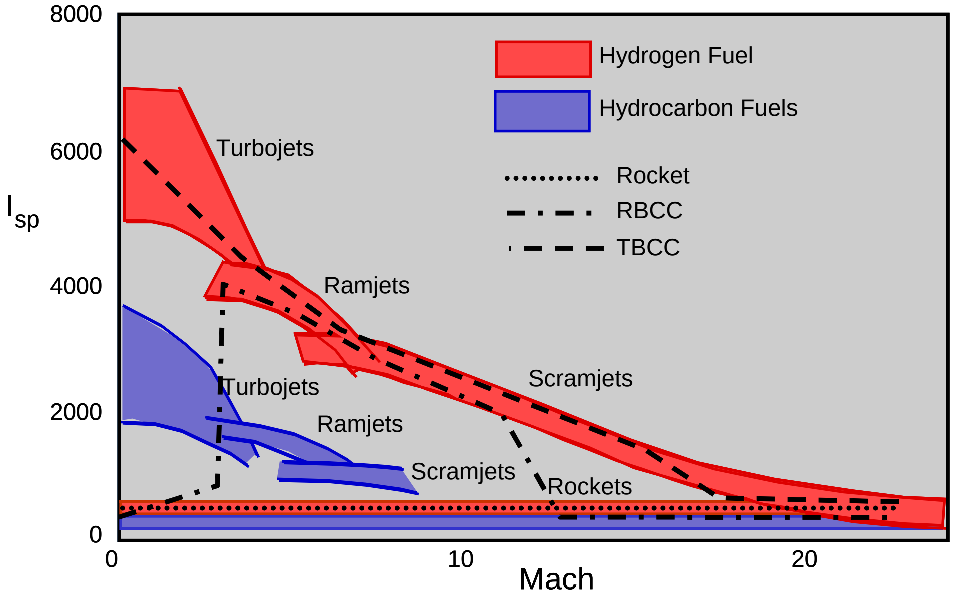
Artist Concept of a Regenerative Aerobraking Capsule during Martian Entry. Collection ports are located aft of nose region to maximize MHD power generation.

National Aeronautics and Space Administration

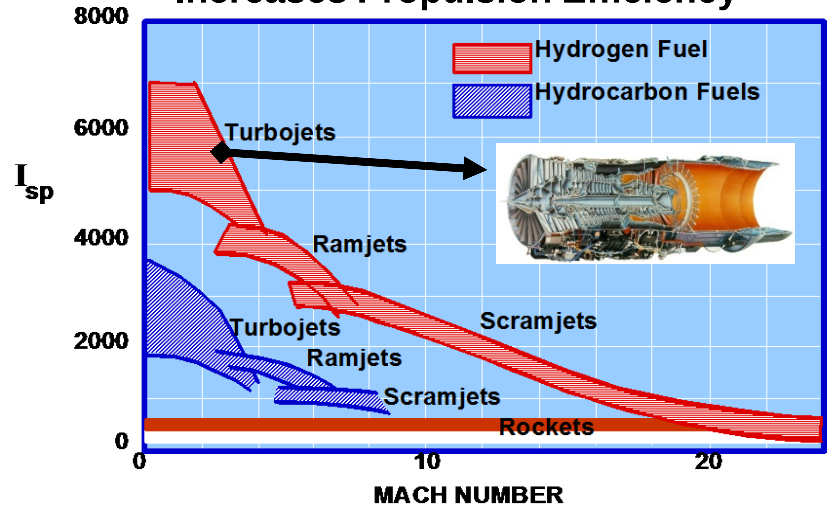
NASA GRC Hypersonics Project:

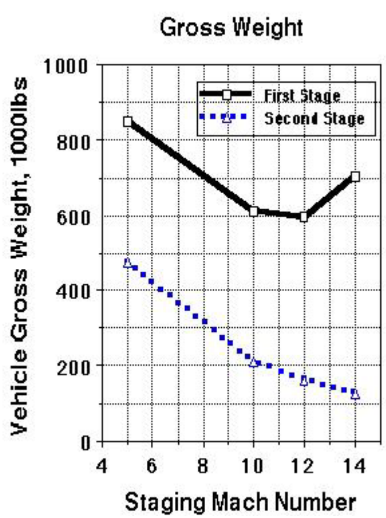
Enable Airbreathing Access to Space: Focus on Turbine- Based Propulsion Systems, Also Consider Other Propulsion Systems (RBCC, PLASMA/MHD, etc)

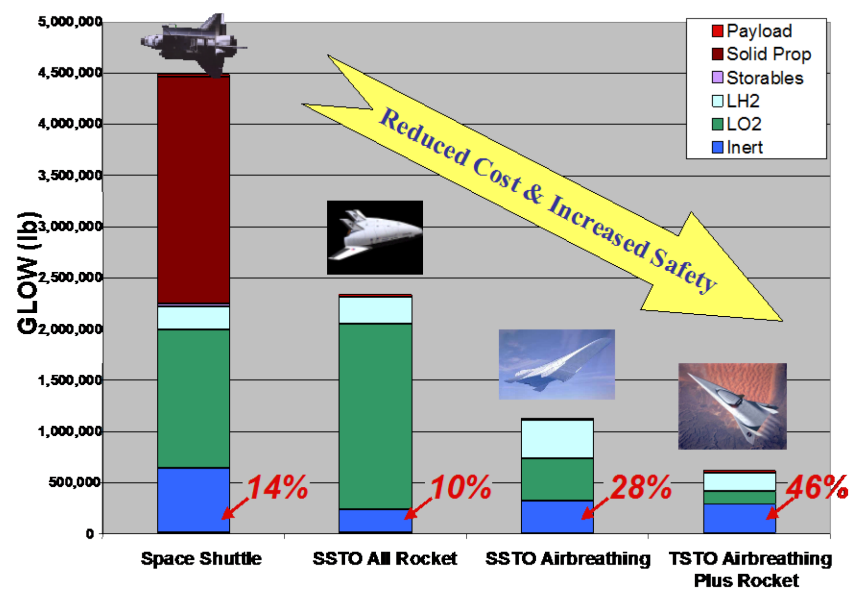
TBCC Propulsion Benefits : Efficiency, Safety, Reliability



Airbreathing Propulsion Significantly Increases Propulsion Efficiency





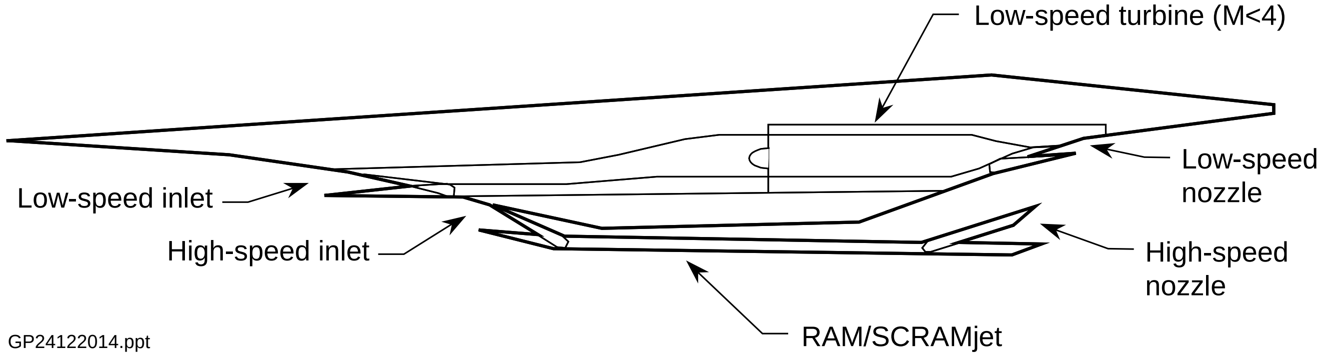


I_{SP} = Thrust/Pound per second of propellant (fuel) flow rate

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.)



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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 g**ases (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)

ROCKET-POWERED 2^{ND} STAGE: ORBITAL VEHICLE

MHD AIRBREATHING 1^{ST} STAGE

Airbreathing 1^{st} 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 consists 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.

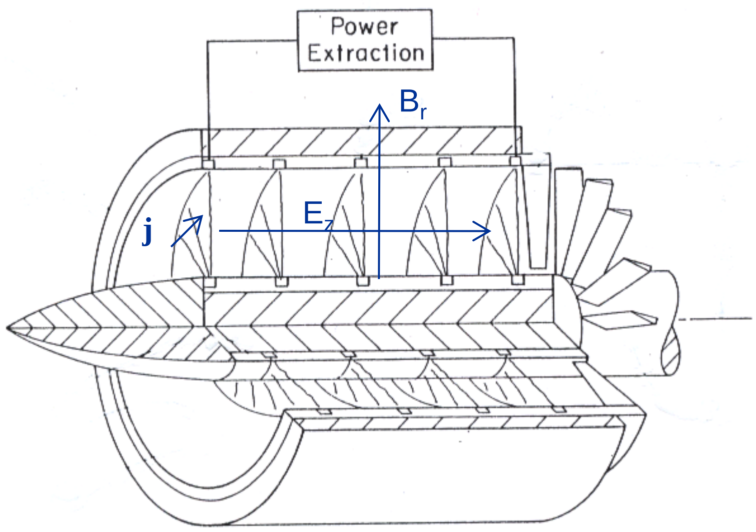
  The MHD power generator is a novel GRC invention (Patent issued). **The resulting engine is a revolutionary power-plant capable of flight to Mach 7.**

- 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 to1950s (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)

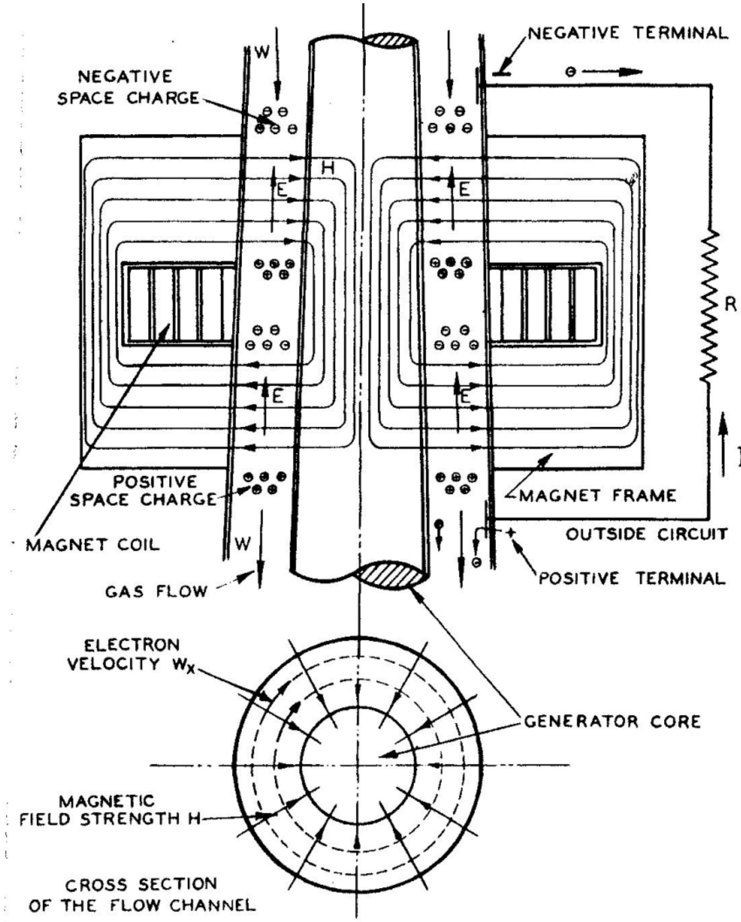


Fig. 1. Scheme of the generator.

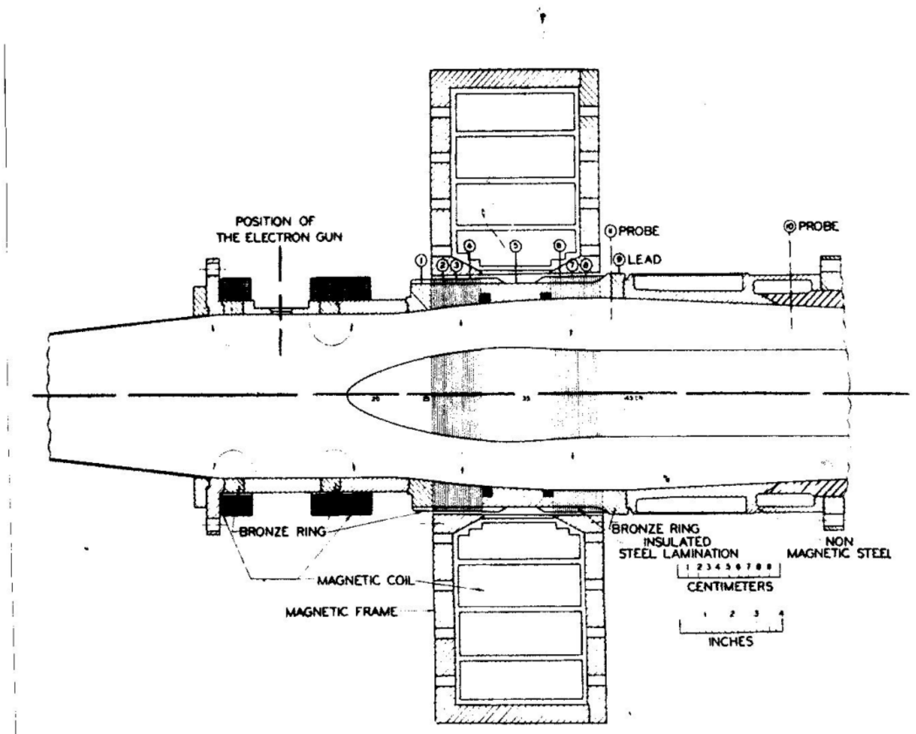
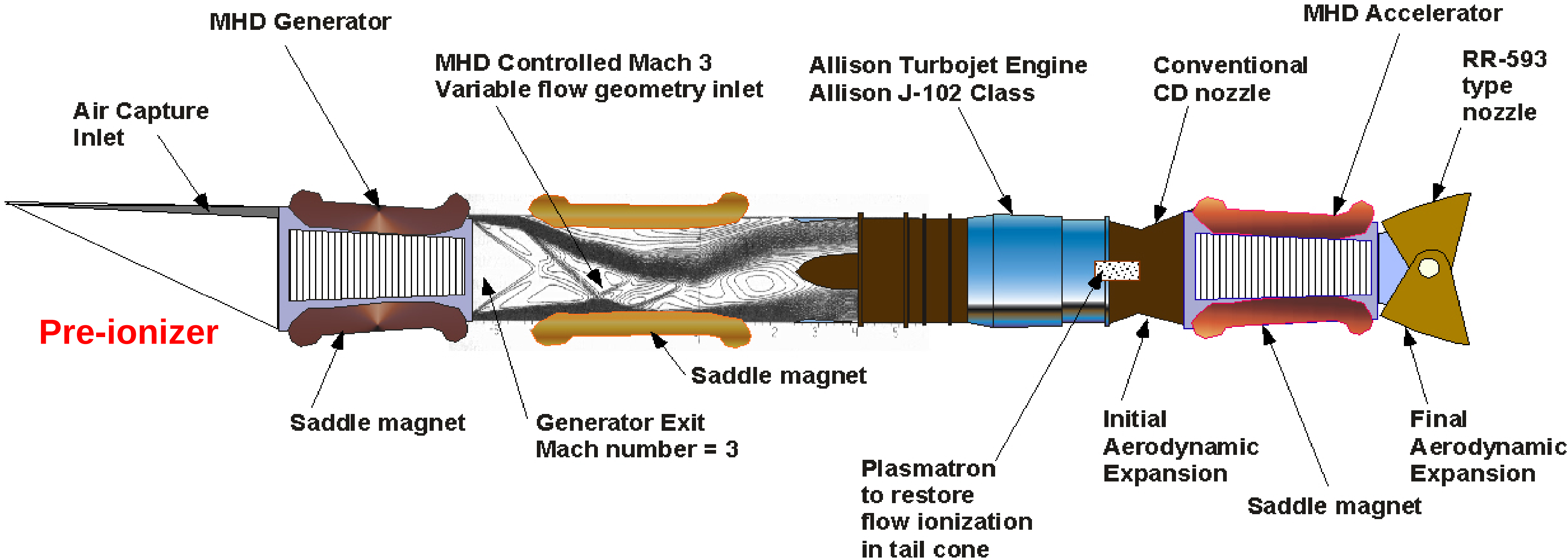


Fig. 5. Experimental generator.

General Arrangement of MHD-Controlled turbojet High-Speed Propulsion (NASA GRC)



GOAL: Extend the operating range of a jet engine to Mach 7+

FURTHER INFO IN: IAF-00-5-5-05. AIAA PAPERS 2003-6922, 2003-4289, 2009-1051. 2011-2230, NASA/TM – 2003-212612. US Patent (6,696,774 B1, 2004),

MHD/PLASMA equations with nonequilibrium air chemistry.

Continuity of Mass

$$\frac{\partial \rho}{\partial t} + \overline{\nabla} \cdot \left(\rho \overline{V} \right) = 0$$

Conservation of Momentum

$$\rho \frac{D\overline{V}}{Dt} = -\overline{\nabla} p + \overline{\nabla} \cdot \vec{\tau} + \frac{1}{\mu_0} \left(\overline{\nabla} \times \overline{B} \right) \times \overline{B}$$

Conservation of Energy:

$$\rho \frac{D\overline{e}}{Dt} = -p \overline{\nabla} \cdot \overline{V} - \Phi + \overline{\nabla} \cdot \left(K \overline{\nabla} T \right) + \frac{\eta}{\mu_o^2} \left(\overline{\nabla} \times \overline{B} \right)^2 + \sum_{i=1}^{11} \overline{\nabla} \left(\rho D_{im} e_i \overline{\nabla} c_i \right)$$

Magnetic Induction:

$$\frac{\partial \overline{B}}{\partial t} = \overline{\nabla} \times \left(\overline{V} \times \overline{B} \right) - \frac{1}{\mu_0} \overline{\nabla} \times \left(\eta \overline{\nabla} \times \overline{B} \right) - \overline{\nabla} \times \left[\frac{1}{n_e e \mu_0} \left(\overline{\nabla} \times \overline{B} \right) \times \overline{B} \right]$$

Conservation of species:

$$\frac{Dc_i}{Dt} = \frac{\dot{w}_i}{\rho} + \frac{\nabla \cdot \left(\rho D_{im} \nabla c_i \right)}{\rho}$$

Conservation of Vibrational Energy:

$$\frac{De_{vib}}{Dt} = \sum_{molecules} \frac{1}{\tau_i} \left(e_{vib,i}^{eq} - e_{vib,i} \right) + \frac{\nabla \cdot \left(\rho D_{im} e_{vib} \nabla c_i \right)}{\rho} + G \frac{d\left(c_i \rho \right)}{dt}$$

Equation of State:

$$P = \sum c_i \rho \Re T / M_i$$

(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

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

Hall Effect

Ion slip

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

$$\frac{\partial \overline{B}}{\partial t} = \overline{\nabla} \times \left(\overline{V} \times \overline{B}\right) - \frac{1}{\mu_0} \overline{\nabla} \times \left(\eta \overline{\nabla} \times \overline{B}\right)$$

- 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.

$$\left.\frac{\partial \overline{B}}{\partial t}\right|_{hall} = -\overline{\nabla} \times \frac{\beta}{\mu_0}\left[\left(\overline{\nabla} \times \overline{B}\right) \times \overline{B}\right]$$

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

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

$$\overline{B}^{*} = 0.5 \cdot \left(\overline{B}^{n+1} + \overline{B}^{n}\right)$$

$$\left.\frac{\partial \vec{B}}{\partial t}\right|_{ionslip} = \vec{\nabla} \times \left[\frac{(1-\alpha)^2}{n_e m_+ \nu_{o+}}\left\{\left(\frac{\overline{\nabla} \times \vec{B}}{\mu_o} \times \vec{B}\right) \times \vec{B}\right\}\right]$$

COMPUTER SIMULATION: AVAILABLE CODES USED

- **(1) MACH2 Code Simulation: For Weakly-Ionized Gas. (2.5-D)**
- Time-dependent, 2- D axisymmetric simulation tool for complex planar or cylindrical geometries. Quasi-neutral, Viscous Compressible Fluid with Elastic-plastic Package, Ablation Models and Multi-Material Capability. **Park non-equilibrium model.**
- Multi-temperature: Electron, Ion, Radiation . Various Radiation Models With Real Semi-empirical Opacities.
- 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 N_2 and O_2. 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

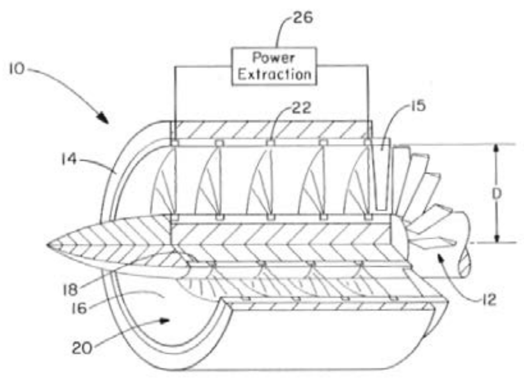
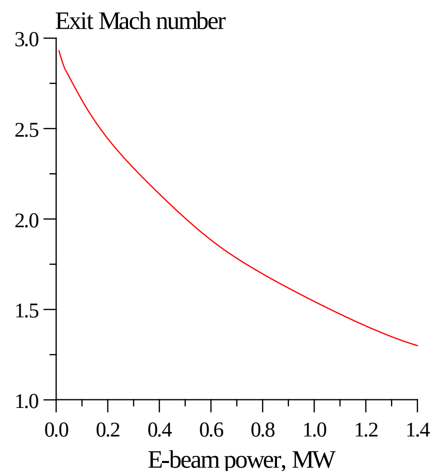
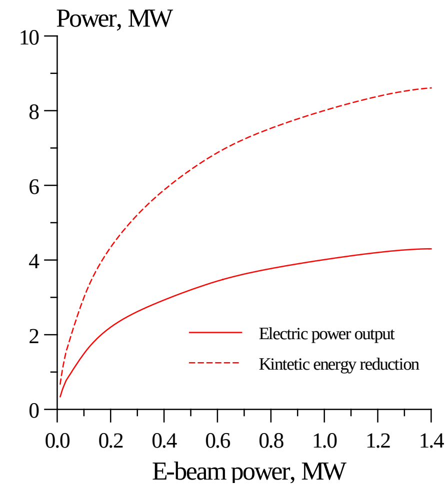


FIG.-1





- 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 Re$_m$ 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: $$\rho(\mathbf{v}\cdot\nabla)\mathbf{v} = \mathrm{j} \times \mathrm{B} - \nabla \mathrm{p}$$

Mass: $$\nabla \cdot (\rho \mathbf{v}) = 0$$

Energy: $$\rho \mathbf{v}\cdot\nabla\left(\frac{|\mathrm{v}|^2}{2} + \mathrm{U}\right) = -\nabla \cdot (\mathbf{v}\mathrm{p}) + \mathbf{j} \cdot \mathbf{E}$$

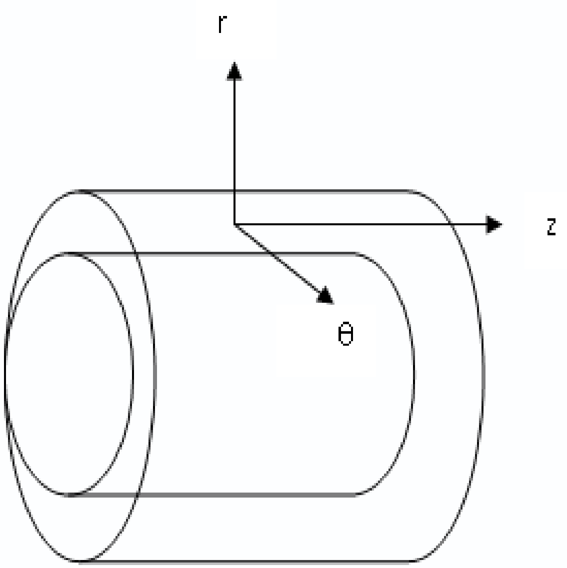
Current: $$\nabla \cdot \mathbf{j} = 0$$

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

- Friction/heat neglected. “Kinetics” neglected.

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, σ
- Zero terms: B_θ, B_z, v_r, j_r, $\mathbf{E}_\theta$, E_r
- Ideal, calorically perfect gas
- **Pure Hall device**: Applied tangential $\mathbf{E}_\theta$ 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

$$\mathrm{Re} = \frac{Inertia\ Forces}{Viscous\ Forces} = \frac{U_0 L}{\upsilon}$$

Magnetic Reynolds Number

$$\mathrm{Re}_m = \frac{\text{Convection of } \vec{\mathrm{B}}}{\text{Diffusion of } \vec{\mathrm{B}}} = \frac{\text{Induced Field}}{\text{Applied Field}} = \frac{U_0 L}{\upsilon_m} = \mu_0 \sigma U_0 L$$

Re_m <<1
Induced magnetic field is small compared to applied field, B = $B_{Applied}$

AND

Electric field can be expressed as Gradient of a potential, E = -gradΦ

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 /z with inputs – B_r, σ, L
- Two temperature plasma model of **nonequilibrium** ionization
  - T_s – bulk gas static temperature
  - T_e – constant electron temperature (1 ev, 11605^{o}K)
- **Hall parameter**

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

Electron cyclotron frequency X mean free time between collisions

- **Hall loading parameter**

$$K_h = \frac{\propto E_z}{\omega\tau v_z B_r}$$

- Geometry specification

$$\frac{d(\rho v_z)}{dz} = \text{constant}$$

Annular MHD Hall Generator Design

Inlet conditions:

$M = 5.02$

$P_s = 32.7$ Torr

$T_s = 420^oK$

Generator parameters:

$B_r = 5$ Tesla

$\sigma = 5$ mho/m

$L = 3$ m

$K_h = -0.09$

$d(\rho v_z)/dz = -21$ kg/m^3-s

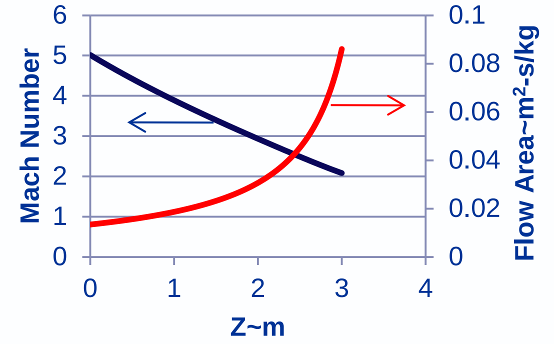
$\eta_{Ng} = 0.63$

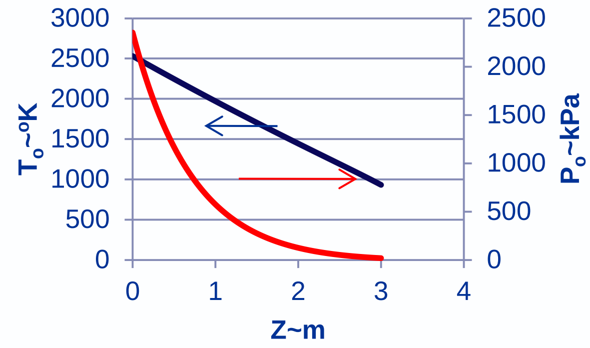
$\eta_s = 0.84$

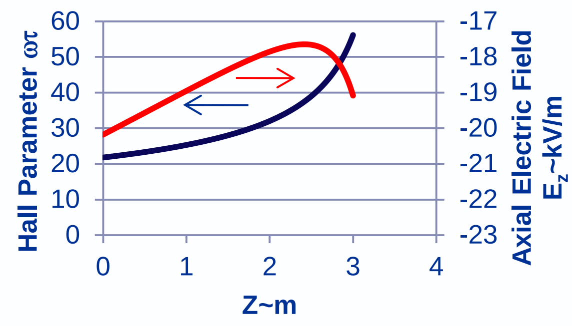
$V = 55.8$ kV

$I = 28.7$ Amp/kg/s

$P_e = 1.60$ MW/kg/s

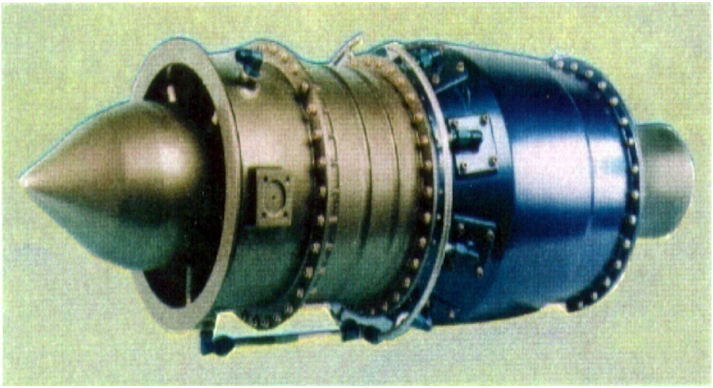






MHD Energy Bypass Demonstration in Turbojet-Based Engines:

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**

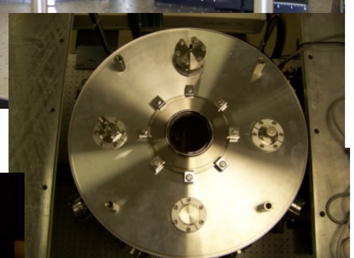
NOTE: *In the Mach 2.0 – 3.0 regime, a SIMULTANEOUS MASS BYPASS may be desirable / advantageous.*

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.

Generation of Plasma with FIW

40 KV 20nsec Power Supply

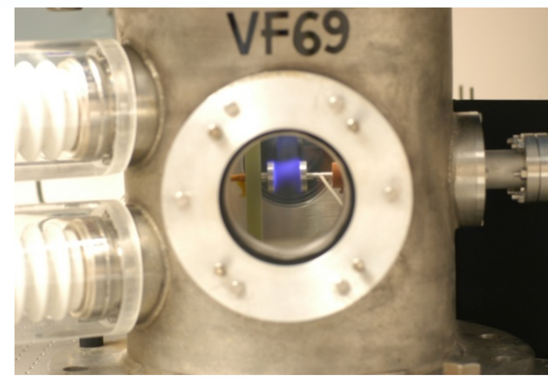


Top View

Plasma

"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, 20ns 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

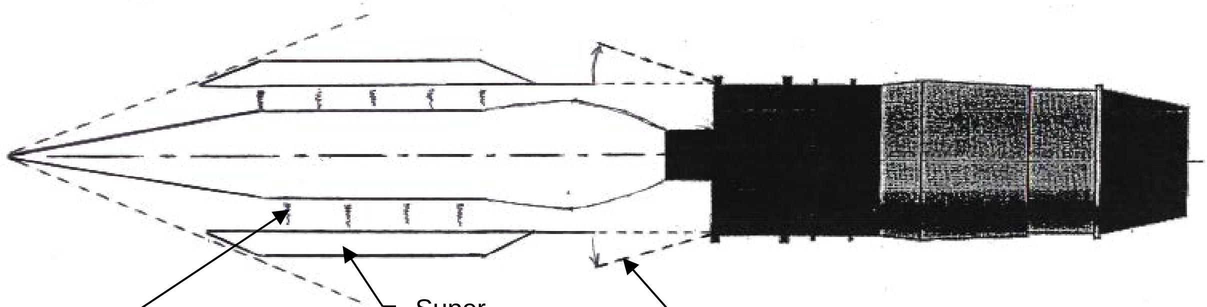
- **Pulser-sustainer discharge[1] ionization process using nanosecond pulses is proposed as the means for the non-thermal ionization**
  - Energizes and sustains electrons at a high T_e while maintaining a low nearly constant ion/neutral temperature T_s
  - σ=1.0 - 5.0 mho/m requires an $n_e/n=1.90\times10^{-6}$-9.52×10^{-6} for T_e=1ev[1]
  - Initial belljar tests[2] indicate an ionization fraction 1.1×10^{-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

1) Nishihara, M., Rich, J. W., Lempert, W. R., Adamovich, I. V., and Gogineni, S., "Low-Temperature M=3 Flow Deceleration by Lorentz Force", Physics of Fluids, Vol. 18, No. 8, August 2006, pp. 086 101-086-111

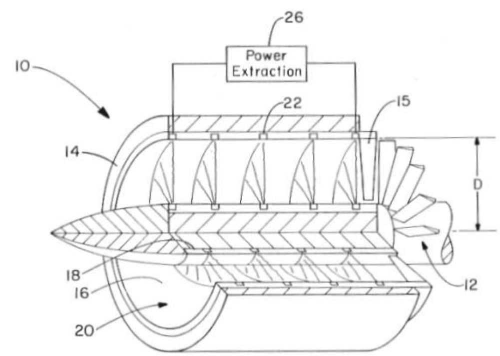
2) Schneider, S.J., Kamhawi, H., and Blankson, I.M., "Efficient Ionization Investigation for Flow Control and Energy Extraction", AIAA-2009-1050, 47th AIAA Aerospace Sciences Meeting, Orlando, FL, January 5-8, 2009.

PLANNED PLASMA/MHD EXPERIMENT

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



MHD Power Extraction Patent



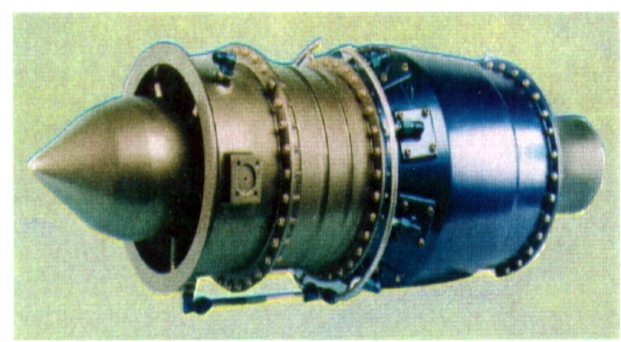
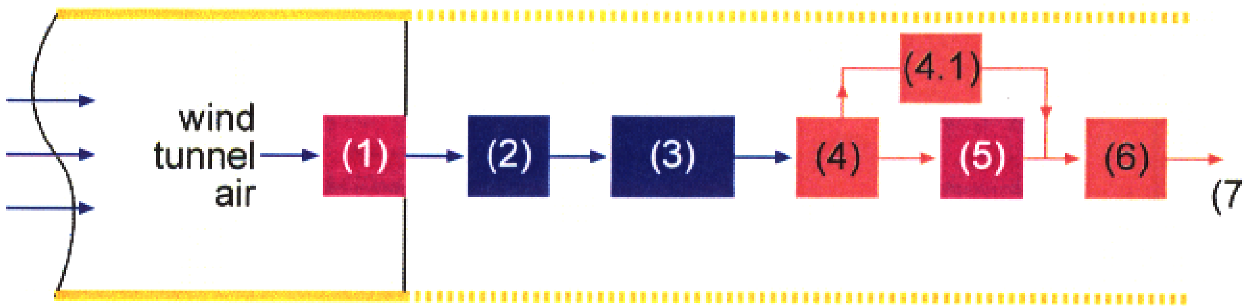


FIG.-1

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.)



(1) inlet air MHD power generation duct
(2) pre-cooler
(3) engine inlet
(4) engine
(4.1) air heater
(5) hot gas MHD power generation duct
(6) thrust nozzle
(7) ambient surroundings

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!**

<u>THANKS to my PLASMA/MHD Colleagues</u>

- **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)**
- **<u>Plasmas/MHD for Flow Control of and Energy Extraction from Weakly and Fully Ionized Hypersonic flows:</u> (Understand the physics of the plasma mechanism for practical aerospace applications. The critical <u>science</u> 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 <u>dielectric liquids</u> (water, hydrocarbon fuels, etc).**
- **<u>Reentry plasmas and antenna breakdown</u>: Mitigation of Reentry Communications Blackout using "Magnetic Windows". Communications and GPS issues.**