NASA GRC Research in Aerospace Propulsion with Potential Collaboration Opportunities

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OAI

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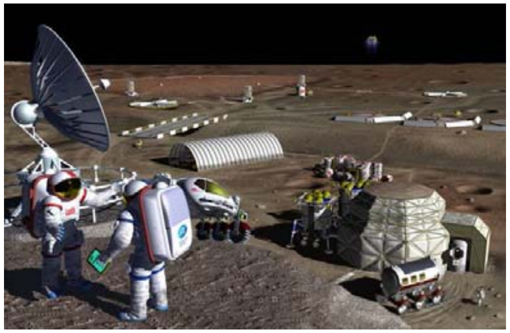
Outline of Presentation

- Introduction(GRC core competencies in propulsion)
- Airbreathing(0<M<2) Propulsion Research
- Hypersonics Propulsion Research
- Electric Propulsion … plasma thrusters, etc
- Other Propulsion Topics
- Opportunities for Collaborative Research
- Summary

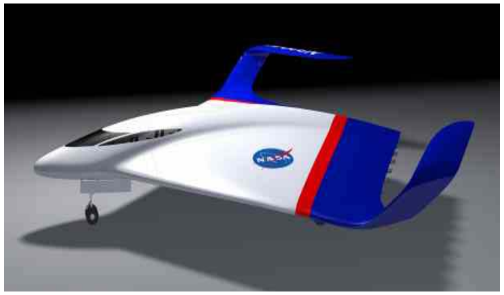
GRC Core Competencies

In-Space Propulsion including Nuclear Systems

Power and Energy Conversion Systems



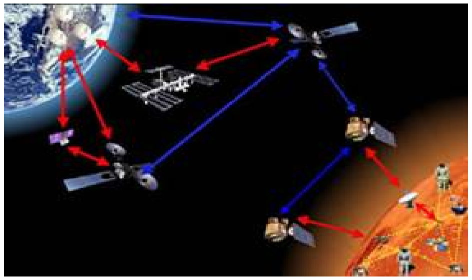
Aeropropulsion Systems

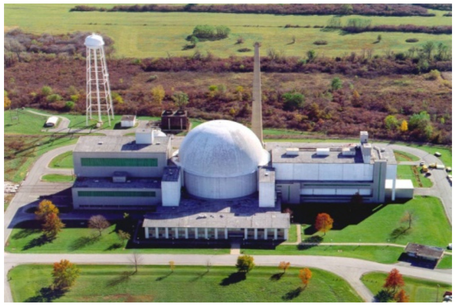


Fluids, Combustion and Reacting Systems Including Gravity Dependence

Interdisciplinary Bioengineering for Human Systems

Aerospace Communications Architectures & Subsystems



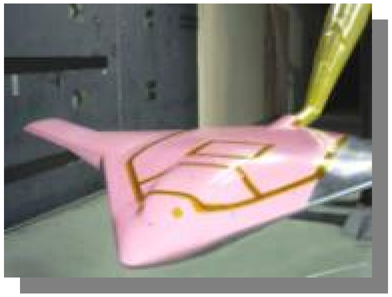


Test and Evaluation for Atmospheric, Space and Gravitational Environments

NASA Fundamental Aeronautics Program

- *Hypersonics*
  - *Conduct fundamental and multidisciplinary research to **enable airbreathing access to space** and **high mass entry into planetary atmospheres***
- *Supersonics*
  - ***Eliminate environmental and performance barriers** that prevent **practical supersonic vehicles** (cruise efficiency, noise and emissions, performance)*
  - *Develop supersonic deceleration technology for **Entry, Descent, and Landing** into Mars*
- *Subsonic Fixed Wing (SFW)*
  - *Develop concepts/technologies for enabling dramatic improvements in **noise, emissions and performance (fuel burn and reduced field length)** characteristics of subsonic/transonic aircraft*
- *Subsonic Rotary Wing (SRW)*
  - *Radically **Improve capabilities and civil benefits of rotary wing vehicles** (vs fixed wing) while maintaining their unique benefits*

*Common for all projects: Develop **prediction and analysis tools** for reduced uncertainty in design process and advanced **multidisciplinary design and analysis capability** to guide our research and technology investments and realize integrated technology advances in future aircraft*



AIAA Top 10 Emerging Aerospace Technologies of 2009

1. "Greener Aviation" Technologies – including emission reduction and noise reduction technologies as used in the Federal Aviation Administration's Continuous Low Emissions, Energy and Noise (CLEEN) program, and the European Environmentally Friendly Engine (EFE) program and "Clean Sky" Joint Technology Initiative.
2. Alternative Fuels – including biofuels, as promoted by the FAA's Commercial Aviation Alternative Fuels Initiative (CAAFI), and the recent FAA grant to the X Prize Foundation to spur development of renewable aviation fuels and technologies.
3. High Speed Flight Technologies – such as supersonic and hypersonic aerodynamics, sonic boom reduction technology, and thermal management aids.
4. Efficient Propulsion Technologies – including open rotors and geared turbofans, such as those used in the European DREAM (valiDation Radical Engine Architecture systeMs) program.
5. Active Flow Technologies – such as plasma actuators.
6. Advanced Materials – such as nanotechnology and composites.
7. Active Structures – such as shape memory alloys, morphing, and flapping.
8. Health Management – such as monitoring, prognostics, and self-healing.
9. Remote Sensing Technologies – including unmanned aerial vehicles and satellites such as those used in NASA's Global Earth Observation System of Systems (GEOSS) program.
10. Advanced Space Propulsion Technologies – including plasma-based propulsion such as the Variable Specific Impulse Magnetoplasma Rocket, and solar sail technologies.

List of Current and Emerging Propulsion Technologies at GRC

- **SFW: Conventional Tube/Wing Architecture** with **podded installation** (geared turbofan, very high bypass ratio, variable area nozzle concepts, etc). Address noise, emission, performance goals.
- **Hybrid Wing Body/Blended Wing** Body Propulsion. Embedded distributed propulsion systems. (Presents an interesting airframe/propulsion/controls integration issue)
- **Distributed Turbo-Electric Propulsion.**
- **Exoskeletal** Engine Concept
- **Constant Volume Combustion:** The Pulse Detonation Turbine Engine
- **Supersonic Propulsion:** Mach 1.6-1.8, small business jets overland. Sonic boom mitigation, cruise emissions, fuel efficiency, noise reduction goals. Commercial jet at Mach1.8-2.0, variable cycle propulsion system, cruise emissions, fuel efficiency, etc
- **PDE's**
- **Supersonic Retropropulsion Technology** for Mars Entry, Descent and Landing
- **Hypersonic propulsion:**Combined-cycle (turbo-ram-scram) engines (TBCC)
- **Hypersonic propulsion: MHD-Controlled Turbojet**
- **RBCC:** Trailblazer RBCC Engine Flow-path
- **Electric Propulsion**: Next Generation Ion Engine Thruster Technology, NASA's Evolutionary Xenon Thruster (NEXT), HiVHAC
- **Radioisotope Electric Propulsion (REP):**
- **Chemical Propulsion:** Non-toxic Fuels, LOX-Methane, LOX-hydrogen. – (in-situ lunar regolith resource).
- **Others:** (Aerocapture, Solar Sails, Plasma Sails, Advanced Chemical Fuels Development, Solar thermal propulsion, etc)

Subsonic Fixed Wing System Level Metrics

.... *technology for improving noise, emissions, & performance*

CORNERS OF THE TRADE SPACE	*N+1 (2015)*** Generation Conventional Configurations relative to 1998 reference*	*N+2 (2020)*** Generation Unconventional Configurations relative to 1998 reference*	*N+3 (2025)*** Generation Advanced Aircraft Concepts relative to user-defined reference*
Noise	*-32 dB (cum below Stage 4)*	*-42 dB (cum below Stage 4)*	*-71dB (cum below Stage 4)*
LTO NOx Emissions (below CAEP 6)	*-60%*	*-75%*	*better than -75%*
Performance: Aircraft Fuel Burn	*-33%***	*-40%***	*better than -70%*
Performance: Field Length	*-33%*	*-50%*	*exploit metro-plex* concepts*

****Technology Readiness Level for key technologies = 4-6*
*** Additional gains may be possible through operational improvements*
**   Concepts that enable optimal use of runways at multiple airports within the metropolitan area*

Approach

- Enable Major Changes in Engine Cycle/Airframe Configurations
- Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes
- Develop/Test/ Analyze Advanced Multi-Discipline Based Concepts and Technologies

Top-Ranked Turbomachinery Technology Challenges

Inlet Flow Distortion Sensitivity and Stability

Tip Leakage Flows in High Pressure Ratio Cores

Combustor/Cooled Turbine Interaction

Endwall Contouring

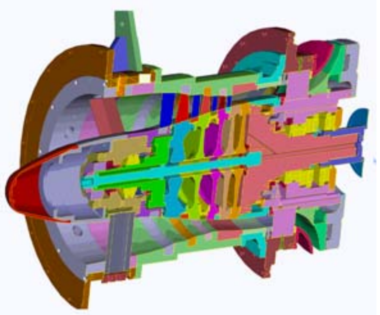
Turbine Tip Flows

Highly Loaded Low Pressure Turbines

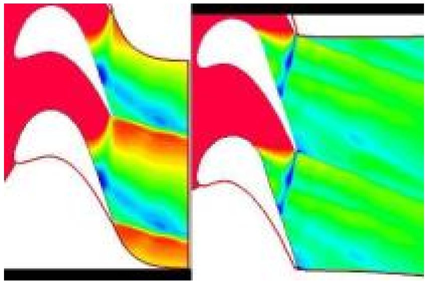
Technologies identified and ranked by NASA-led technical working group (TWG) consisting of representatives from industry, university & government agencies.

Set of white papers prepared by TWG

FA-SFW AeroT Research Overview

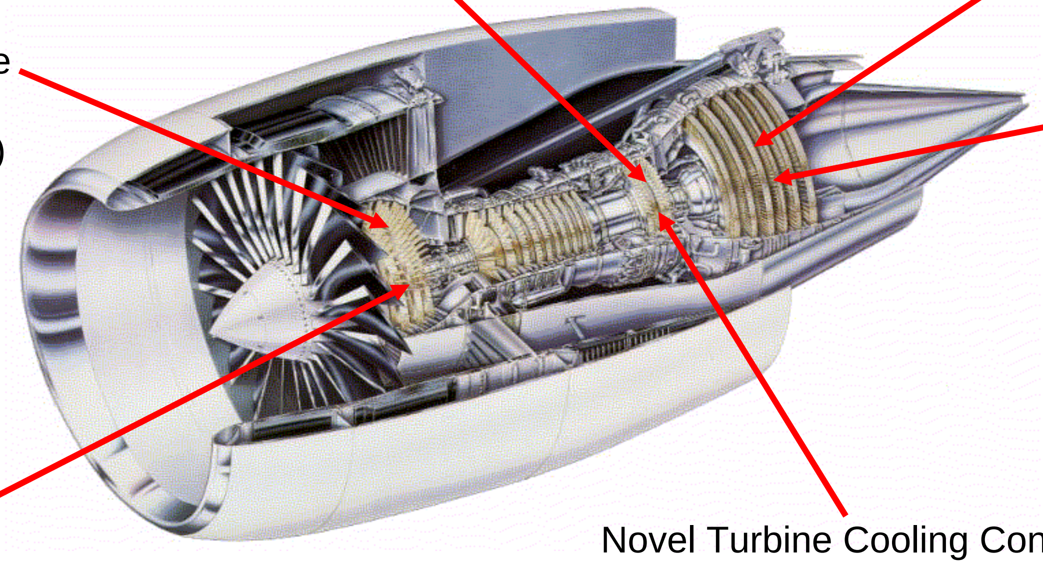


Low-Shock Design,
High Efficiency,
High Pressure
Turbine

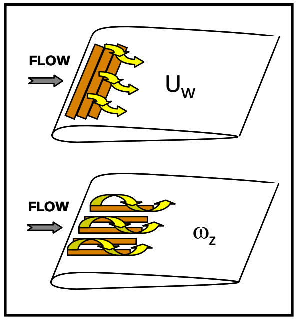


Aspiration Flow Controlled,
Highly-Loaded,
Low Pressure Turbine

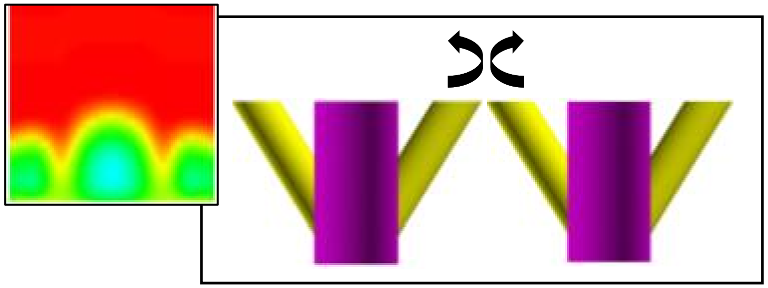
Highly-Loaded, Multistage
Compressor (higher
efficiency and operability)



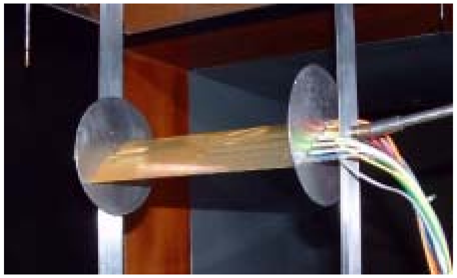
Low Pressure
Turbine Plasma
Flow Control



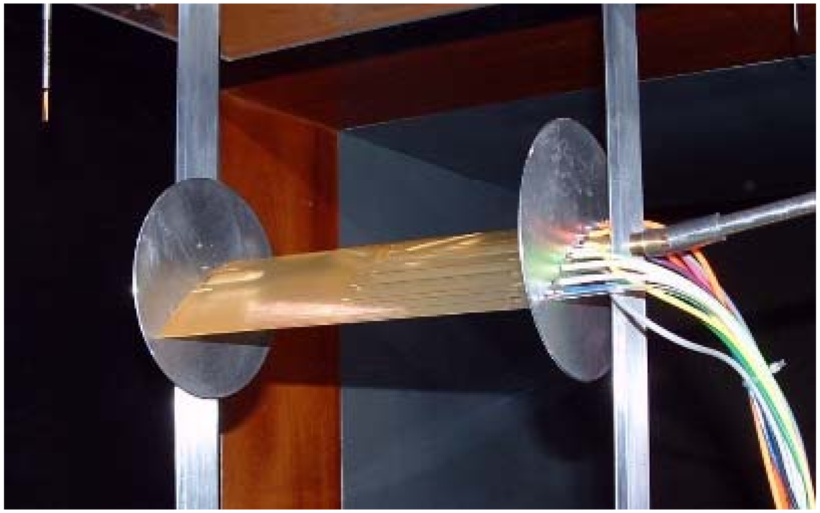
Novel Turbine Cooling Concepts

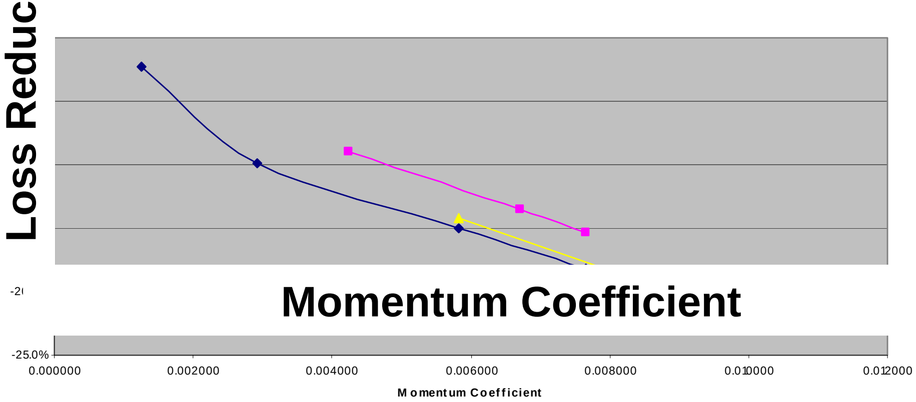


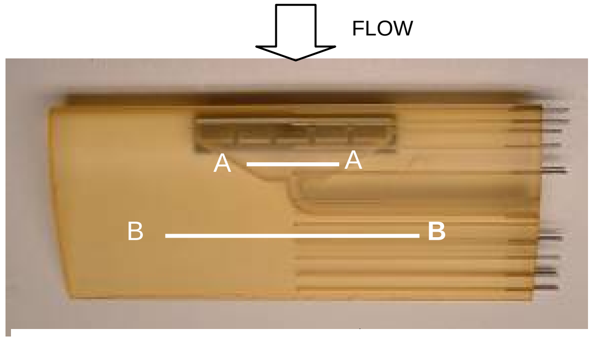
Compressor
Synthetic Jet Flow
Control (reduced
flow losses)



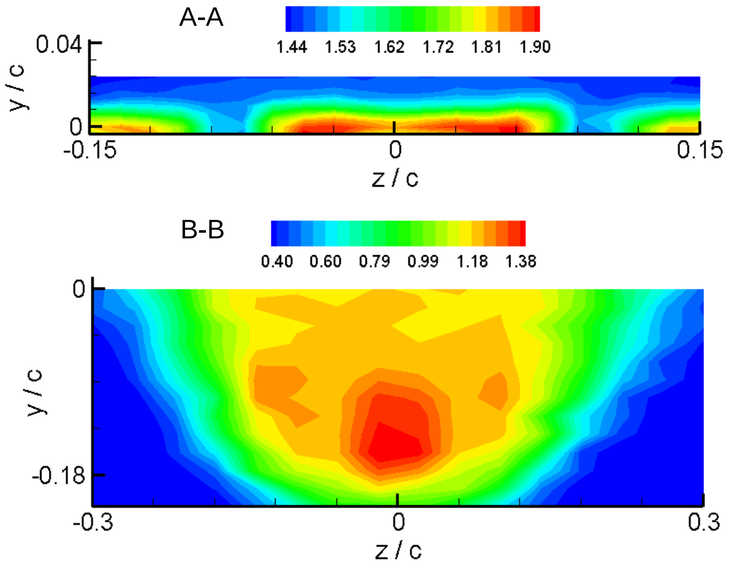
Turbomachinery Flow Control Development







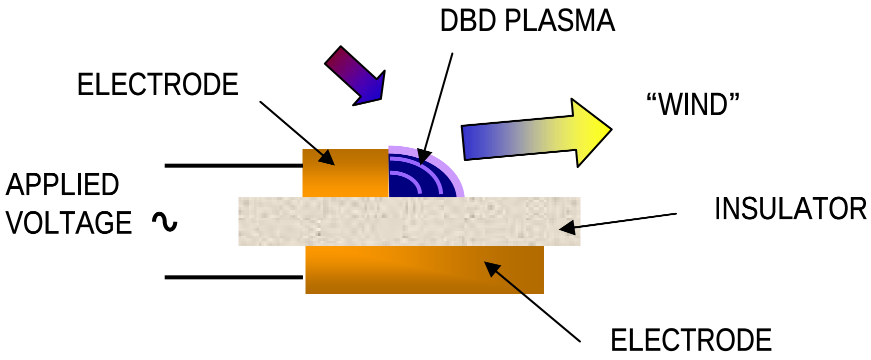
Mean velocity contours:



10% to 20% reduction in aerodynamic loss achieved with zero net mass flow devices

Experimental Study on Flow Control over a Blade by Acoustic Excitation (Synthetic Jets)

Flow Control Using Dielectric Barrier Discharge Plasma Actuators – Round 1 NRAs



DBD PLASMA

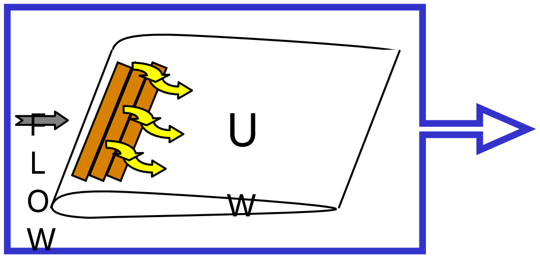
ELECTRODE

"WIND"

APPLIED VOLTAGE ∿

INSULATOR

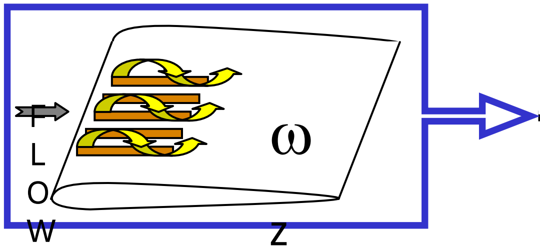
ELECTRODE

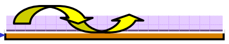


Electrode perpendicular to flow

Active Flow Control via

Oscillating wall jet





Electrode parallel to flow

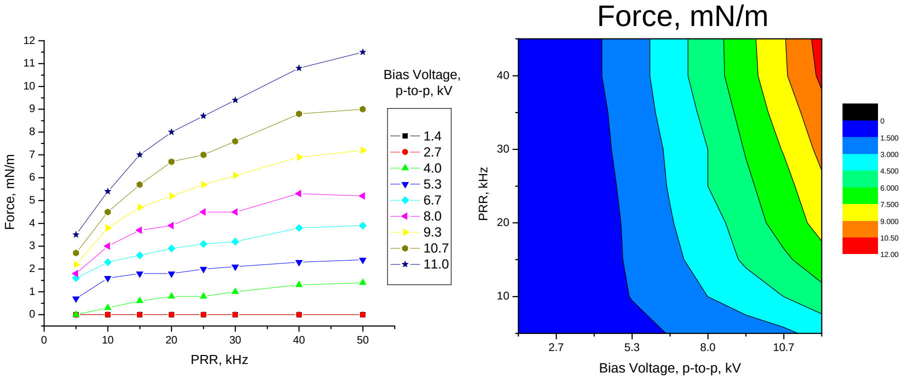
Active Flow Control via

Streamwise vortices

Advantages of GDP actuators:

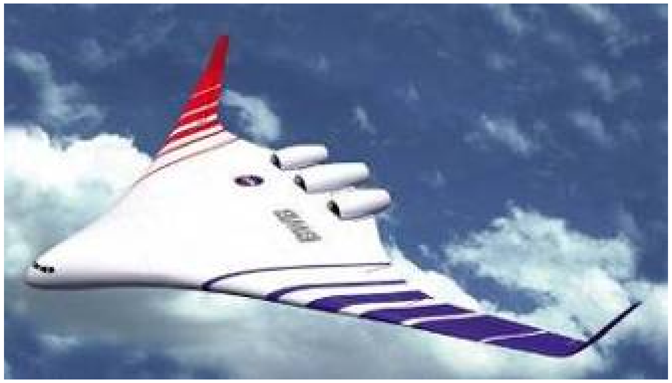
- Pure solid state device
- Simple, no moving parts
- Flexible operation, good for varying operating conditions
- Low power
- Heat resistance – w/ proper materials

Force Versus Pulse Repetition Rate & Bias



Princeton Nanosecond Pulsing NRA
Large force induced with voltage bias

Blended Wing Body (BWB) Aircraft: Aerodynamic and Propulsion Benefits and Challenges (I)



CURRENT ARCHITECTURE:

Blended Wing Body with Boundary-Layer Ingestion Inlets/Nacelles: Reduced ram drag, lower wetted area, lower structural weight, etc

Anticipated Benefits:

Large aerodynamic efficiency (L/D)

Reduced Noise

Reduced fuel burn benefits to HWB aircraft with embedded engines implies reduced emissions.

Challenges:

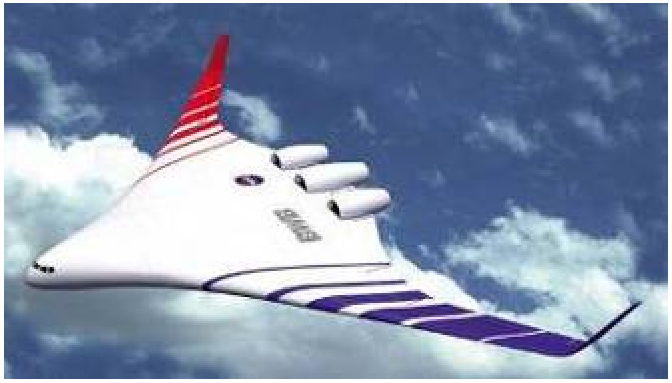
No Tail: stability and control a critical issue ((statically unstable and may need active flight control (B2))

Non-circular fuselage cross-section

Inlet Flow Distortion problems

Propulsion/Airframe Integration: Engines mounted above upper surface near trailing edge. Interactions between WING, ENGINES, and CONTROL surfaces introduce design complexity.

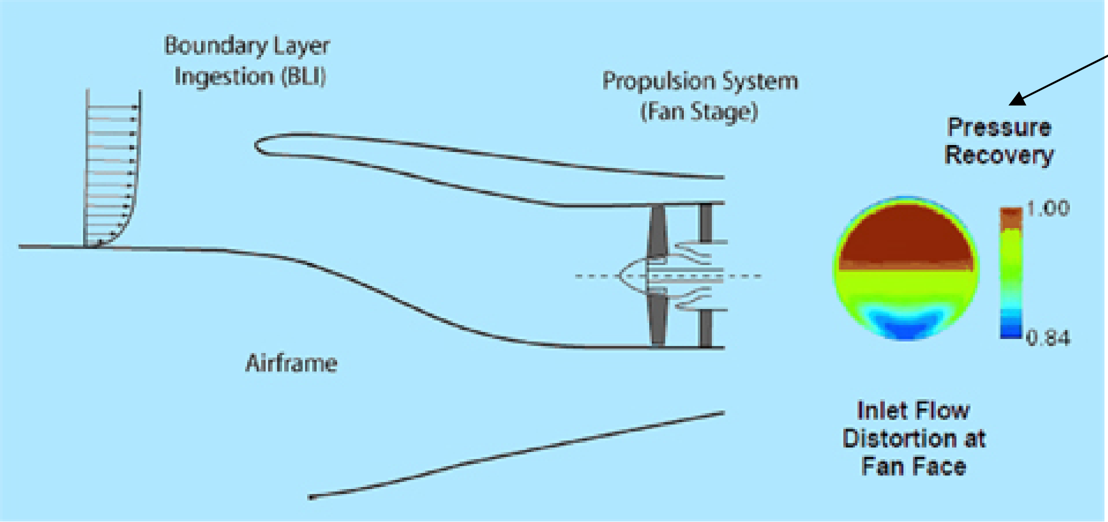
Blended Wing Body (BWB) Aircraft: Aerodynamic and Propulsion Benefits and Challenges(II)



<u>Boeing and NASA Findings</u>:
Noise and fuel burn benefits to HWB aircraft with embedded engines

<u>Challenges</u>: system weight, engine aft noise propagation, and engine-out maneuverability

<u>Recommendation</u>:
Shorten and move engines forward and reduce offset, while retaining BLI (Boundary Layer Ingestion)

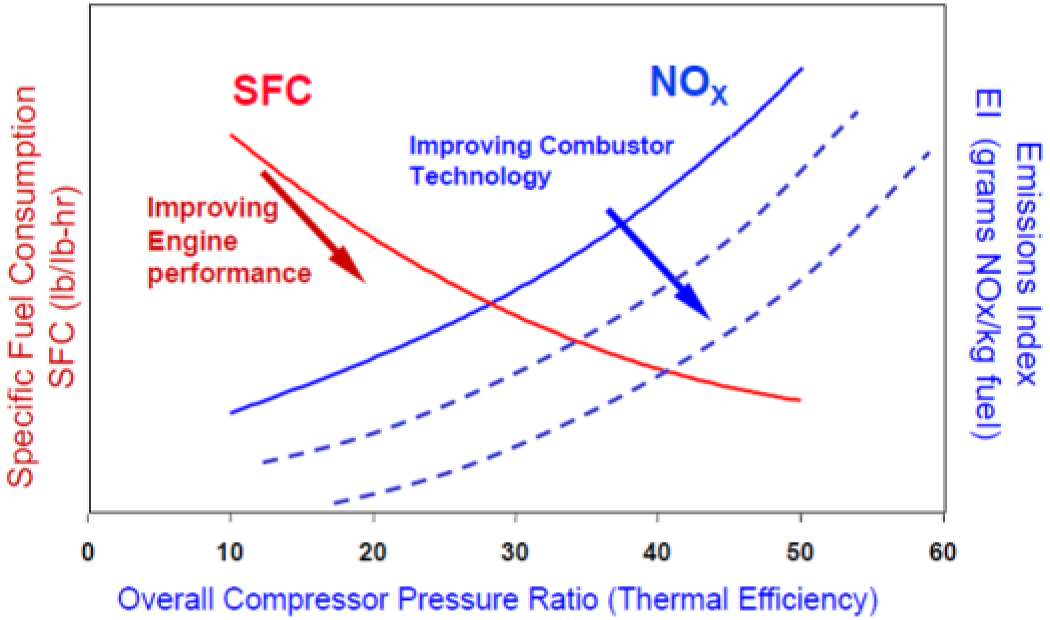


<u>Distorted inlet flow</u> propagated to fan-face for hybrid wing vehicle embedded engine, highlighting <u>challenges</u> in fan design and operation.

Core/Combustor Technology

Low NOx combustor concepts for high OPR environment

Increase thermal efficiency without increasing NOx emissions



Injector Concepts

- *Partial Pre-Mixed*
- *Lean Direct Multi-Injection*

Enabling Technology

- *lightweight CMC liners*
- *advanced instability controls*

- *Improved fuel-air mixing to minimize hot spots that create additional NOx*
- *Lightweight liners to handle higher temperatures associated with higher OPR*
- *Fuel Flexibility*

- *DoD HEETE Program is developing higher OPR compressor technology*

  …. ERA will focus on new combustor technology for reduced NOx formation

FA-SFW AeroT NRA Investment

Round 1 (N+1)

6 NRAs awarded to universities in LPT flow control

(UofWI, UofMN, OSU, Princeton, USNA, ISU)

Integrated Embedded Propulsion Systems (N+2)

3 Round 2 NRAs awarded (work began Oct. 2007)

Performing Organization	Topic Area
U. of Tennessee-Chattanooga	High Fidelity Modeling
The Boeing Company	Inlet Flow Control
United Technologies	Inlet/Fan Interaction

We hope to release a fundamental research NRA in spring 2010

http://nspires.nasaprs.com/external/

Airbreathing Hypersonic Propulsion

- Hypersonic Propulsion (Turbine-Based Combined Cycle (TBCC) Propulsion, Mode Transition, Bleed Modeling, Aero-servo-thermoelastic issues in hypersonics, Fuels, etc

Propulsion Technical Challenges

- **Design and Analysis Tool Development**
  - Improvement and validation in the areas of: 1) CFD tools concentrating on RANS modeling addressing combustion, LES, and other algorithms emphasizing combustion physics (steady and unsteady), 2) engineering level performance and design tools concentrating on cycle performance tools, scaling techniques, and system weight algorithms, and 3) multidisciplinary tools including conjugate problems in aerodynamics, heat transfer, and mechanical loads.
- **Fundamental Propulsion Physics & Modeling**
  - Acquire comprehensive data sets for the development of physical models, relevant to problems unique to hypersonic propulsion-aerodynamic physics and analysis, e.g. turbulent combustion, flame holding and ignition.
- **Propulsion Materials & Structures**
  - Improve life and durability, achieve weight and volume reduction of structural components and enhance life prediction tools for high-speed propulsion systems.
- **Propulsion / Airframe/ Controls Integration**
  - Address the integrated performance, control and coupled-design issues of the entire propulsion-airframe entity inclusive of ground to flight performance extrapolation techniques.
- **Scramjet / Ramjet Propulsion**
  - Improve the characterization of: (a) fuel-air mixing, flame holding, ignition and turbulent flame propagation (in relevant scramjet and ramjet environments), (b) the mode transition mechanisms, control thereof and relevant fluid-dynamics of airbreathing propulsion inclusive of shock interactions, (c) the quantification of hypervelocity propulsive physics, with particular emphasis on the ultra-high-speed performance aspects of the scramjet, inclusive of LOX addition.
- **High–Mach Turbine Propulsion**
  - Quantify and address the critical technical barriers of high-Mach turbine flow path inclusive of those pertaining to the inlet, variable cycle turbine engine, after-burner / hyper-burner, nozzle, and the interactions between these components.
- **Turbine Based Combined Cycle Propulsion AND Mode Transition**
  - Address issues associated with the integration of a turbine engine with an adjacent scramjet flowpath in a turbine-based combined-cycle (TBCC) propulsion system inclusive of vehicle integration.
- **Rocket Based Combined Cycle Propulsion**
  - Address challenges associated with the high degree of integration of the rocket component with the airbreathing flowpath to improve performance, system structural efficiency and thrust-to-weight. Explore the integration of advanced rocket cycles.
- **Advanced Concepts**
  - Explore advanced hypersonic propulsion concepts including, but are not limited to, **magnetohydrodynamics**, novel combustor designs, advanced thermal management, advanced sensor development, advanced engine controls, and advanced fuels.

THE TECHNOLOGY OF "INTEGRATION"

- **AIRFRAME-PROPULSION-CONTROLS INTEGRATION:** The need to carefully integrate the propulsion system with the vehicle airframe for optimum overall performance is a **fundamental requirement** of air-breathing hypersonic vehicles.
- The **"technology of integration"** is of unique significance in the development of hypersonic vehicles where each component affects every other component. Unfortunately, engineering practice usually leads to a subdivision by components in the design, development, and manufacturing processes; so that the **"technology of integration"** is not well-advanced. **Consequently, the development of a hypersonic vehicle requires an investigation and demonstration of an integrated design.**

- **Thermal management and structural integration** are other aspects of the integration problem. Thermal management is critical to defining a practical hypersonic vehicle concept since the **fuel** is usually the only hest sink available at hypersonic speed.
- PAI is a **highly non-linear** phenomenon. There are some vehicle design issues that are sufficiently complex and dependent in some unknown way on scale that they may not be reliably resolved even by combining test results from a number of separate facilities.

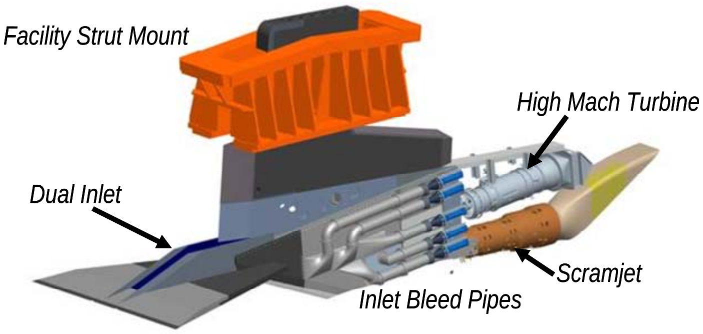
- **CRITICAL TECHNOLOGIES IN AIRFRAME/PROPULSION INTEGRATION**

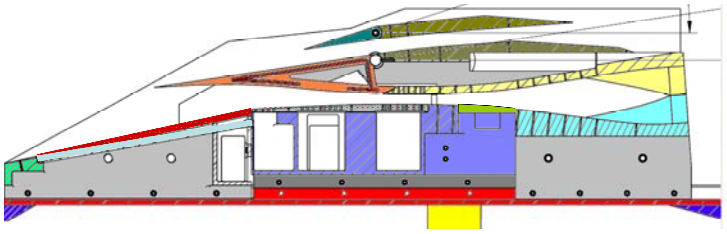
(1) MISSION/CONFIGURATION CONSTRAINTS (Alternate Concepts)
(2) FLOW-PATH OPTIMIZATION
(3) INSTALLED PERFORMANCE ASSESSMENT

TBCC Technology Development

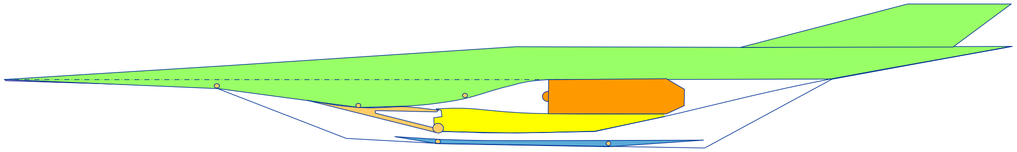
(I) TBCC Propulsion System Development

(II) MODE TRANSITION for TBCC Engines – a dynamic phenomenon. (From Turbojet to Ram / Scram and return)



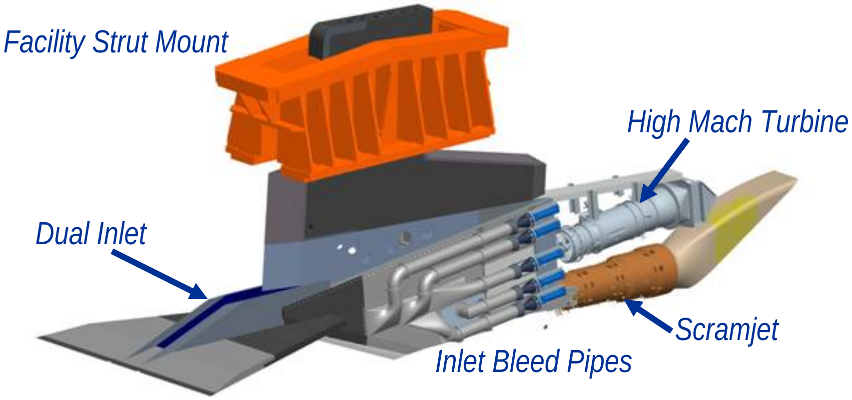


FAP Hypersonics - TBCC/CCE Propulsion System Design & Integration



Test Approach

1. Inlet w/ simulated Engine backpressure
2. Demonstrate mode transition control strategies and ability to recover from inlet unstart
3. Add engines/ nozzle for integrated system test



RESEARCH OBJECTIVES

1. Proof of concept of over/under split flow inlet for TBCC.

   -Demonstrate mode transition at large-scale.

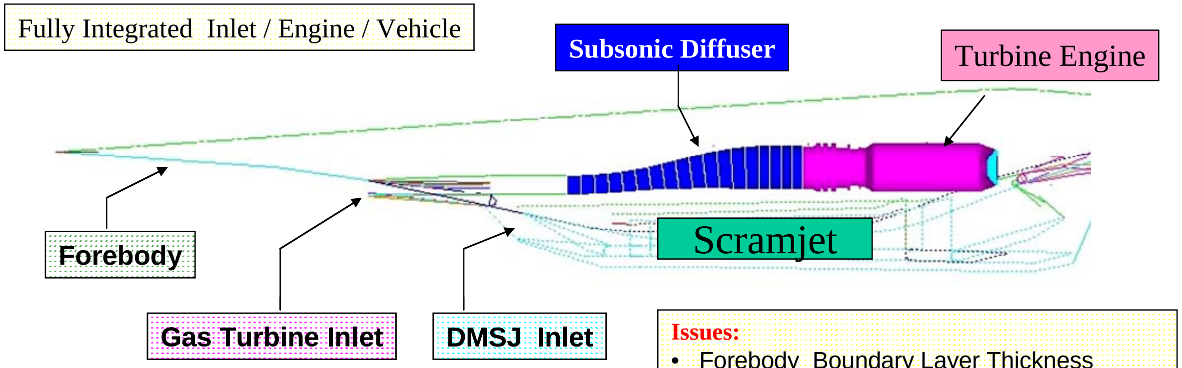
   - Develop an integrated database of performance & operability.

2. Validate CFD predictions for each inlet's design approach, and performance and operability prediction.
3. Develop realistic distortion characteristic throughout the mode transition Mach number range.
4. Testbed for future mode transition controls research
5. Testbed for integrated inlet/engine propulsion system tests

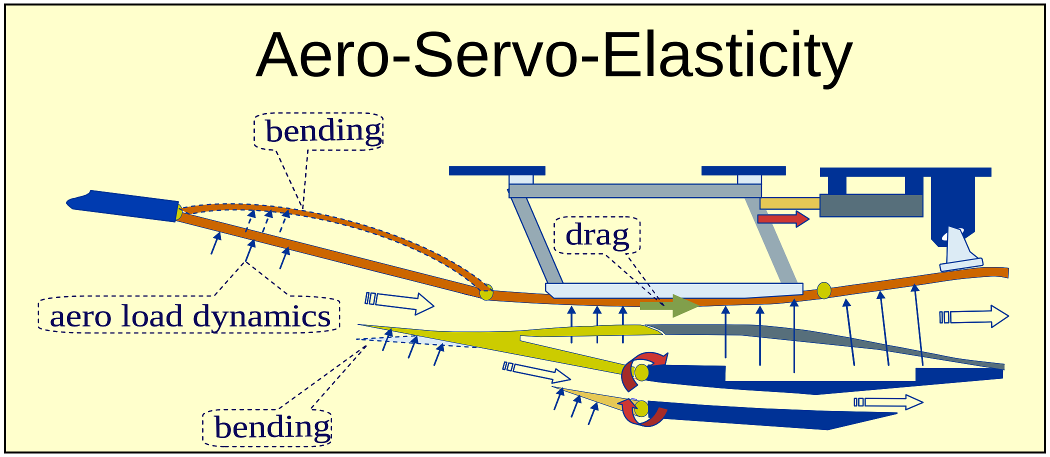
TBCC Mode Transition Study Provides Unique Databases to Assess SOA Design and Analysis Capabilities to predict Performance, Operability and Integration / Interaction Issues of Wide Mach Range Propulsion Systems

Mode Transition

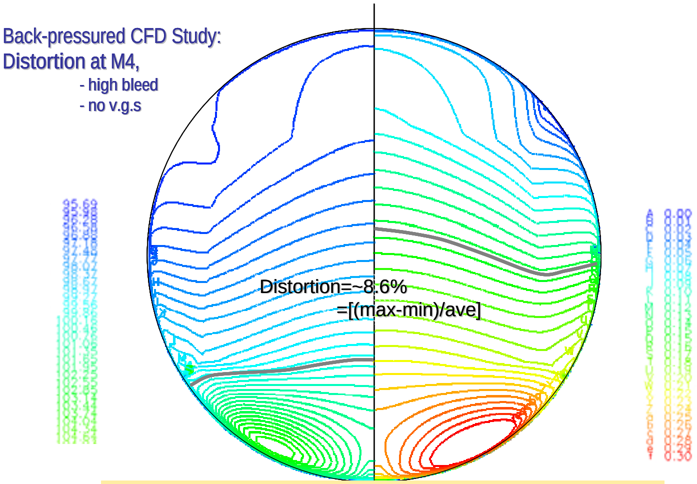
- What is the process for safe and optimum mode transition?
- Can we model components adequately to perform a controlled mode transition?
- Can we predict and avoid inlet and/or engine unstart?
- Can we predict low/high speed inlet/engine interaction? - backpressure and cowl positioning effects?
- Can our design tools utilize this data to optimize the configuration?



Issues:
- Forebody Boundary Layer Thickness
- Propulsion System Mode Transition
- Wide Operating Range / Variable Geometry
- Integration / Interaction Issues
  - inlet / engine compatibility - unstart
  - minimize frontal area/ maximize thrust

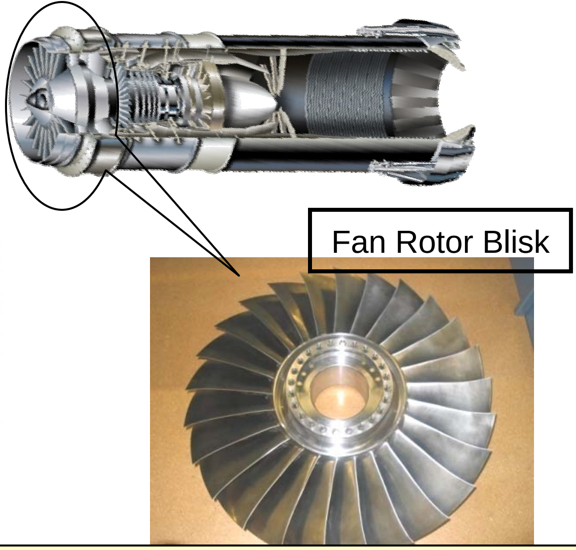

Aero-Servo-Elasticity

Inlet / Engine Interactions: Distortion, Backpressure



CFD indicates distortion at Turbine Engine Inlet may be high

Turbine Based propulsion



Inlet Distortion Screens

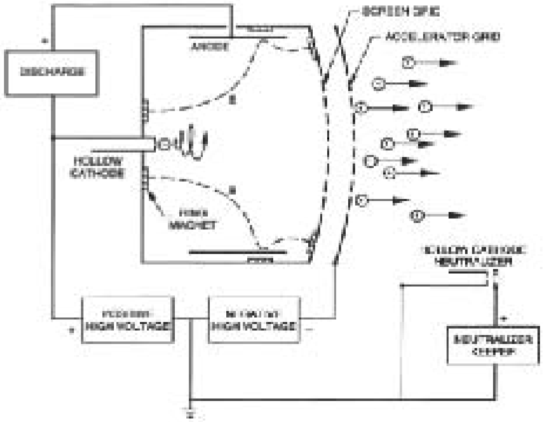
Used to simulate distortion and evaluate impact o n engine/fan performance & operability.

- What impact does engine inlet distortion have on performance and operability?
- Can our tools predict distortion into engine? -With and without bleed?
- Can our tools predict impact of distortion on engine performance & operability?
- What is the trade off between bleed and inlet exit profile? Are VG's req'd?
- Can we predict inlet /engine interaction? - backpressure and cowl positioning effects?
- Can Engine unstart inlet and visa versa? Can we detect to avoid unstart? Can we recover from inlet unstart?
- Can we Ram Start a turbine engine at High Mach conditions?

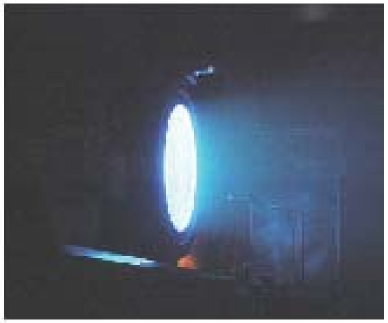
ELECTRIC PROPULSION

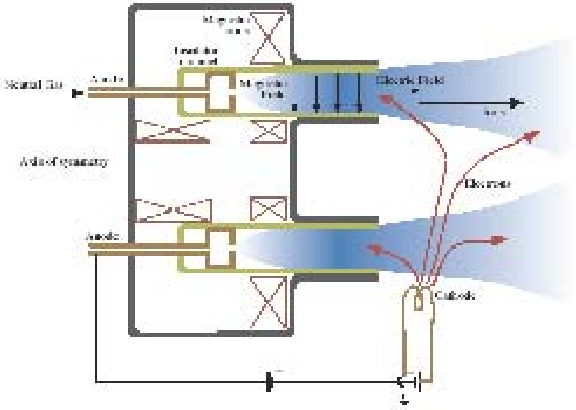
Electrostatic Thrusters

- generate high voltages for ion (plasma) acceleration

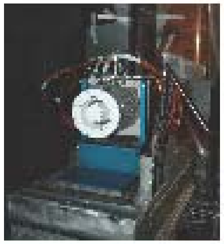


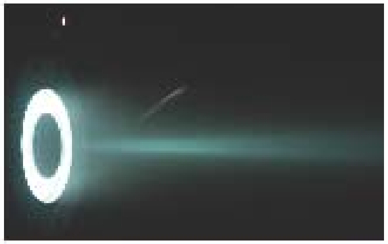
<u>Ion</u> thrusters use closely spaced high voltage grids to create an electrostatic field





<u>Hall</u> thrusters use magnetically trapped electrons to create an electrostatic field

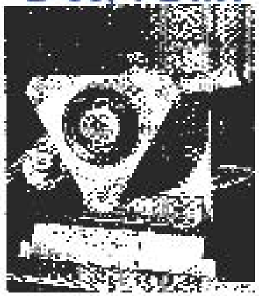




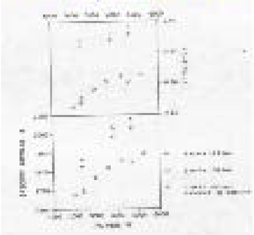
Hall Thruster Development at NASA GRC: < 10 kW

SPT-100, 1.35 kW

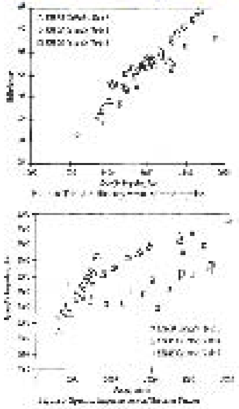
D-55, 1-2 kW



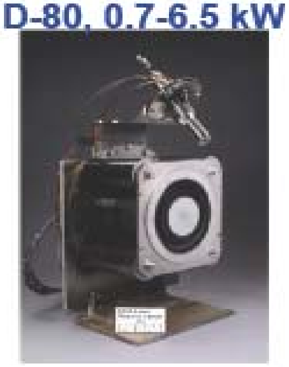
T-160, 4.5 kW



SPT-140, 5 kW



D-80, 0.7-6.5 kW



NASA-120M
2 kW, TRL-3

NASA-173M
5 kW, TRL-3

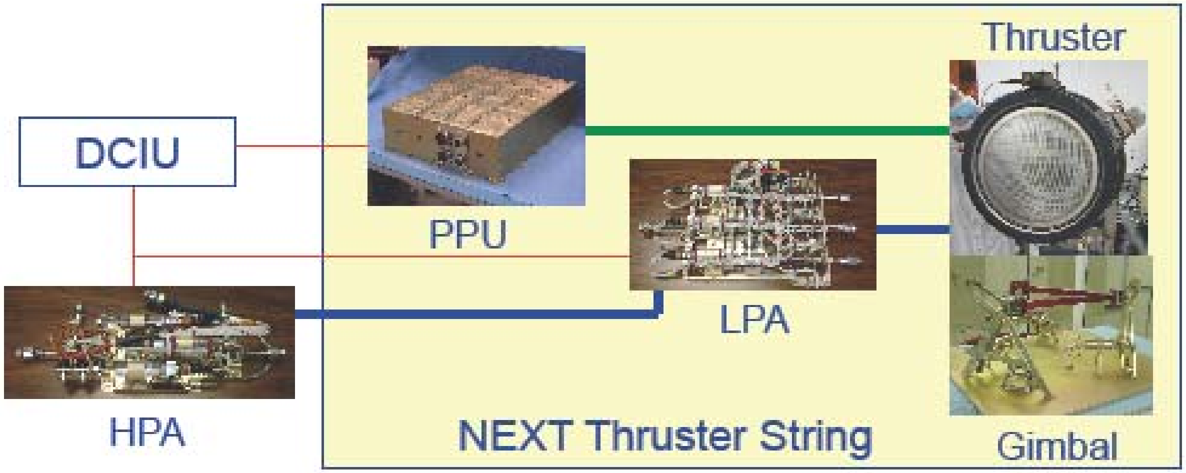
NASA-77M
0.2-2.8 kW

NASA-103M.XL
0.3-3.5 kW

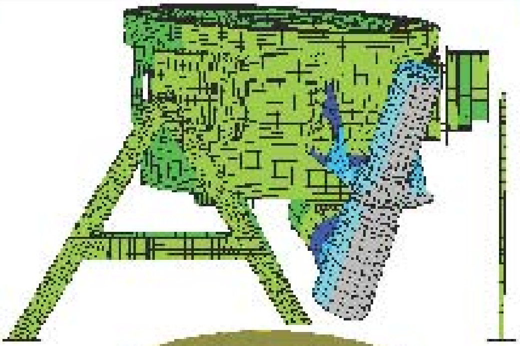
HIVHAC 3.5 kW EM Thruster
TRL-4/5

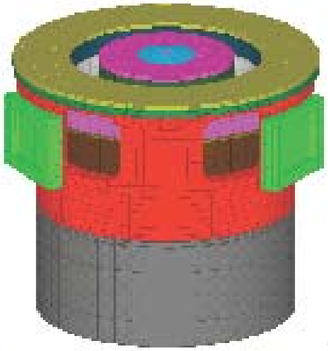
NEXT (NASA's Evolutionary Xenon Thruster) Ion Propulsion System

- Thruster String composed of Thruster/Gimbal Assembly, Power Processing Unit (PPU), and Propellant Management System (PMS) Low Pressure Assembly (LPA)
- High Pressure Assembly (HPA) and DCIU complete system
- Thruster Strings are added for mission performance reasons and for failure tolerance (Nomenclature: N+1)
- Overall system is configurable to meet mission needs



Hall Thruster Development at NASA GRC: HIVHAC EM Thruster





- In December of 2007 *Aerojet was* tasked to design, build, and test an engineering model (EM) flight like 3.5 kW long life Hall thruster.
- The EM thruster design evolves the design of NASA-103M.XL thruster and incorporates and leverages lessons learned from the NASA-77M and NASA-94M thruster designs and Aerojet's experience in manufacturing the BPT-4000 flight Hall thruster.
- The HIVHAC EM thruster is designed to have a thruster lifetime > 15,000 hrs and a xenon throughput of ~ 300 kg.
- The EM thruster design integrates of Aerojet's 6.35 mm flight qualified hollow cathode assembly.
- The EM thruster design minimizes mass, part count, and complex manufacturing processes
- Some key design features include:
  - Integrated magnetic structure
  - Low cost anode design
  - Heritage 6.35 mm hollow cathode
  - Low cost propellant isolator
  - Thermally efficient electromagnet design
- The EM thruster is being fabricated at Aerojet's Redmond facility where the flight BPT-4000 Hall thruster systems are built
- Some component fabrication is being performed at NASA GRC to meet manufacturing schedule

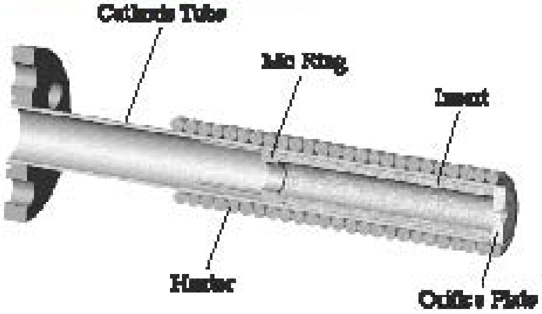
- Two EM thrusters will be assembled in July 2009 and delivered to NASA GRC to begin testing in August 2009

- *The HIVHAC EM thruster will be @ a TRL 4/5 in CY09*

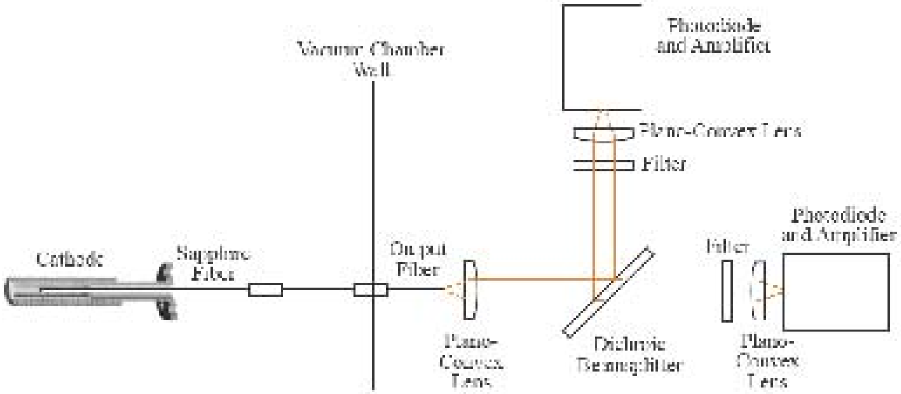
Research Topics of Interest for the Hall Thruster Program: *Erosion Modeling*

- Hall thruster lifetime is limited by *hollow cathode* life and *erosion of Boron Nitride discharge channel walls*
- Hollow cathode lifetime issues are being addressed and lifetimes up to 30,000 hours have been demonstrated
- Discharge channel erosion models still do not accurately predict erosion profiles or rates for Hall thruster operation
- Hall thruster discharge channel erosion is caused by *ions* impinging on channel walls and causing *sputtering*
- To accurately model Hall thruster erosion we need:
    - ➢ *accurate prediction of ion flux to wall for different Hall thruster configurations (geometric and magnetic) and operating conditions*
    - ➢ *accurate sputter yield predictions for various ion energies*
- *Model development to date has been mostly semi-empirical (need lots of data to calibrate code), hydrodynamic or hybrid (need data to calibrate code and not a predictive tool), or based on molecular dynamic particle in cell codes (elaborate, computationally expensive)*

Research Topics of Interest for the Hall Thruster Program: *Hollow Cathode Emitter Measurement*



- Hollow cathode lifetime issues are being addressed and lifetimes up to 30,000 hours have been demonstrated
- However, the HIVHAC thruster uses a modified cathode configuration
- To confirm life capability of the HIVHAC thruster, the emitter temperature profile has to be measured
- NASA GRC has all the components needed to assemble a fiberoptic emitter temperature measurement test rig
- The test rig can be used for both the NEXT and the HIVHAC programs



$$\frac{V_{out,1}}{V_{out,2}} = \frac{R(\lambda_1)\tau_o(\lambda_1)\tau_f(\lambda_1)\varepsilon(\lambda_1)\lambda_2^5\Delta\lambda_{f,1}}{R(\lambda_2)\tau_o(\lambda_2)\tau_f(\lambda_2)\varepsilon(\lambda_2)\lambda_1^5\Delta\lambda_{f,2}}\exp\left[\frac{c_2}{T}\left(\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right)\right] = C_1(\lambda_1,\lambda_2)\exp\left(\frac{C_2(\lambda_1,\lambda_2)}{T}\right)$$

Source AIAA-2004-4116

$$\frac{V_{out,1}}{V_{out,2}} = \frac{R(\lambda_1)\tau_o(\lambda_1)\tau_f(\lambda_1)\varepsilon(\lambda_1)\lambda_2^5\Delta\lambda_{f,1}}{R(\lambda_2)\tau_o(\lambda_2)\tau_f(\lambda_2)\varepsilon(\lambda_2)\lambda_1^5\Delta\lambda_{f,2}}\exp\left[\frac{c_2}{T}\left(\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right)\right] = C_1(\lambda_1,\lambda_2)\exp\left(\frac{C_2(\lambda_1,\lambda_2)}{T}\right)$$

NOVEL AIRBREATHING ENGINE CONCEPTS

(1) EXOSKELETAL ENGINE

(2) MHD-TURBOJET ENERGY BYPASS ENGINE
(MHD-CONTROLLED TURBOJET)

EXOSKELETAL ENGINE CONCEPT (ESE)

- Consist of a **DRUM ROTOR** **with rotating blades mounted inside serving the usual functions of fan, compressor, and turbine.**
- **Rotor blades are carried in COMPRESSION by the rotating outer casing.**
- **Eliminates the shafts and discs and creates an OPEN channel along engine centerline - - a unique feature that may be exploited for a variety of purposes.**
- **Drum rotor design driven by ability to use light-weight materials, CMC materials for higher temperatures.**
- **Opportunities for research in basic design rules and an understanding of design methods for this concept. Identify technology barriers that must be resolved to enable the ESE.**

- **Many potential advantages: Significant reduction in overall system weight with a corresponding increase in thrust to weight ratio, elimination of bore stresses in rotating components, increased HCF life for blades, enhanced containment capabilities for greater safety of aircraft and passengers, etc**

- **USES of CENTER DUCT:**

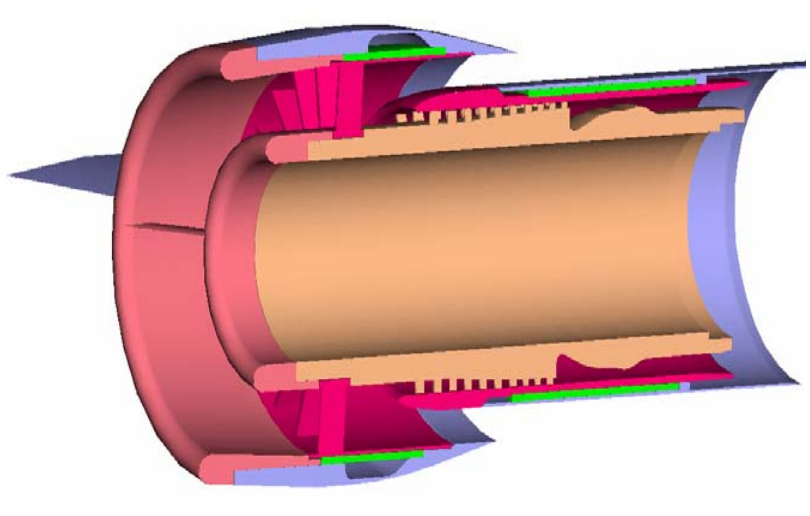
(1) Ramjet Duct – translating center-body for operation to Mach 5. Somewhat similar to J-58 (SR-71) turbine bypass system. Research and simulation opportunities in inlet operation, mode transition,

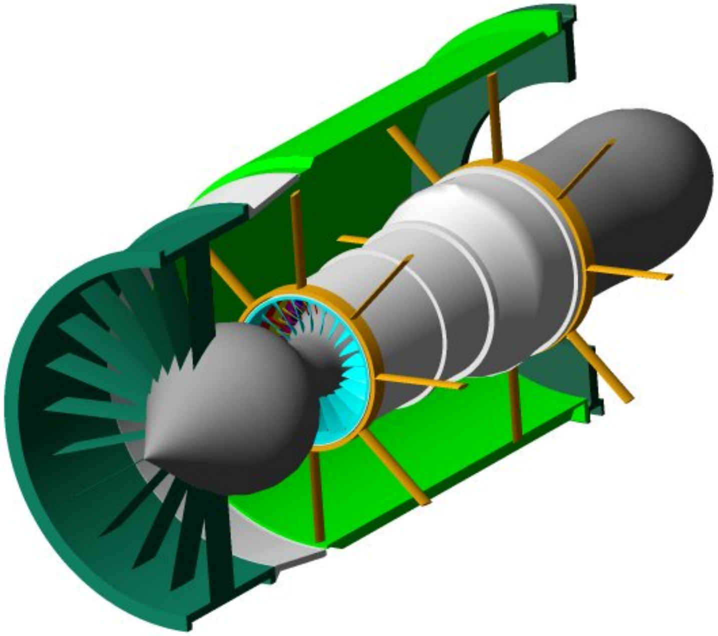
(2) PDE

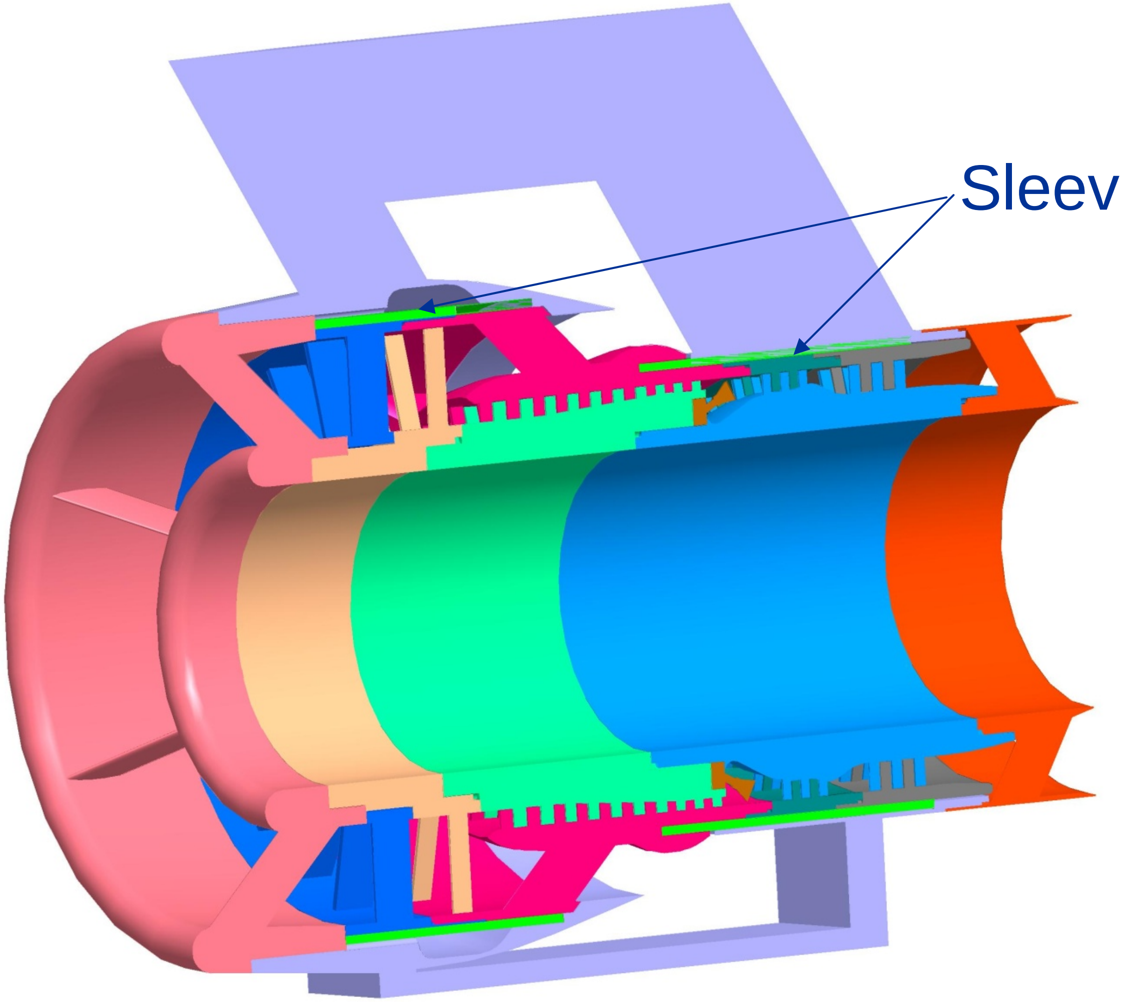
(3) Noise reduction – inverted velocity profile. Preliminary analysis has begun to quantify the benefits. This is an area of research that invites further study.

(4) Fuel Storage - cruise missile application

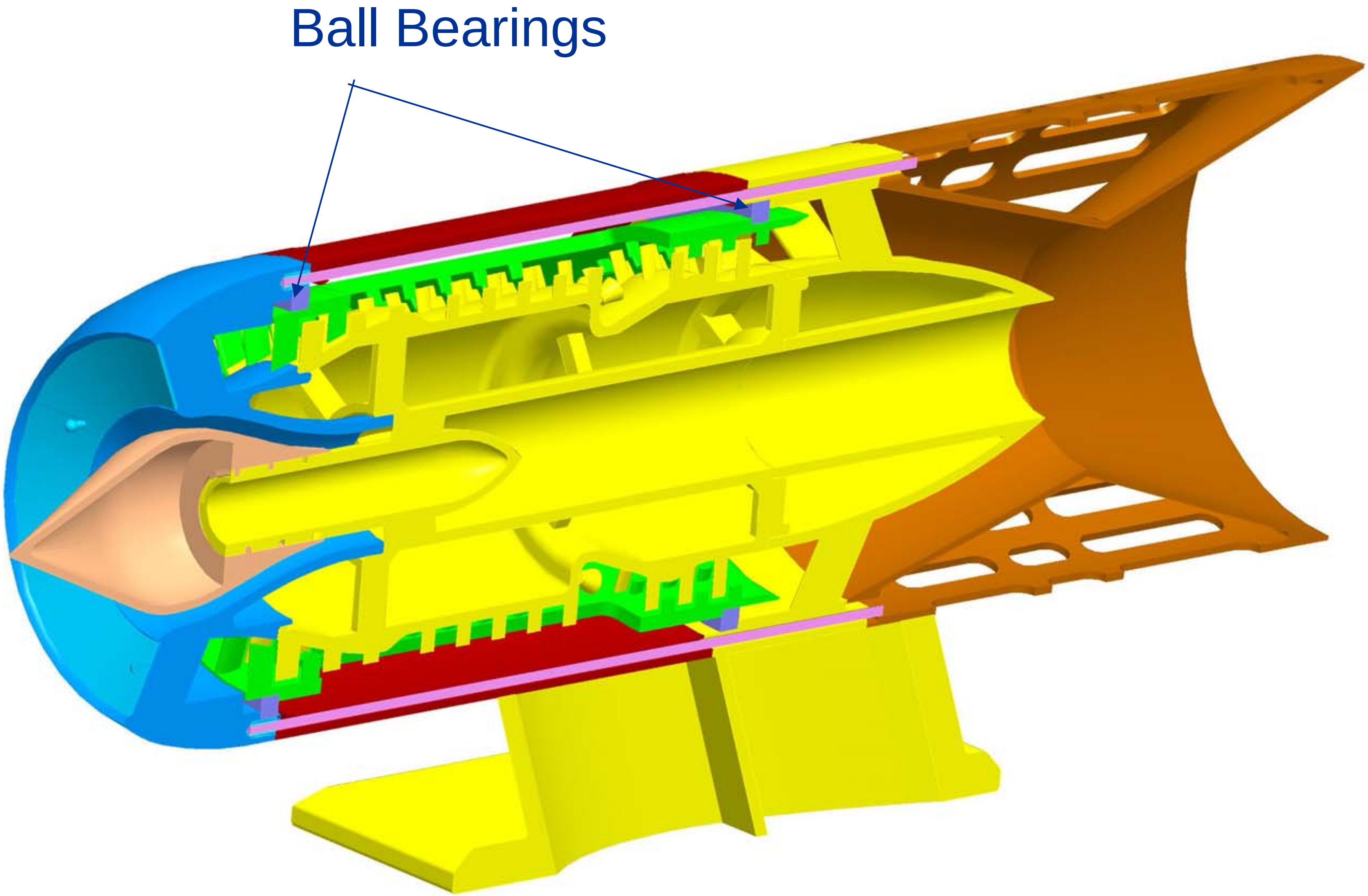
EXOSKELETAL ENGINE CONCEPT: Cutaway Views



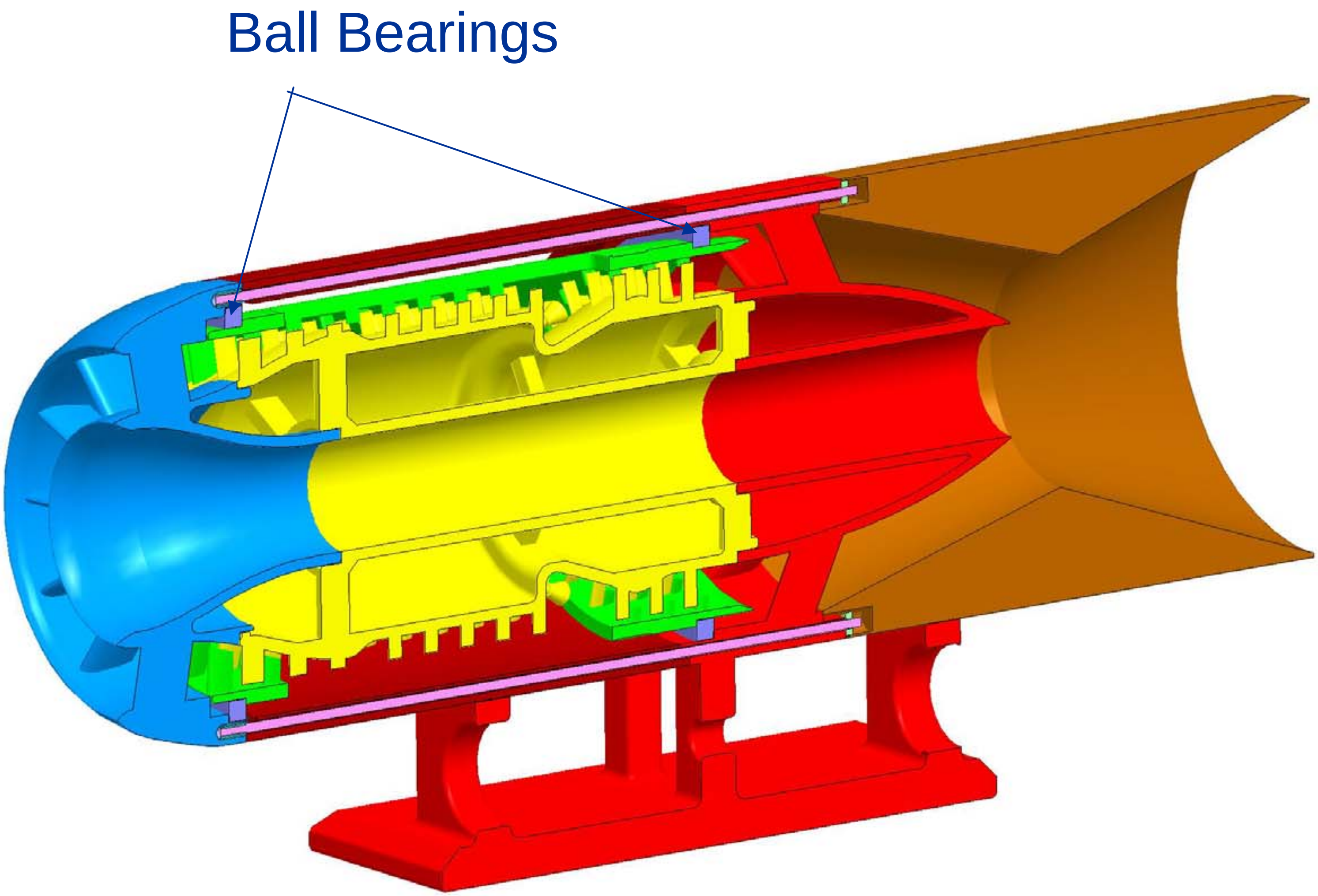




3/2000 Rapid Prototype - Solano



8/2001 Rapid Prototype - Blaser



2/2001 Rapid Prototype – Blaser

Figure 1: Exoskeletal Mach 5 Turboramjet Concept

Fig: 1a

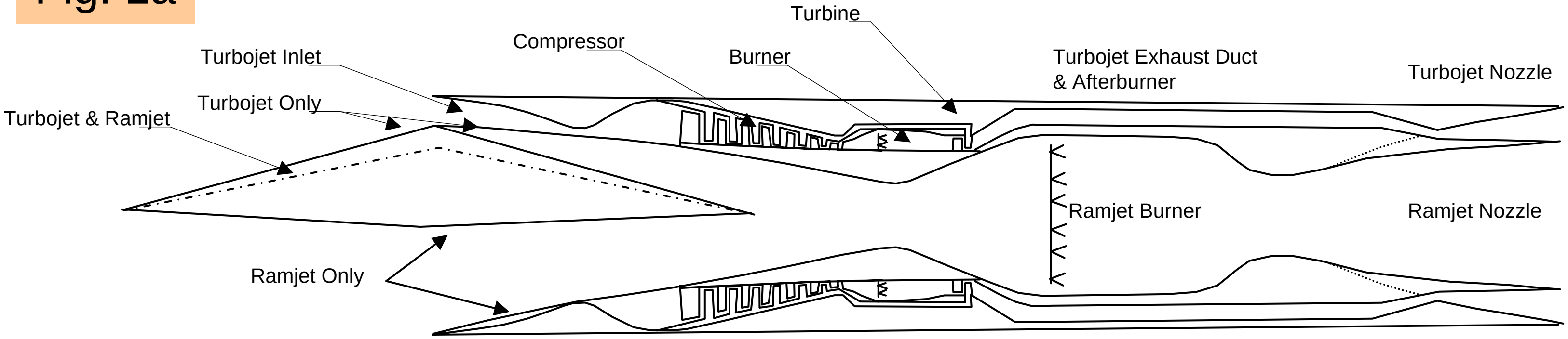
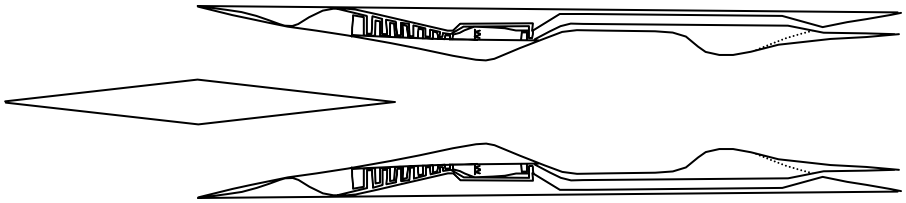


Fig: 1b

Ramjet Mode (Mach 3 – 5)



Diameter-------------22 inches
Length--------------112 inches

Inlet Maximum Areas
Turbojet-------------130 sq in
Ramjet---------------364 sq in

“The New Kid on the Block”

PLASMA/MHD Flow Control/Propulsion

2 TYPES OF PLASMA:

(1) WEAKLY-IONIZED PLASMA (WINP)
These are artificially generated **COLD** plasmas via various methods (Fast Ionization Wave (FIW) method).
Electron temperature about 1-2 eV (up to 30,000K), Gas temperature about 600K (max), etc. Plasma can be highly localized in flow-field.

(2) REENTRY PLASMAS (Nature’s mandate)
Generally fully-ionized in shock layer (gas-cap) of reentry vehicles.
Gas temperatures to 20,000K (Apollo 13, Mach 35 at start of entry).

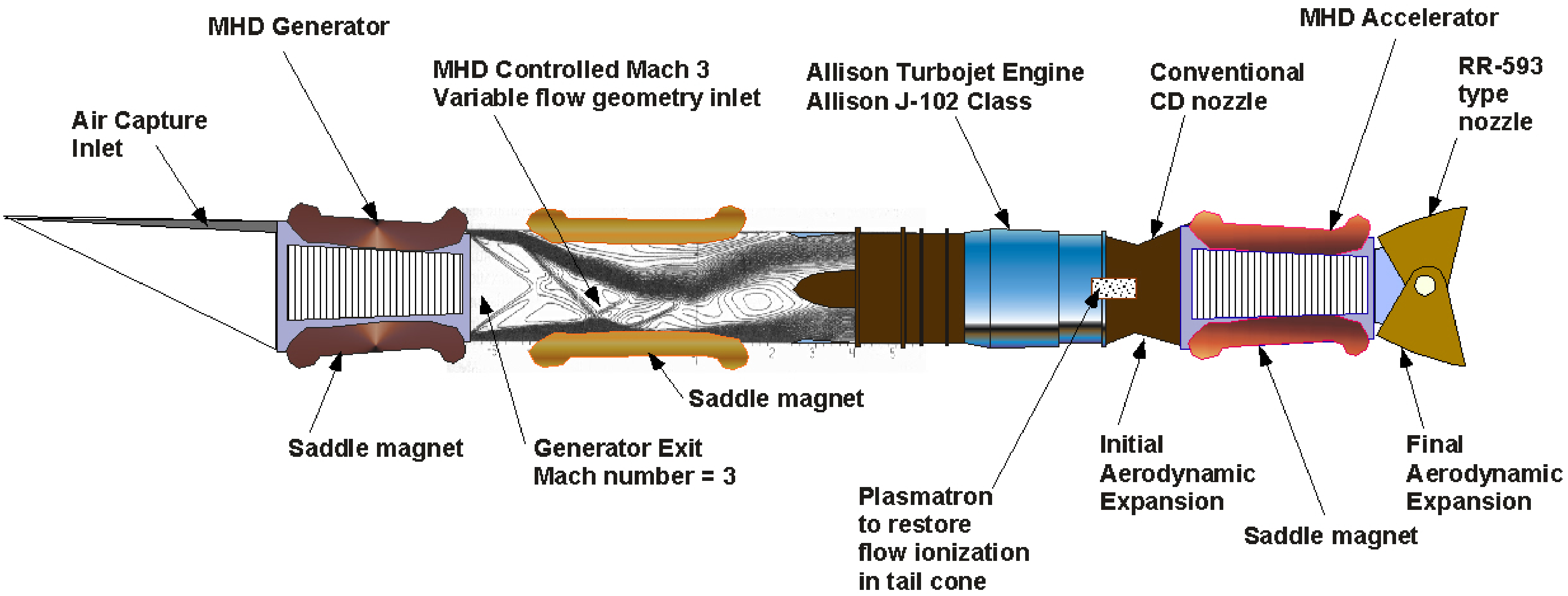
GRC Interests and Efforts:

(1)Plasma Assisted Ignition and Combustion

(2)Hydrocarbon Fuel Reforming

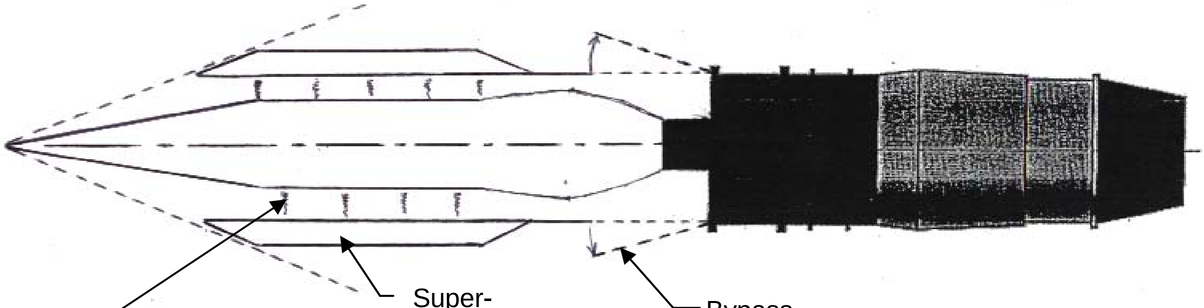
(3)MHD-Controlled turbojet (Magnetogasdynamic Power Extraction and Flow Conditioning in a Gas Turbine)

GENERAL ARRANGEMENT OF MHD-CONTROLLED TURBOJET HIGH-SPEED PROPULSION



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

MHD/Turbojet Engine Concept



Mach 7 Inlet

MHD Generator
(Axisymmetric
Hall Type)

Variable geometry
Mach 3 Inter-stage
region

Turbojet Engine
Allison J-102 Class

e-beam guns

Super-
conducting
Magnet

Bypass
doors

MHD Power Extraction Patent

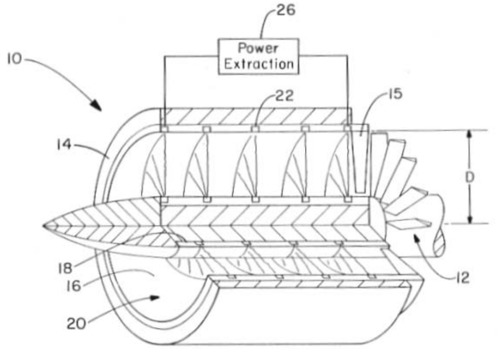
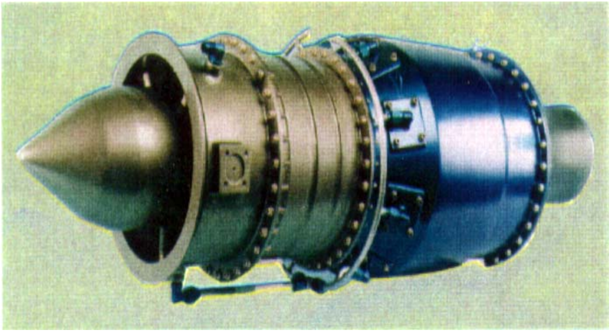
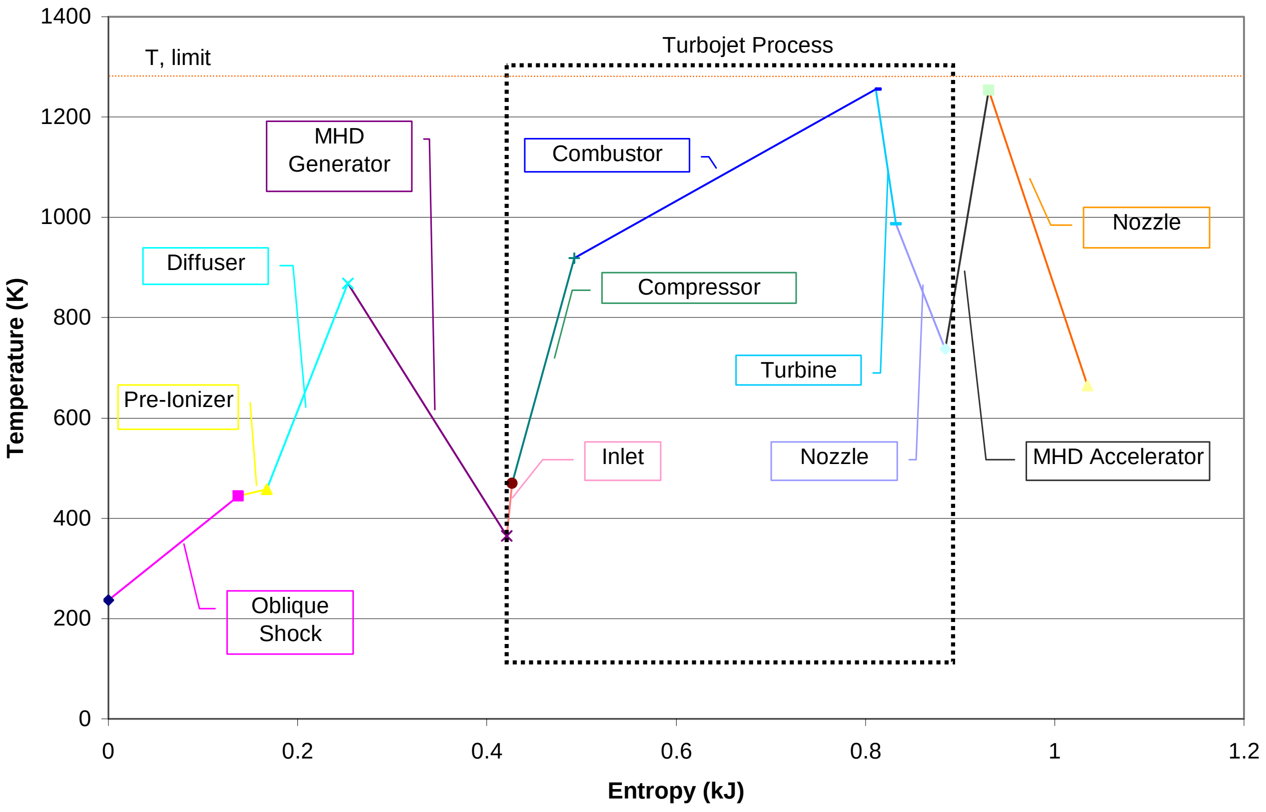


FIG.-1

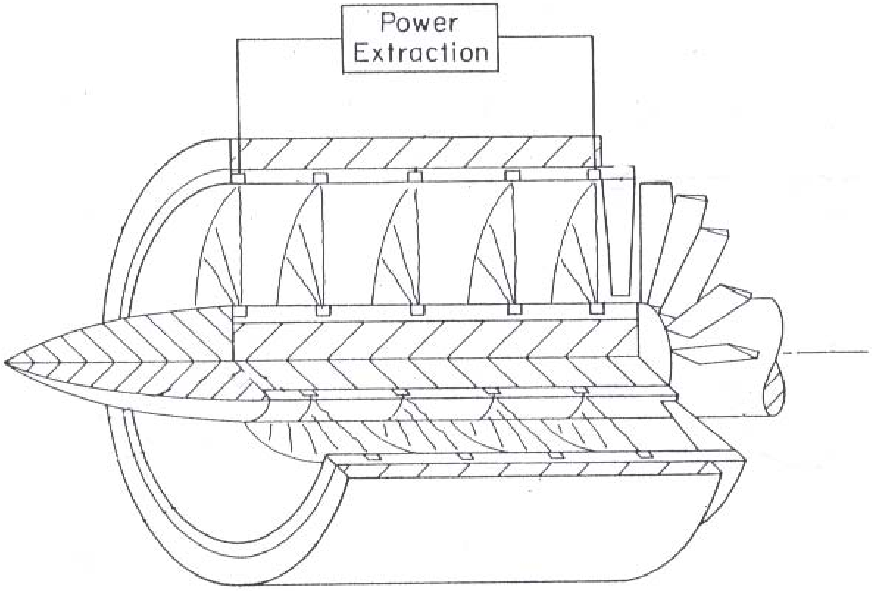


T-S Diagram for MHD bypass concept



Annular Hall Type MHD Generator for Use with a Turbojet

(Based on Hall Thruster Design for Space: E-beam Ionization, or pulsed FIW techniques ~ preferred)



US patent (6,696,774 B1; 2004). Issued to GRC (Blankson and Schneider).

Preliminary Results

MHD Bypass Engine Application –OSU Evaluation

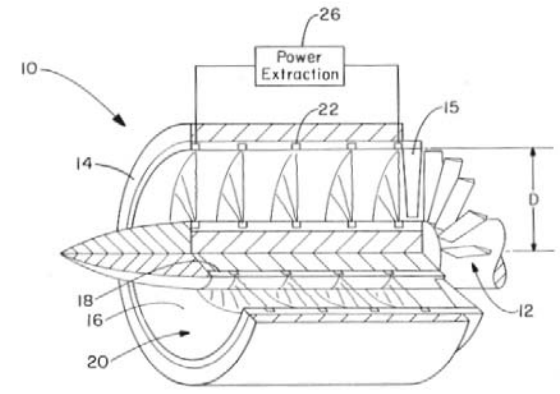
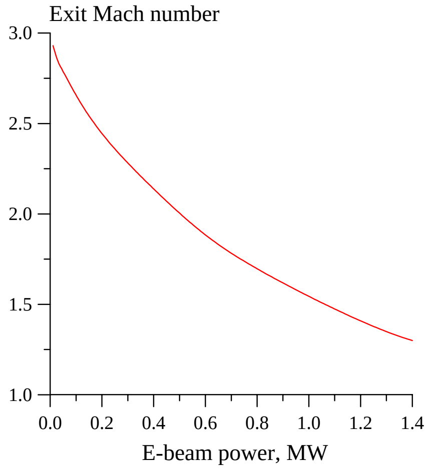
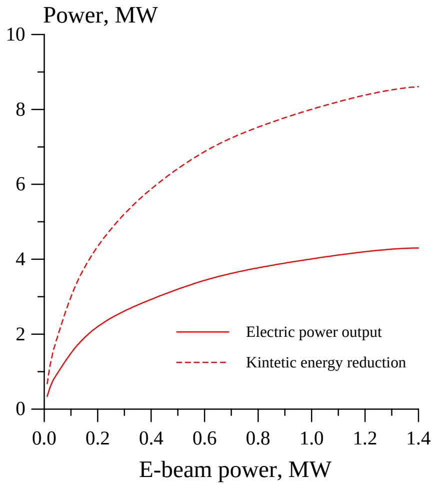


FIG.-I





- •OSU quasi-1D, nonequilibrium MHD air flow code used
- •Ionization by uniformly distributed e-beam
- •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

MHD – CONTROLLED TURBOJET: Initial Analysis

- **MHD Engine Bypass Concept has 2 Major Advantages:**

  (1) Turbomachinery operates over entire Mach range from 0 – 7. No mode transition. No deadweight engines carried aloft.

  (2) Hydrocarbon Fuel only.

- **CRITICAL TECHNOLOGIES in: Ionizers (electron beam, microwave, high-voltage pulsed power, etc devices) for sustained conductivity, design of the "Interstage region"**

- **ISSUES: Approaches to reduce total pressure loss must be explored, Energetics/economics of this cycle: Competitive with new available technologies**.

- This Mach 7 (projected) Engine is based on the combination to **two proven technologies** (each over 50 years old) : (1) Deceleration of an ionized supersonic/hypersonic stream by applied magnetic fields (MHD) and, (2) Conventional Turbomachinery.

Opportunities for Research (Plasma/MHD)!

- **Innovative research** needed to continue advances in component development as well as to be able to control the hypersonic environment within, on and near the vehicle, e.g. thermal management systems.
- **New design variables** for the 21st Century based on our ability to exploit: flowfield electrical and magnetic properties, take advantage of interdisciplinary synergies

--- **Plasma Devices** (plasma and applied electromagnetic fields). Vehicle control using plasmas. Shock-wave control.

--- **MHD (Magnetohydrodynamic)** Flow manipulation (Russian AJAX). Ability to extract energy from flowfield and use it as an asset, not a liability.

- **High Energy-Density Fuels** for airbreathing engines.
- Dramatically lighter, more durable, high temperature **TPS** (thermal protection systems).
- **Control of** boundary layer transition: use of non-conventional methods.
- **Develop Accurate and Efficient Simulation of Hypersonic flows with Plasma/MHD/Chemistry. Nonequilibrium molecular multi-temperature (no-thermal) plasma flow models (computational code) incorporating key processes of charged species production and removal, a master equation for the vibrational levels of diatomic molecules, a Boltzmann equation for plasma electrons, and a Poisson equation for the electric field. Ohm's law to include, ion slip effects, Hall currents, and electron pressure gradients.**

NASA Glenn University Student & Faculty Opportunities

- *LERCIP (Lewis' Educational and Research Collaborative Internship Program)*
  - *Undergraduate & Graduate Students*
  - *January 31 Application Deadline*
- *MUST (Motivating Undergraduates in Science & Technology Program)*
  - *Focused on engaging students from underserved and underrepresented groups*
  - *February 2 Application Deadline*
- *GSRP (Graduate Student Research Program)*
  - *January 31 Application Deadline*
- *USRP (Undergraduate Student Research Program)*
  - *January 31 Application Deadline (summer session)*
  - *February 29 Application Deadline (fall session)*
  - *October 22 Application Deadline (spring session)*
- *NGFFP (NASA Glenn Faculty Fellowship Program)*
  - *February 15 Application Deadline*

http://www.nasa.gov/offices/education/programs/index.html

$$j_x = \sigma_\beta\left[-\frac{\partial\varphi}{\partial x} + vB + \beta\left(\frac{\partial\varphi}{\partial y} + uB\right)\right]$$

$$j_y = \sigma_\beta\left[-\frac{\partial\varphi}{\partial y} - uB + \beta\left(-\frac{\partial\varphi}{\partial x} + vB\right)\right]$$

$$\frac{\partial j_x}{\partial x} + \frac{\partial j_y}{\partial y} = 0 \;\; \left(\sigma_\beta = \frac{\sigma}{1+\beta^2}, \beta = \alpha B\right)$$

$$\Delta\varphi + \frac{\partial\varphi}{\partial x}\left[\frac{\partial \ell n \sigma_\beta}{\partial x} + \beta\frac{\partial \ell n(\beta\sigma_\beta)}{\partial y}\right] + \frac{\partial\varphi}{\partial y}\left[\frac{\partial \ell n \sigma_\beta}{\partial y} - \beta\frac{\partial \ell n(\beta\sigma_\beta)}{\partial x}\right]$$

$$= \sigma_\beta^{-1}\left\{\frac{\partial}{\partial x}\left[B\sigma_\beta(v + \beta u\right] - \frac{\partial}{\partial y}\left[B\sigma_\beta(u - \beta v)\right]\right\}$$

$$f_x = j_y B,\; f_y = -j_x B,\; q = -j_x\frac{\partial\varphi}{\partial x} - j_y\frac{\partial\varphi}{\partial y}$$

Summary and Conclusions

- **GRC is aligned with and focused on achieving NASA mission success.**
- **GRC has a unique combination of talented people and one-of-a-kind facilities & tools, well aligned to our eight interdisciplinary core competencies.**
- **Our core competencies have positioned us to strategically encourage and accommodate further partnerships and investment.**
- **NUMEROUS COLLABORATIVE RESEARCH OPPORTUNITIES EXIST.**
- **Opportunities exist in Aero and Space, across the Mach number range.**

BACKUP SLIDES

MHD Energy Bypass with a Conventional Turbojet:

MAGNETOGASDYNAMIC POWER EXTRACTION AND FLOW CONDITIONING FOR A GAS TURBINE

(In partnership with Ohio State University.) !!!

This Mach 7 (projected) Engine (an AJAX-like development) is based on the combination to 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.

Note that the turbomachine operates over the entire Mach number range (0-7) (ie. **no dead-weights, no mode-transition!).**

Additional Information is available at:

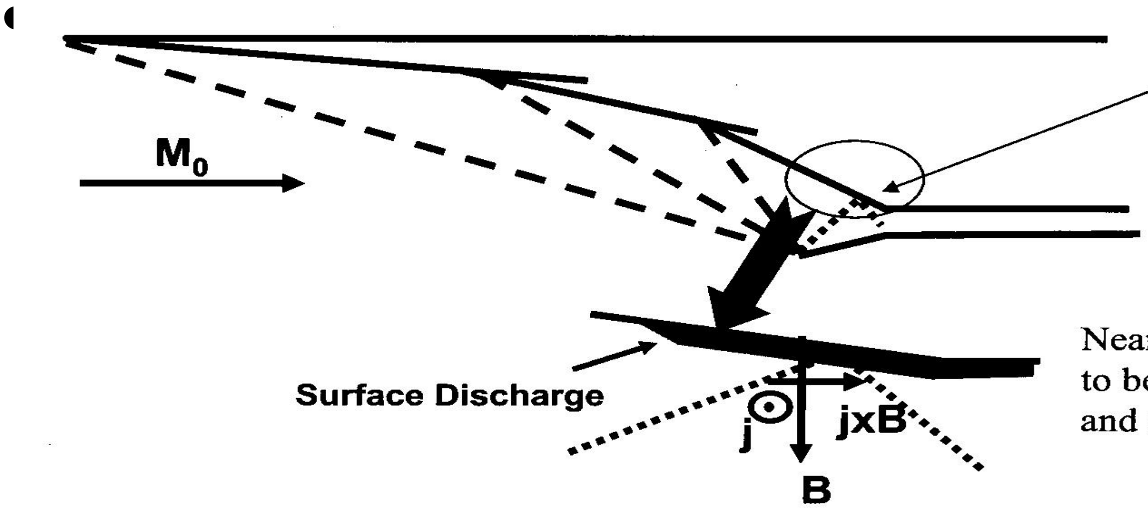
(1) AIAA Paper 2003-6922, presented at 12th AIAA International Space Planes and Hypersonic Systems Conference, 15-19 December, 2003/Norfolk, VA.

(2) S.N.B. Murthy and I.M. Blankson, "MHD Energy Bypass for Turbojet-Based Engines", IAF-00-5-5-05, presented at 51st International Astronautical Congress, October 2-6, 2000, Rio de Janeiro, Brazil

(3) "Magnetogasdynamic Power Extraction and Flow Conditioning for a Gas Turbine", AIAA Paper 2003-4289 (Also NASA/TM – 2003-212612).

(4) US Patent (6,696,774 B1, 2004) Magnetogasdynamic Power Extraction and Flow Conditioning in a Gas Turbine. (Issued to Blankson and Schneider)

Plasma for Flow Control: MHD Flow Control in Inlets



Shock-Wave/Boundary-Layer Interaction Limits Allowable Internal Contraction Ratio

Near-surface MHD flow control to be used to suppress separation and expand inlet operability

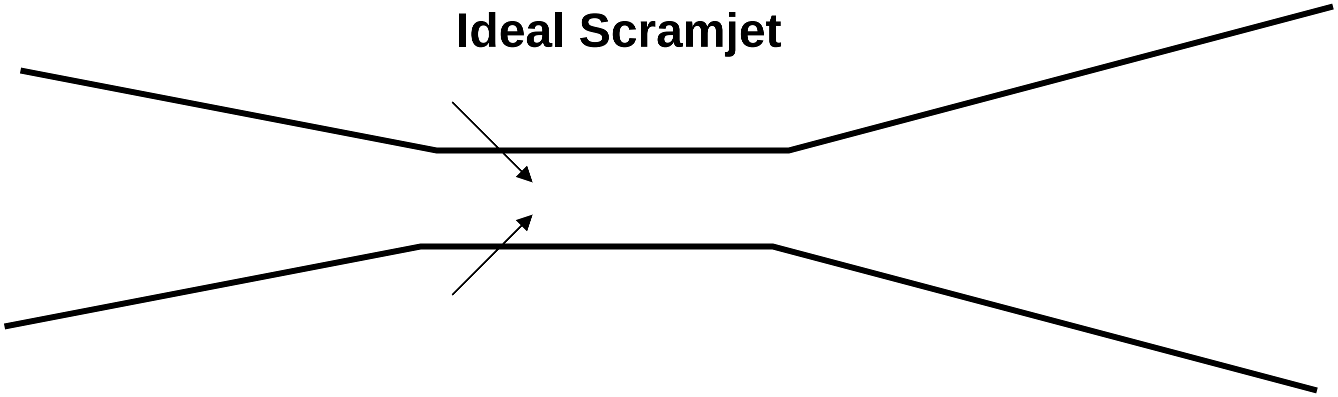
Advantages of Technique
Limited ionization region
Small volume required with high B-field
Near wall velocities low, $St = \sigma B^2 L/\rho U$
Phenomenon is controllable

Disadvantage of Technique
Power input required
Mass penalty due to magnet

Plasma Assisted Combustion

(**Ignition, Combustion, Fuel Reforming).**

Ideal Scramjet



- Minimize energy required for ignition and flame stabilization, expand combustion limits
- Provide volumetric ignition (off-wall)
- Thermal vs Non-equilibrium processes
- <u>Various mechanisms are being investigated</u>: plasma jet generators, microwave torches, pulsed nanosecond discharges, RF discharges, microwave assisted combustion, surface microwaves, subcrirical microwaves, etc.

Plasma Assisted Combustion:

Opportunities

- Directions for Research
  - Minimizing energy input
  - Distinguishing between homogeneous and heterogeneous mixtures
  - Operation at realistic pressures and temperatures
  - Investigation of heavier hydrocarbons
  - Investigation of liquid fuels
  - Refinement of reaction mechanisms

MHD/PLASMA: POTENTIAL APPLICATIONS

- Turbomachinery-based MHD Energy bypass engines: extends the operating range of gas-turbines to Mach 7. (Energy Extraction)
- Jet noise reduction
- Aerodynamic drag and heat transfer reduction of aerospacecraft
- Localized control of hypersonic separated flows, flow control of hypersonic inlets, mitigation of off-design issues for airbreathers, etc
- Rearrangement of thermal and mechanical loads on structural elements of aircraft
- Steering/maneuvering of aircraft by electromagnetic forces and moments
- Sonic boom mitigation
- Control of high altitude (rarefied environment) vehicles: replacement of RCS with plasma actuators.
- CEV: Applications in Martian atmosphere
- CEV: Lunar dust mitigation and control
- PLASMA-ASSISTED IGNITION/COMBUSTION
- SPACE SITUATIONAL AWARENESS:Track/ID unknown reentry vehicle from EM signature
- ANTI-RADAR CLOAKING
- Protection against RF MICROWAVE radiation

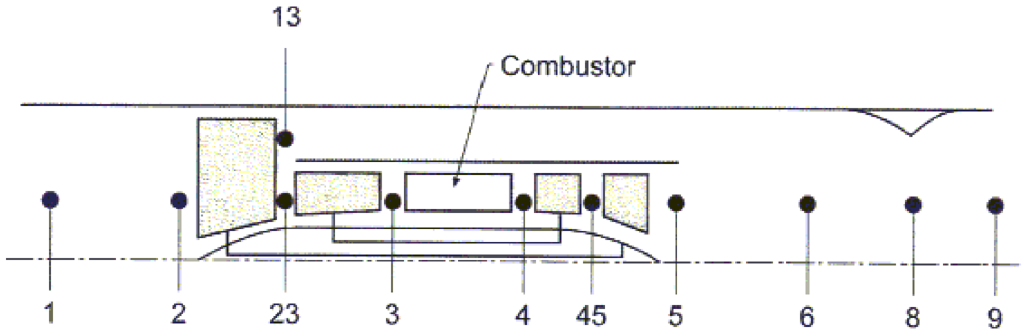
OBJECTIVES:

(1) 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 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) or a ramjet, individually, or in various combined configurations. The MHD power generator is a novel GRC invention (Patent pending). **The resulting engine is a revolutionary power-plant capable of flight at Mach 7.**

(2) Develop a MHD CE/SE code capable of computing **viscous compressible MHD flows with real-gas effects.** The CE/SE method requires no special treatment to maintain the divergence-free condition on the magnetic field. (Regarding the methodologies used for solving MHD equations, the finite difference and the finite volume methods based on the flux-vector splitting or the approximate Riemann solvers occupy the dominant position. The main difficulty in these methods is the imposition of the divergence-free condition **div B =** 0 for the magnetic field, which results in a loss of the hyperbolicity of the ideal MHD equations. Violating the **div B =** 0 constraint leads to loss of momentum and energy conservation.)

(3) **Ultimate goal is to establish a competitive capability in MHD/Plasma Technology for aerospace applications.**

Cycle Model of Turbofan Engine with MHD



Station numbering scheme

(afterburner not shown)

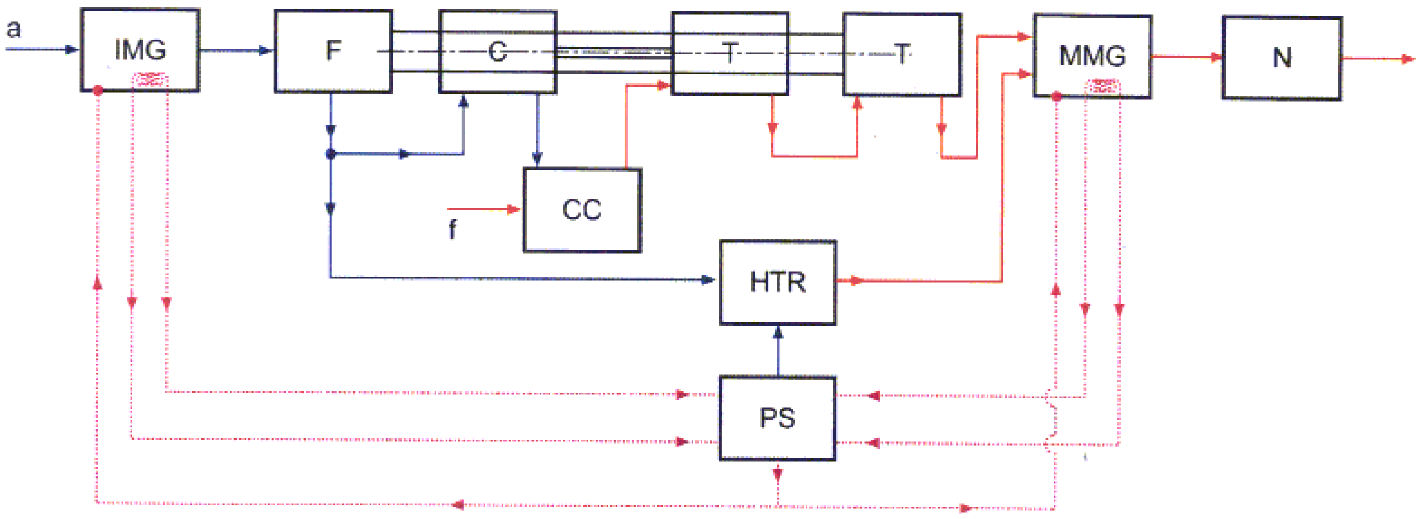
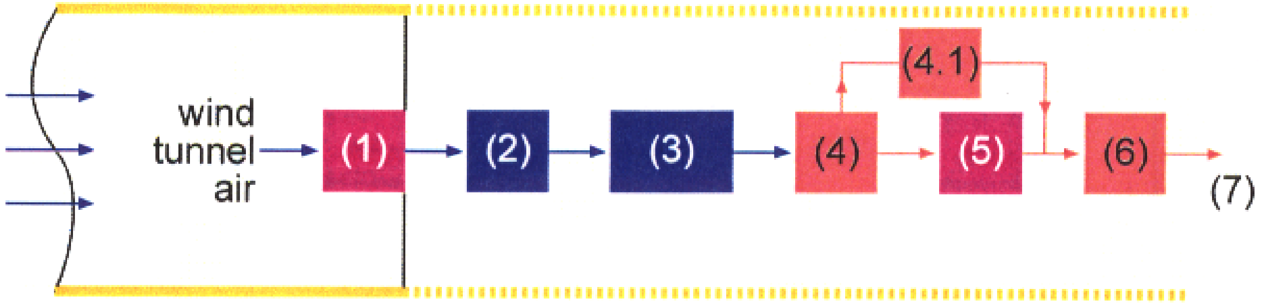


Figure 1. Turbofan Engine with MHD
IMG: Inlet Magnetic Generator
MMG: Mixer Magnetic Generator

Experimental Method for Conducting an Engine Test



(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.

FUTURE PLASMA/MHD RESEARCH

- **Innovative research** needed to continue advances in component development as well as to be able to control the hypersonic environment within, on and near the vehicle, eg. thermal management systems.
- **New design variables** for the 21st Century will be based on our ability to exploit: flowfield electrical and magnetic properties, take advantage of interdisciplinary synergies

--- **Plasma Devices** (plasma and applied electromagnetic fields). Vehicle control using plasmas. Shock-wave control.

--- **MHD (Magnetohydrodynamic)** Flow manipulation (Russian AJAX). Ability to extract energy from flowfield and use it as an asset, not a liability.

- **High Energy-Density Fuels** for airbreathing engines
- Dramatically lighter, more durable, high temperature **TPS** (thermal protection systems).
- **Control of** boundary layer transition.
- IONIZER – research into more efficient, low cost and low-weight ionizers.
- Applications of MHD to Reentry Vehicle Control – Extreme high temperatures and heat transfer rates in shock layer of blunt-nosed hypersonic vehicle.
- Ionization and subsequent conductivity of air in shock layer –natural to consider electromagnetic control of this class of flows.
- Prior analytical work indicates: a magnetic field applied to this conductive shock layer could use the Lorentz force to increase drag (by opposing fluid motion) of vehicle, and by slowing the flow near the surface, reduce heat transfer and skin friction.
- Old Proposed Example – MAGNETIC FLAP on Apollo capsule – electromagnetic coil used to produce lift and control moments.

MAGNETOGASDYNAMIC POWER EXTRACTION:

OSU Nonequilibrium Flow Code

- **Master equation for vibrational populations of N_2 and O_2**
- **Boltzman equation for electrons**
- **Nonequilibrium air chemistry including ion-molecule reactions**
- **Nonequilibrium electron kinetics (ionization, recombination, and attachment)**
- **One-dimensional gas dynamics**
- **Generalized Ohm's law**
- **Validated by comparing with electric discharge, shock tube, and MHD experiments**

Details in AIAA 2003-4289

Plasma and MHD Aerodynamics

- Thermal Energy Deposition
- Electrostatic forces for low speeds
- Lorentz force for higher speeds

Micro-Flow Control

- Input O(ε) → Effect O(1)

- Maslov et.al. - Vortex Sep. Control
- Cybyk et.al. – SparkJet
- Leonov et. al. – Airfoil BL Control
- Starikovskii et. al. – Airfoil BL Control
- Bobashev et. al. – MHD BL Control

- Significant interest in **low-speed** apps.
- Corke et. al. – Overview of DB Actuator
- Enloe et. al. – DB Actuator Physics

Large Scale Flow Control

- Efficiency >> 1 required

- Kolesnichenko et. al. – Drag Reduction
- Timofeev et. al. – Sliding Discharge
- Khodataev et. al. - μwave efficiency
- Macheret et. al. – MHD Lift generation

MHD Energy Bypass with a Conventional Turbojet:

MAGNETOGASDYNAMIC POWER EXTRACTION AND FLOW CONDITIONING FOR A GAS TURBINE

(In partnership with Ohio State University.) !!!

This Mach 7 (projected) Engine (an AJAX-like development) is based on the combination to 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.

Note that the turbomachine operates over the entire Mach number range (0-7) (ie. **no dead-weights, no mode-transition!).**

Additional Information is available at:

(1) AIAA Paper 2003-6922, presented at 12th AIAA International Space Planes and Hypersonic Systems Conference, 15-19 December, 2003/Norfolk, VA.

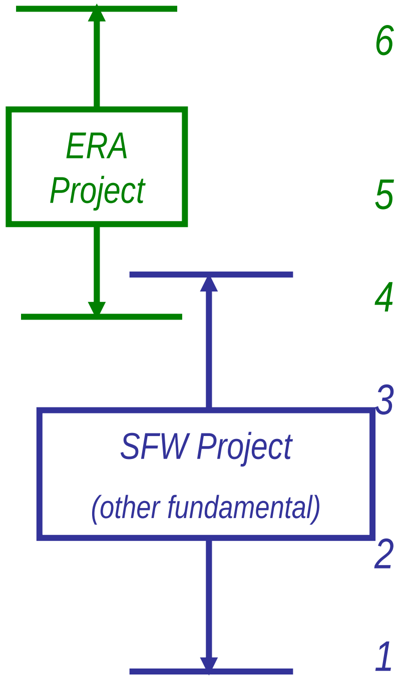
(2) S.N.B. Murthy and I.M. Blankson, “MHD Energy Bypass for Turbojet-Based Engines”, IAF-00-5-5-05, presented at 51st International Astronautical Congress, October 2-6, 2000, Rio de Janeiro, Brazil

(3) “Magnetogasdynamic Power Extraction and Flow Conditioning for a Gas Turbine”, AIAA Paper 2003-4289 (Also NASA/TM – 2003-212612).

(4) US Patent (6,696,774 B1, 2004) Magnetogasdynamic Power Extraction and Flow Conditioning in a Gas Turbine. (Issued to Blankson and Schneider)

Technology Maturation Perspective on SFW and ERA Projects

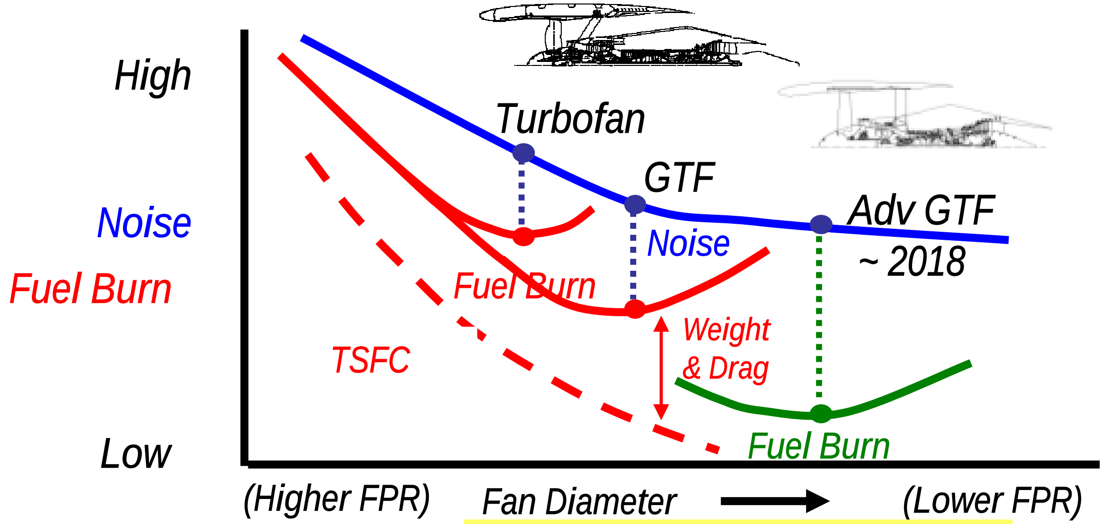
TRL	NASA Definition (NPR 7120.8)
9	Actual system flight proven through successful mission operations
8	Actual system completed and “flight qualified” through test and demonstration
7	System prototype demonstrated in operational environment
6	System/sub-system model or prototype demonstration in relevant environment
5	Component and/or breadboard validation in relevant environment
4	Component and/or breadboard test in laboratory environment
3	Analytical and experimental critical function, and/or characteristic proof-of-concept
2	Technology concept and/or application formulated
1	Basic principles observed and reported



Propulsion Airframe Integration

UHB Installation that minimizes or avoids performance penalties

Increased size of system may drive need for alternate configurations



Lord, Sepulveda, et al

PAI Challenges Increase

- *Increasingly large diameters present increasingly difficult installations for conventional low wing configurations, and may require alternate configurations/installations to take advantage of propulsive efficiency*

  …. significant vehicle level trade space to explore

Proposed Task Approach

Approach;

The overall objective requires the accomplishment of several tasks: (2-year research and 2-year build and test follow-on).

1. CE/SE MHD Code development for multidimensional flows.
2. CE/SE MHD Code development incorporating viscous and real-gas flows.
3. Conduct cycle analyses to establish the operating conditions for a jet engine cycle, that are optimal for kinetic energy transfer from inlet air to a downstream location in the engine.
4. Establish a model for a jet engine with energy bypass for determining the design and operating conditions in which the thrust-to-weight ratio, thrust per unit mass of fuel consumption, and effectiveness of energy utilization are maximized;
5. Establish the resulting engine thrust to weight ratio and thermodynamic efficiency, using electrical conductivity, magnet mass, and MHD energy conversion as some of the parameters. Conduct a preliminary design for the scheme.
6. Conduct laboratory scale tests to experimentally establish the efficiency of the MHD conversion of the kinetic energy of the externally ionized gas in the proposed scheme.
7. Outline a method of conducting a test on a jet engine for demonstrating and assessing the performance of a MHD energy bypass system incorporated into a jet engine. The jet engine under consideration is the existing Allison J-102

Relationship to Other Work and Collaborations

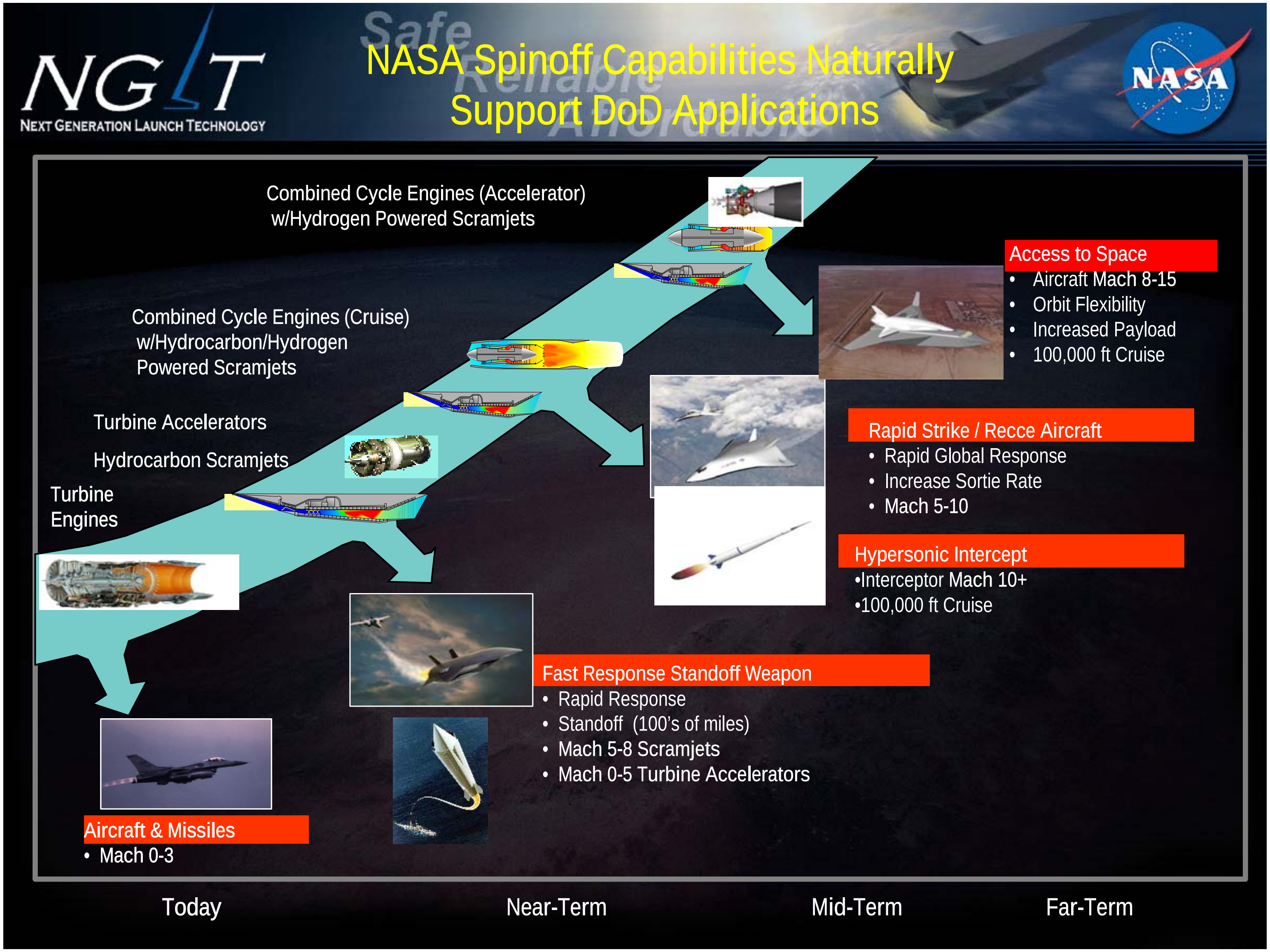
A preliminary assessment of this concept has shown feasibility. Major efforts are needed in the design of the ionizer. The concept is a novel approach for optimum design of combined-cycle engines that incorporate turbomachinery and MHD. This is essential to aeronautics and especially to Glenn Research Center because of the incorporation of turbine engine cycles into this integrated turbine-MHD configuration. The Power and On-board Propulsion Division has numerous programs in electric propulsion for in-space applications as well. This research is directly related to ongoing work in NASA and industry (see attachment) to develop both low-cost alternatives for access-to-space, and novel concepts for high Mach number propulsion an airframes exploiting MHD and plasmas.
OSU: model and calculation scheme on a parametric basis for the interaction between a weakly ionized air stream and an applied magnetic field, when the ionization is undertaken with different means (e.g. High – energy microwaves, electron beam,) SANDIA: Microwave ionization technology. IVTAN (Russia) Pulsed Microwave ionization.

Proposed Work for FY2003 – FY2006 (I)

- Year 1
  - Make improvements to CE/SE Code for viscous and 3-D flows and Test MHD codes using known results.
  - Incorporate Boltzman and Poisson solvers in CNPD code
  - Develop master equations for vibrational levels of air
  - It is desired to develop in-house, a numerical capability (CFD code) to simulate the above phenomena under a single code platform that combines electromagnetics and classical and real gas dynamics.
  - Refine operating conditions for a MHD bypass turbo-jet cycle.
  - Development of INLET system for Bypass Engine from Mach 0 – 7.
  - In phase-I of this work we intend to study MHD interactions with inlet processes in a simple two-dimensional or axi-symmetric geometries using CE/SE code.

  - To formulate the technical conditions for the feasibility of the MHD Bypass engine cycle that incorporates a gas turbine powerplant.

APPLICATIONS SPECTRUM



NGLT
NEXT GENERATION LAUNCH TECHNOLOGY

NASA Spinoff Capabilities Naturally Support DoD Applications

Combined Cycle Engines (Accelerator) w/Hydrogen Powered Scramjets

Combined Cycle Engines (Cruise) w/Hydrocarbon/Hydrogen Powered Scramjets

Turbine Accelerators

Hydrocarbon Scramjets

Turbine Engines

Access to Space
- Aircraft Mach 8-15
- Orbit Flexibility
- Increased Payload
- 100,000 ft Cruise

Rapid Strike / Recce Aircraft
- Rapid Global Response
- Increase Sortie Rate
- Mach 5-10

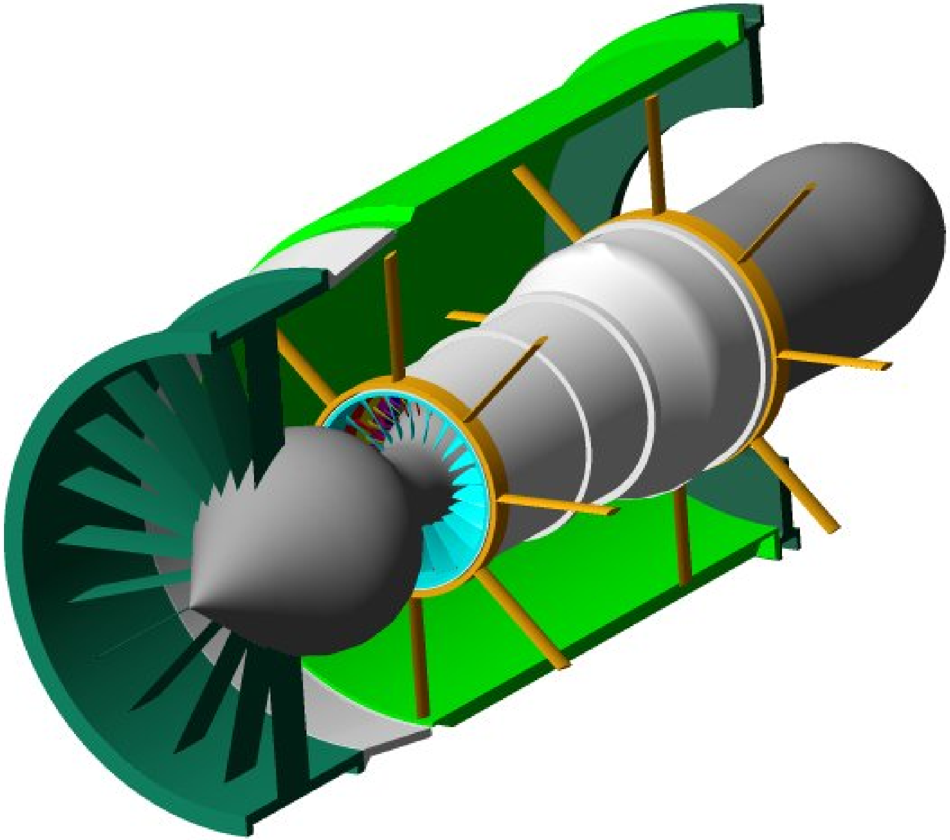
Hypersonic Intercept
- •Interceptor Mach 10+
- •100,000 ft Cruise

Fast Response Standoff Weapon
- Rapid Response
- Standoff (100's of miles)
- Mach 5-8 Scramjets
- Mach 0-5 Turbine Accelerators

Aircraft & Missiles
- Mach 0-3

Today | Near-Term | Mid-Term | Far-Term

Exoskeletal Engine Cutaway View



A FEW CHARACTERISTICS OF THE HYPERSONIC FLOW FIELD

- **Definition of Hypersonic Flow**: ----- Mach number
  (Velocity Energy/Temperature Energy) ~ M squared

- **Energy in the Flowfield** --- KE of Space Shuttle at Reentry =1/20th Energy of Hiroshima Bomb. KE is dissipated in about 15 minutes (ballistic entry). Could exploit “lifting reentry” but requires higher L/D.

- **High stagnation temperatures**, high heat transfer to vehicles, Viscous interaction, shock-boundary layer interaction… (stagnation Enthalpy curve, Edney’s chart, X-15 Pylon)

- **Real-gas effects (M > 8):** Changes in gas characteristics around vehicles, changes in chemical constituents of air

- NEW PARADIGMS: **(1) Speed**, Global Range from CONUS
  - Airbreathing vehicles (Mach 0 - 10+?)
  - Transatmospheric options (Mach to 25)

  (2) Thermal management for slender air-breathing vehicles.

WHAT'S NEW! RESEARCH AND DEVELOPMENT FOR SUSTAINED AIRBREATHING HYPERSONIC FLIGHT

- **COMPONENT OPERABILITY OVER ENTIRE MISSION MACH RANGE.**
- **Long-duration hypersonic flight for slender lifting vehicles.**
- **Aerothermal load prediction methods and validation. Prediction of complex shock-wave systems, shock/boundary layer interactions, wake interactions, flow separation interactions evolving spatially and temporary.**
- **Six -degree-of-freedom dynamic motion - hypersonic vehicle maneuverability and agility. Vortex dynamics under high-enthalpy, viscous non-equilibrium chemically reacting conditions. Unsteady aerodynamics characteristics of maneuvering hypersonic flight vehicles.**

Boundary-layer transition - a critical aspect of hypersonic flight vehicle design.

PROPULSION/AIRFRAME INTEGRATION
: Some aspects of Vehicle Design

The need to carefully integrate the propulsion system with the vehicle airframe for optimum overall performance is a *fundamental* requirement of air-breathing hypersonic vehicles.

API/PAI consists of all aspects of how the propulsion system is integrated into the vehicle including, type and location of inlets, nozzles, and engine cycles.

For the MACH 4 – 8 air-breathing missile, additional elements of integration include: structures, warhead, controls, guidance, and launchers.

Thermal management is another aspect of propulsion integration and is critical to defining a practical hypersonic vehicle concept since the fuel is usually the only heat sink available at hypersonic speed.

Other aspects of API include:

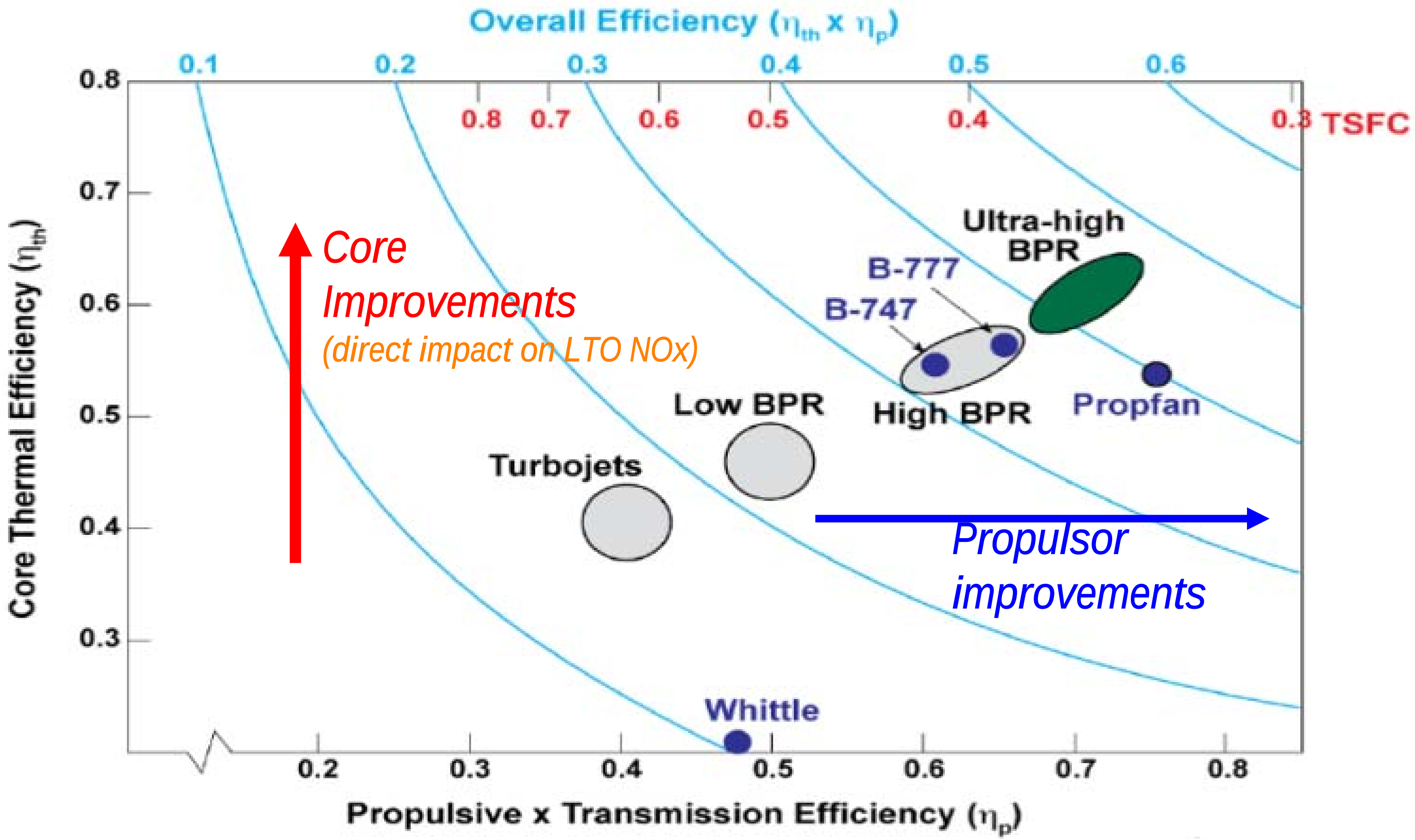
Non-Intrusive Diagnostics (Interference-free experimental data, ie. Without fouling the experiment).

Ability to extrapolate W.T. to Flight using Test Data that lacks Simulation of key Parameters.

Ability to Validate design Methodology with Flight data.

Propulsion Systems

Propulsion system improvements require advances in propulsor and core technologies



Core Improvements

(direct impact on LTO NOx)

Propulsor improvements

Alan Epstein
Pratt & Whitney Aircraft

Propulsor Technology

Ultra high bypass ratio propulsor

Ducted v Unducted trade, noise v efficiency

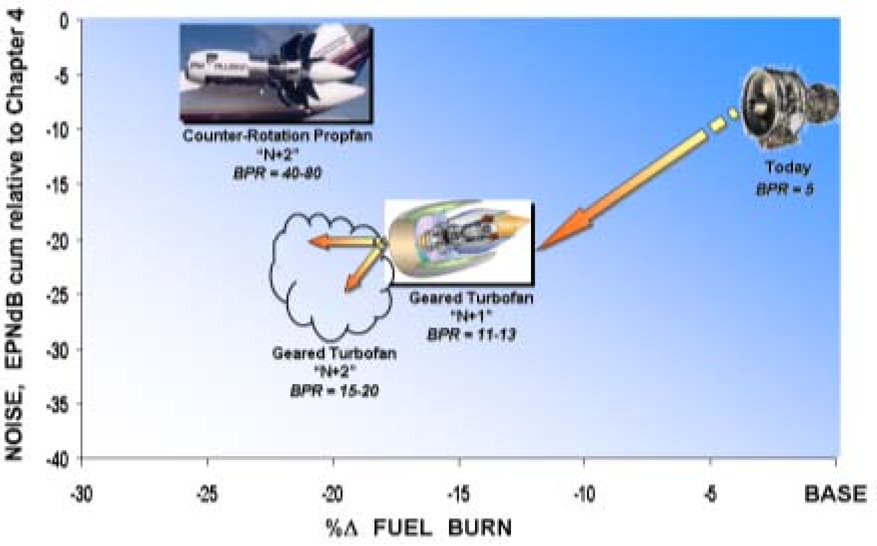
Concepts

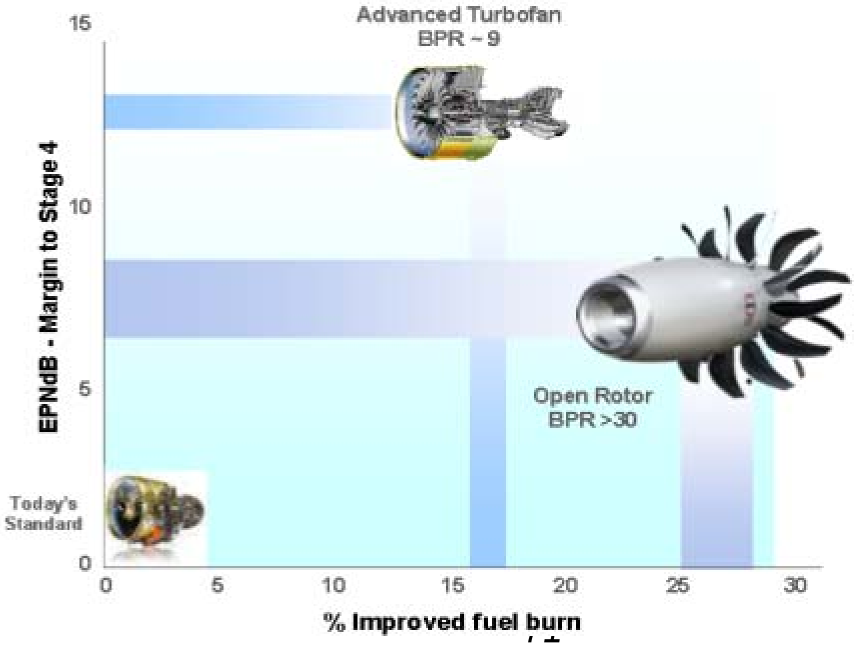
- *Ducted UHB*
    - *short inlets, laminar flow nacelles*
    - *SMA variable area nozzle*
    - *soft vane, over-the-rotor treatment*
- *Unducted UHB (Open Rotor)*
    - *increased rotor spacing, lower blade count*
- *Embedded for boundary layer ingestion*
    - *inlet flow control, distortion tolerant fan*

Challenges

- *Open Rotor - reduced noise while maintaining high propulsive efficiency*

- *Ducted UHB - nacelle weight & drag with increasing diameter*



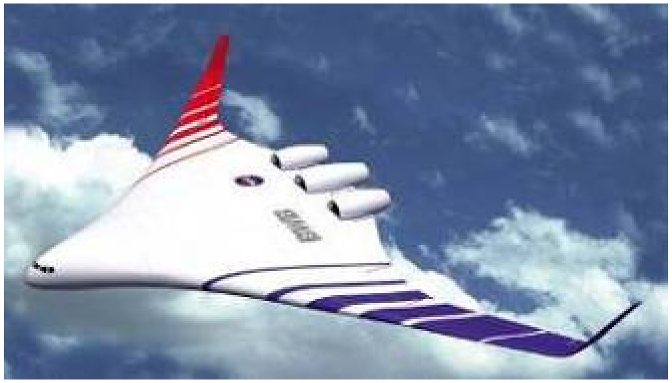


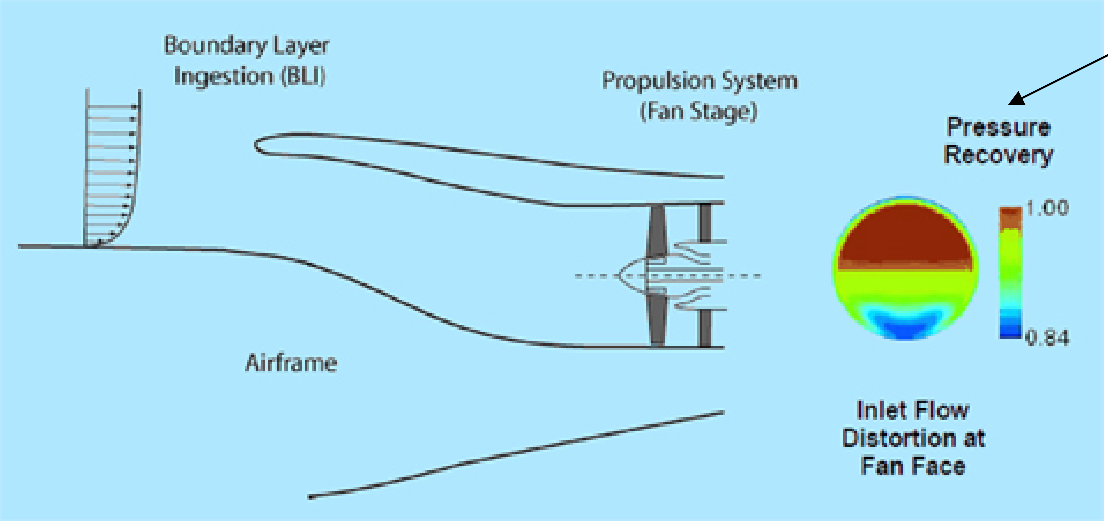
Addressing N+2 Performance – Fuel Burn Technical Challenges

<u>Boeing and NASA Finding</u>:
Noise and fuel burn benefits to HWB aircraft with embedded engines

<u>Challenges</u>: system weight, engine aft noise propagation, and engine-out maneuverability

<u>Recommendation</u>:
Shorten and move engines forward and reduce offset, while retaining BLI





Distorted inlet flow propagated to fan-face for hybrid wing vehicle embedded engine, highlighting <u>challenges</u> in fan design and operation.

APPROACH: COUPLED GROUND-TEST (HTF), THEORETICAL WORK, AND FLIGHT-TEST

INTEGRATION-IN- STEPS: **INTERACTIONS TESTING**: Build-up Methodology, 5 Configurations to be tested (combustor, combustor+isolator, combustor+isolator+inlet, combustor+isolator+inlet+nozzle , … complete engine(vehicle).

TURBO-RAM TRANSITION.

SCRAMJET SCALING: -- issue is lack of a set of scaling parameters for scram engine components and engine as a fully integrated system.

ANALYTICAL AND COMPUTATIONAL METHODS DEVELOPMENT FOR PAI

FLIGHT PERFORMANCE: use of **full scale** flight - test article.

MOTIVATION (Vehicle Scaling,..)

(I) There exists a critical need for an airbreathing hypersonic research vehicle that can be used to demonstrate integrated aerodynamic, propulsion, and structural technologies for hypersonic vehicle design and to develop a research database for reducing the risk involved in the development of operational hypersonic vehicles. (Ideally an air-breathing X-15, X-43 is first step)

(II) The **"technology of integration"** is of unique significance in the development of hypersonic vehicles where each component affects every other component. Unfortunately, engineering practice usually leads to a subdivision by components in the design, development, and manufacturing processes; so that the **"technology of integration"** is not well-advanced.

Consequently, the development of a hypersonic vehicle requires an investigation and demonstration of an integrated design.

Turbo-electric Distributed Propulsion

SFW System Level Metrics

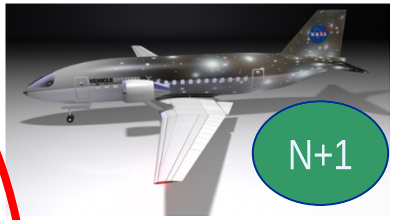
…. technology for dramatically improving noise, emissions, & performance

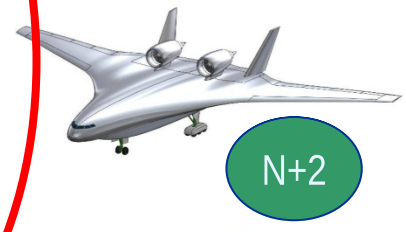
CORNERS OF THE TRADE SPACE	N+1 (2015)*** Generation Conventional Tube and Wing (relative to B737/CFM56)	N+2 (2020)*** Generation Unconventional Hybrid Wing Body (relative to B777/GE90)	N+3 (2025)*** Generation Advanced Aircraft Concepts (relative to user defined reference)
Noise	- 32 dB (cum below Stage 4)	- 42 dB (cum below Stage 4)	55 LDN (dB) at average airport boundary
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-40%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metro-plex* concepts

*** Technology readiness level for key technologies = 4-6

** Additional gains may be possible through operational improvements

* Concepts that enable optimal use of runways at multiple airports within the metropolitan area

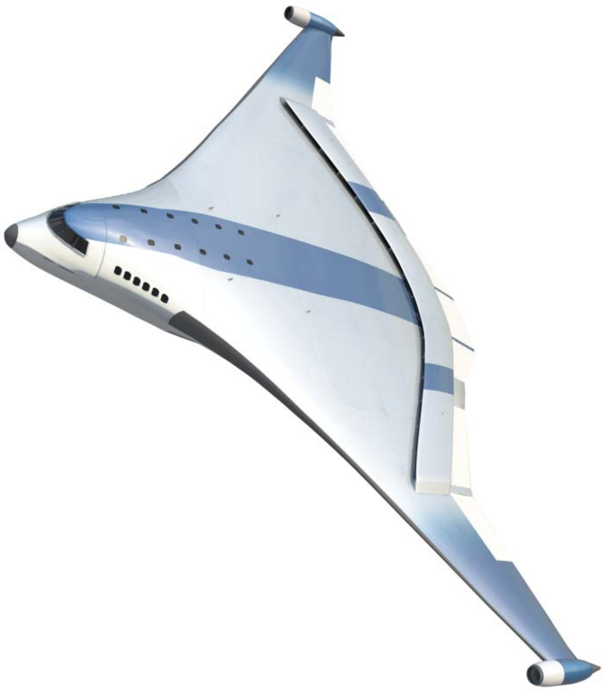




Approach

- *Enable Major Changes in Engine Cycle/Airframe Configurations*
- *Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes*
- *Develop/Test/ Analyze Advanced Multi-Discipline Based Concepts and Technologies*
- *Conduct Discipline-based Foundational Research*

Turboelectric Distributed Propulsion / HWB advantages



Fuel Burn and Emission:

- 2 large engine cores and multiple motor-driven fans give very high bypass ratio.
- Higher propulsive efficiency via spanwise BLI and wake fill-in
- High engine core inlet pressure recovery

Noise:

- Low community noise due to low pressure fans, airframe shielding, climb & descent profile
- Low core jet exhaust noise
- Low cabin noise due to remote location of propulsion systems

Field Length:

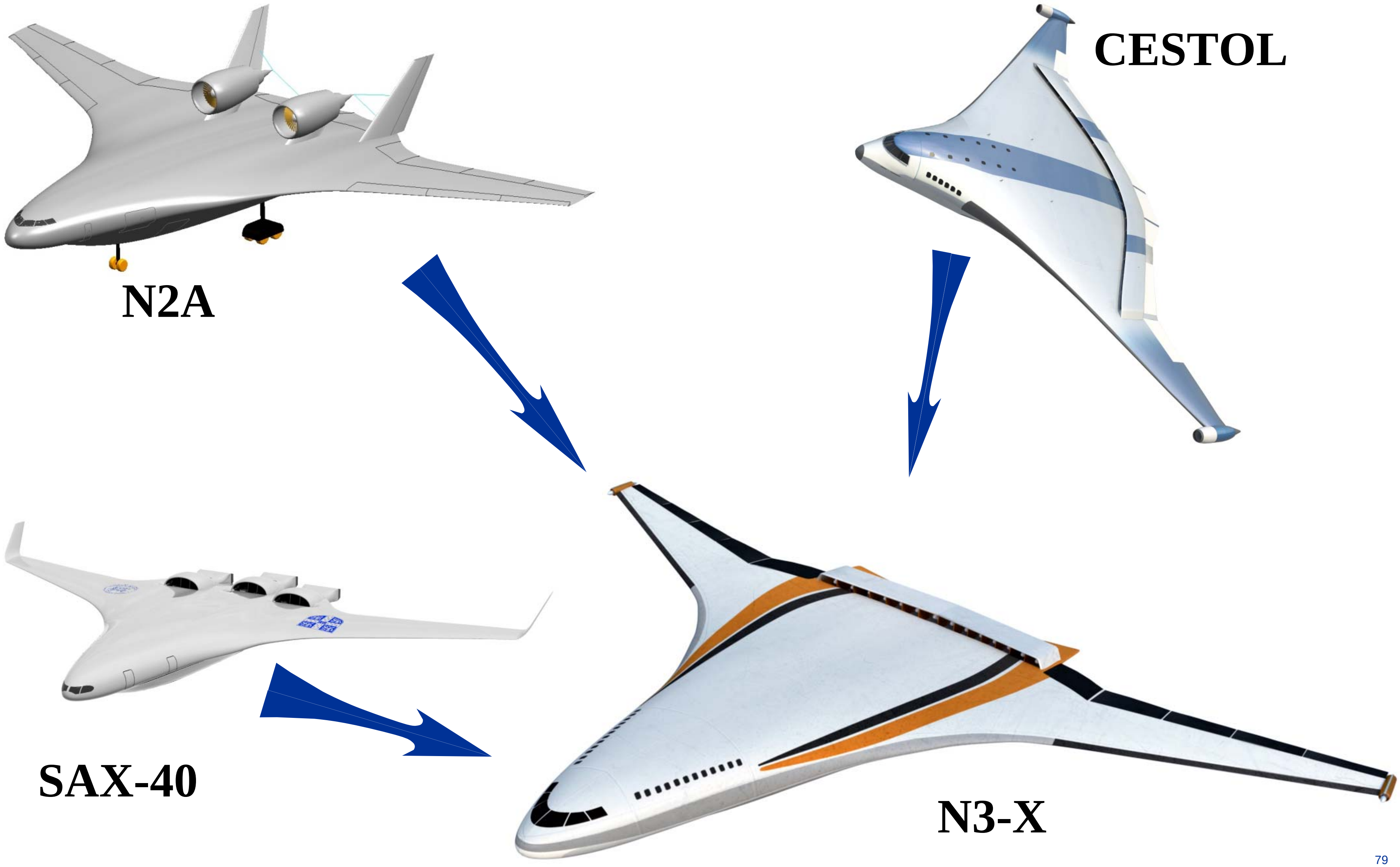
- Direct spanwise powered lift using low pressure fan air

The turboelectric approach contributes to every corner of the NASA's SFW 'N+3' trade space!

Possible advantages of using a turboelectric drive system on an arbitrary “platform”

- Decoupling of the propulsive device from the power-producing device -> High performance and design flexibility
- High EBPR -> High fuel efficiency
- Speed of the power turbine shaft in the turbine engine is independent of the propulsor shaft speed. -> Electrical system as a gearbox with an arbitrary gear ratio
- Minimal engine core jet noise due to maximum energy extraction
- Symmetric thrust with an engine failure
- Asymmetric fan thrust using fast response electric motors
- Cryogenic H2 as fuel and cooling fluid for superconducting system

Turbo-electric Distributed Propulsion Vehicle (N3-X)



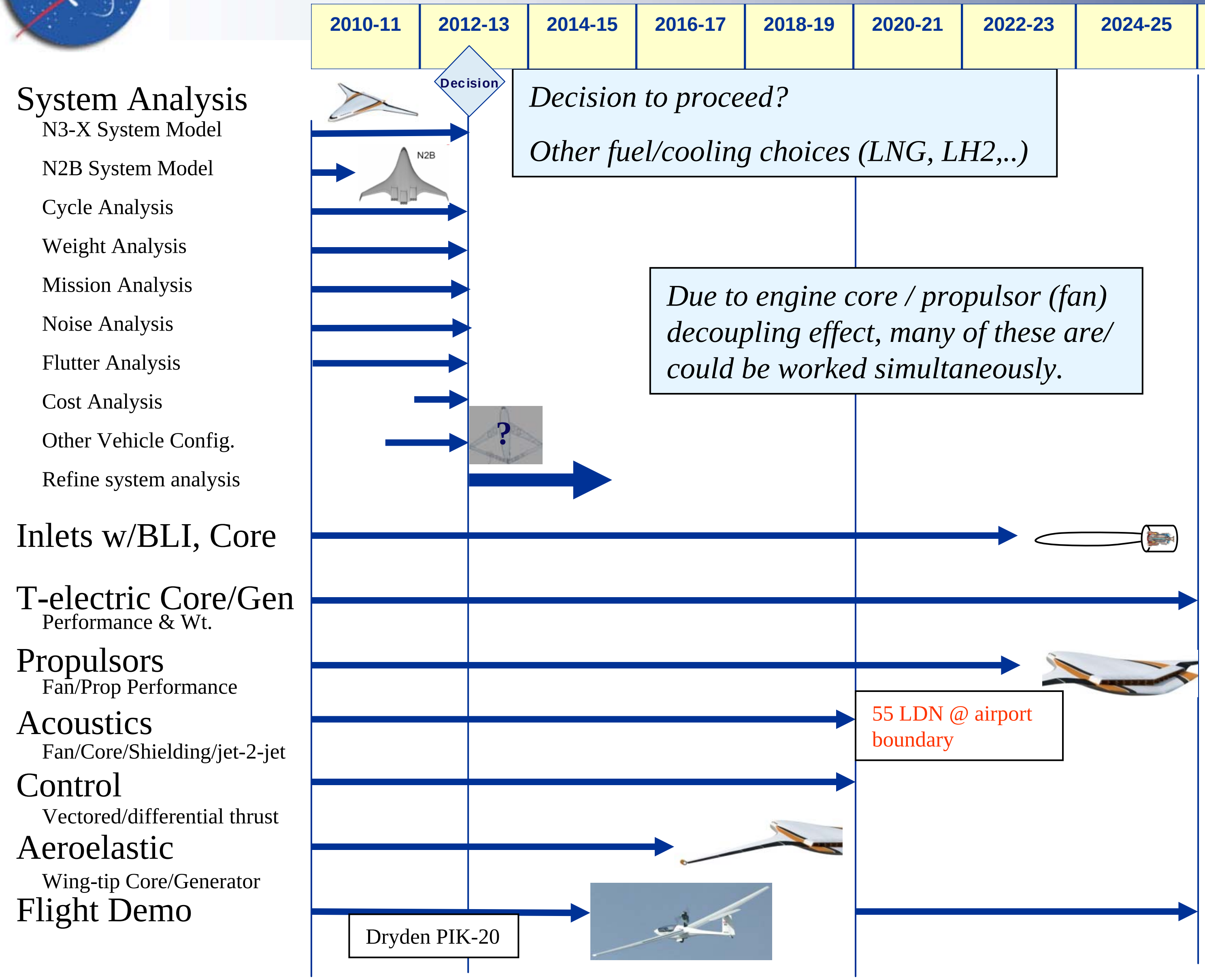
N2A

CESTOL

SAX-40

N3-X

Turboelectric Distributed Propulsion (TDP) Aircraft Roadmap



System Analysis

N3-X System Model

N2B System Model

Cycle Analysis

Weight Analysis

Mission Analysis

Noise Analysis

Flutter Analysis

Cost Analysis

Other Vehicle Config.

Refine system analysis

Decision to proceed?

Other fuel/cooling choices (LNG, LH2,..)

Due to engine core / propulsor (fan) decoupling effect, many of these are/ could be worked simultaneously.

Inlets w/BLI, Core

T-electric Core/Gen
Performance & Wt.

Propulsors
Fan/Prop Performance

Acoustics
Fan/Core/Shielding/jet-2-jet

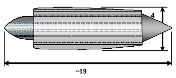
55 LDN @ airport boundary

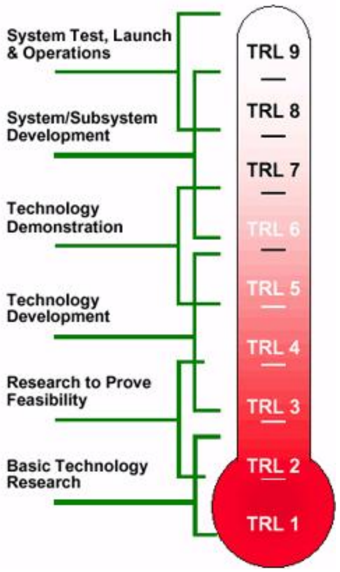
Control
Vectored/differential thrust

Aeroelastic
Wing-tip Core/Generator

Flight Demo

Dryden PIK-20





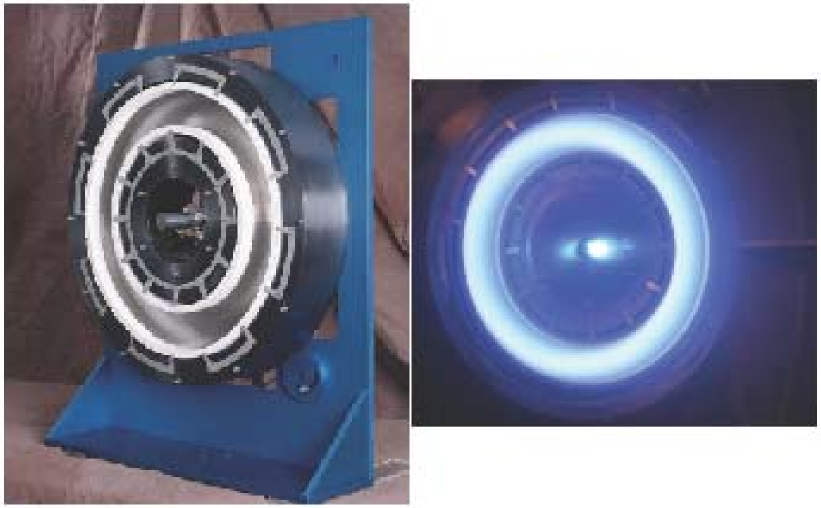
Overall TRL 3 TRL 4/5 TRL 6

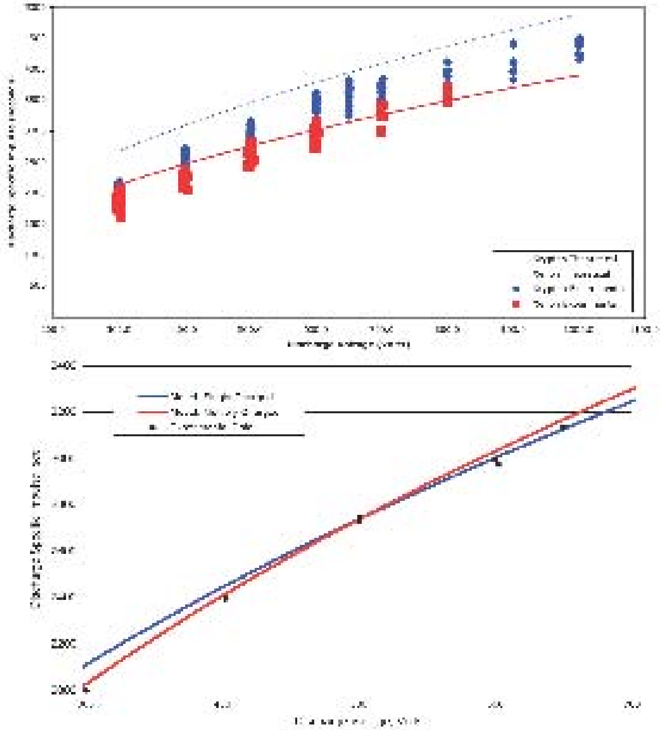
Ioffe Institute Ballistic Range Tests Showing Effects of Weak Ionization
Velocity = 2000 m/s

Without Pre-ionization

With Pre-ionization

Hall Thruster Development at NASA GRC: NASA-457M v1

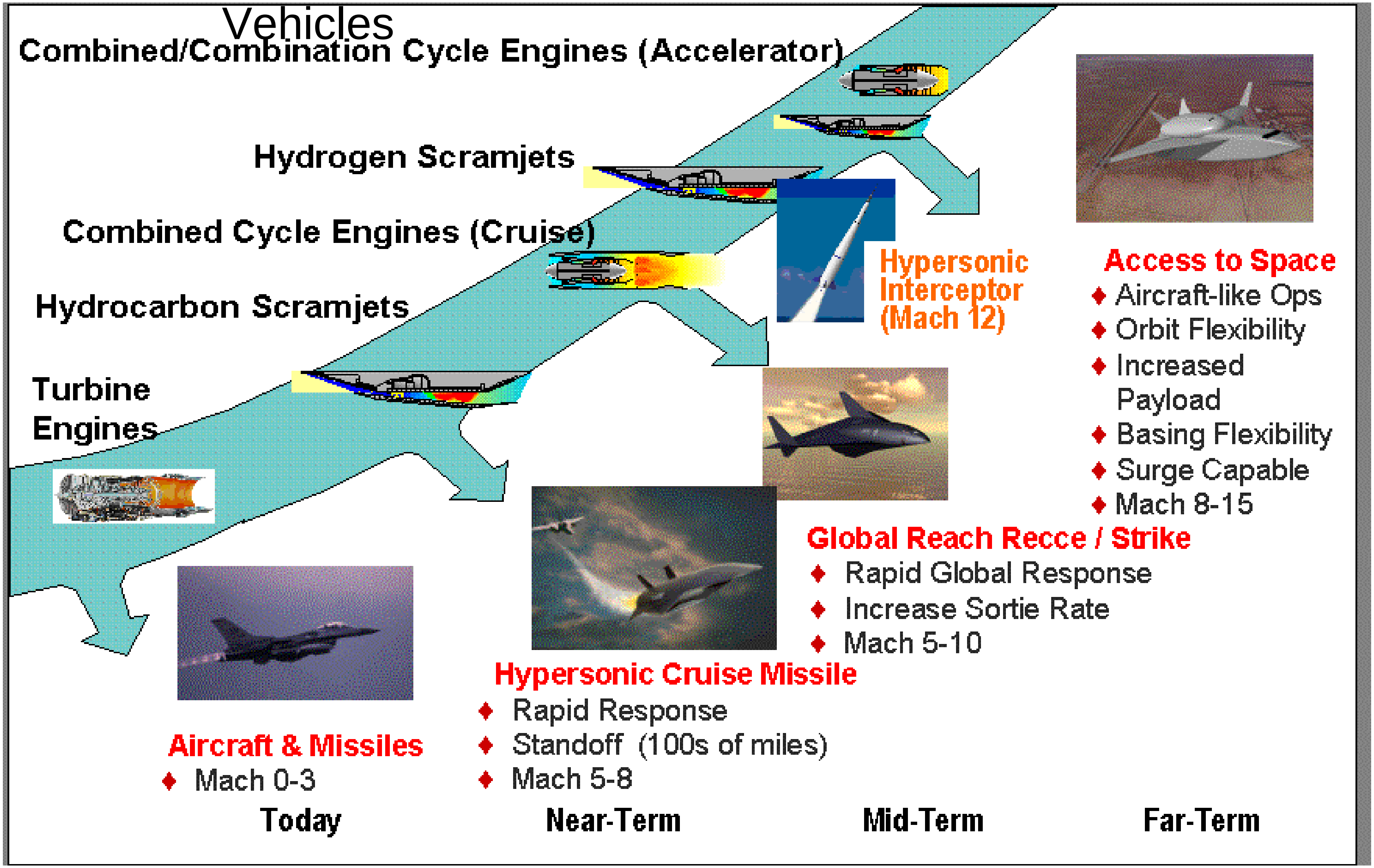




- **NASA's Space Solar Power Concept and Technology Maturation Program initiated preliminary research and development high power Hall thrusters technology to enable space solar power systems and other high power spacecraft**
- **The *NASA-457M v1* was designed to operate at a power level of 50 kW but was tested to a power level of 74 kW**
- **The thruster was operated at discharge voltages between 300 and 1000 V and at discharge currents between 26 and 111A**

- **Xenon propellant thruster operation demonstrated a discharge specific impulse of ~3245 sec and a discharge efficiency of 65% at 72 kW**
- **Krypton propellant thruster operation demonstrated a discharge specific impulse of ~4495 sec and a discharge efficiency of 63% at 50 kW**

Potential Applications of Hypersonic Vehicles



Combined/Combination Cycle Engines (Accelerator)

Hydrogen Scramjets

Combined Cycle Engines (Cruise)

Hydrocarbon Scramjets

Turbine Engines

Aircraft & Missiles
- Mach 0-3

Hypersonic Cruise Missile
- Rapid Response
- Standoff (100s of miles)
- Mach 5-8

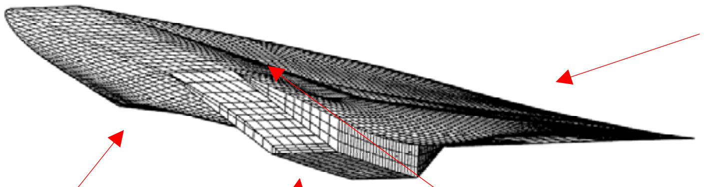
Hypersonic Interceptor (Mach 12)

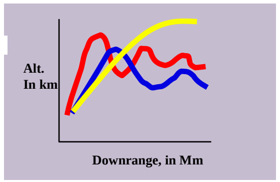
Global Reach Recce / Strike
- Rapid Global Response
- Increase Sortie Rate
- Mach 5-10

Access to Space
- Aircraft-like Ops
- Orbit Flexibility
- Increased Payload
- Basing Flexibility
- Surge Capable
- Mach 8-15

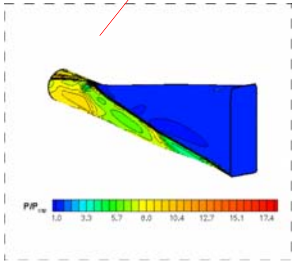
Today	Near-Term	Mid-Term	Far-Term

Air-breathing Hypersonics Research Issues





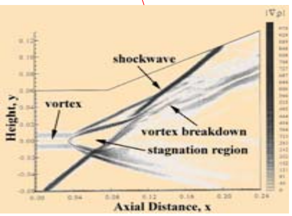
Trajectory selection
Periodic cruise
Multi-staging
Off-design optimization
Transonic drag
Landing/takeoff



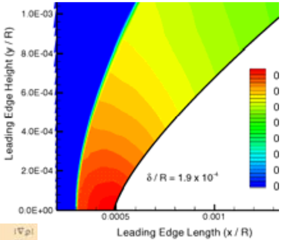
Engine/airframe integration
High efficiency inlet
Starting/unstarting
Unsteady flows

CH4+3/2 CO2->CO+ 2H2O
CO+1/2O2 ->CO2
Kf=1.2x10e10 Kb=5x10e8
SiH4 + 5O2 -> SiO2 +
4H2O

Finite-rate chemistry
Fuel selection and handling
Piloting and enhancers
Nozzle reactions
Engine/attitude coupling



Engine selection - combined cycles
Internal flows
Fuel injection and mixing
Multimode operation



Leading edge physics
Shock location
Off-design aerodynamics
Sharp leading edge heating
Advanced materials
Boundary layers (transition, etc.)

CFD: External/Internal Flows Validation above M=8

Hypersonic Stability and Control

Structural Concepts and Active Cooling.

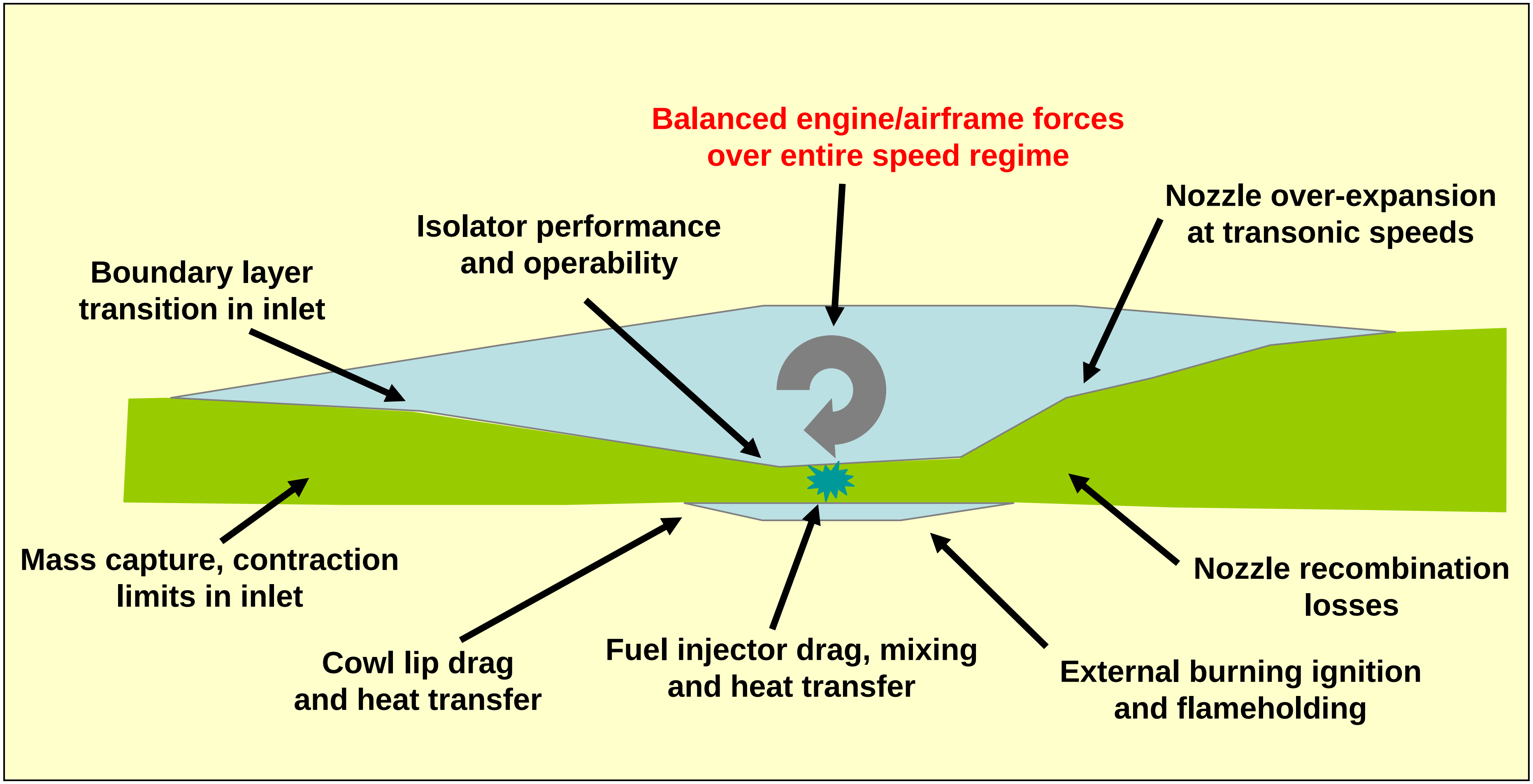
Materials: long-life, high temperature, re-usable. TPS.

Airbreathing propulsion:
- scramjet performance
- flowpath optimization
- installed performance
- engine/airframe integration

TEST FACILITIES !!!!!!!

Aircraft/Spacecraft maneuvering and reentry

Design Challenges Encountered for Airbreathing Hypersonic Vehicles



Balanced engine/airframe forces over entire speed regime

Isolator performance and operability

Nozzle over-expansion at transonic speeds

Boundary layer transition in inlet

Mass capture, contraction limits in inlet

Nozzle recombination losses

Cowl lip drag and heat transfer

Fuel injector drag, mixing and heat transfer

External burning ignition and flameholding

Component Operability over entire mission Mach range!

PROPULSION/ AIRFRAME/CONTROLS INTEGRATION ISSUES ADDRESSED AT NASA

Being worked in R & T base program

- Ground effects at take off
- Transonic drag, base drag reduction
- Forebody design; flow uniformity, boundary layer transition
- Nozzle design; flow chemistry, 3-D effects
- Static/ dynamic stability, controls effectiveness
- Off-design effects; reduced power, inlet unstart
- Installed performance prediction
  - test techniques, powered models
  - nose-to-tail analysis using CFD
- Forebody/ nozzle integrated propulsion tests

Flow Path Optimization

Validity/ accuracy of numerical methods is key factor (especially at conditions of maximum sensitivity)

Forebody/ inlet interactions

- Forebody performance (non-isothermal wall)
- Forebody sensitivity (pitch, yaw, drag)
- B/L state; Shock/ B-L-interaction.

Internal engine flowfield

- Inlet distortion
- B/L entering combustor
- Non-uniformity and chemistry of flow exiting combustor

Nozzle/ afterbody interaction

- Engine exhaust stream influence on aftbody
- Assessment and control of aftbody performance.

Installed Performance Assessment

- Maximum sensitivity/uncertainty at:
  - Transonic speed
  - Hypersonic powered flight M > 5
- Ground effects at takeoff (for canister-mounted vehicles)
- Powered configuration testing
  - Usually done with small subscale models
- Scaling of ground data to flight ((viscous flows, chemistry (real gas effects, etc.))
  - Ground-test vehicle and flight vehicle are same <u>size</u> and <u>shape</u>

Background

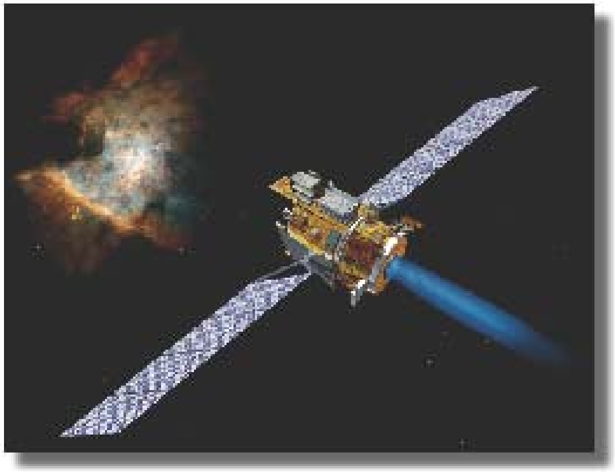
<u>Electric propulsion</u> (EP) uses electrical power to provide kinetic energy to a gas propellant

- Decouples kinetic energy from limitations of chemical energy
- Provides higher exhaust velocities than chemical engines
  - Reduces propellant mass needed to provide a given impulse
  - Allows reduction in launch mass <u>or</u> increase in payload; can provide substantial benefits in mission cost
- Opens launch window over chemical systems in certain scenarios
- Electric propulsion primarily benefits large total impulse missions
  - Orbit raising, repositioning, long-term station keeping
  - Robotic planetary and deep space science missions
  - Precise impulse bits for formation flying (pulsed EP systems)
- Electric propulsion employed on over 200 spacecraft, including
  - EO-1, SMART-1, and DS-1, DAWN, GOCE, Hayabusa

Background

Additional considerations…

- Significantly lower thrust to weight than chemical engines
  - Small but steady acceleration, vs. short-burn chemical engines
  - EP engines must be designed for long life (thousands of hours)



- Increased dry mass due to:
  - Solar arrays
  - Power processing unit
  - Other EP specific hardware
- Spacecraft integration considerations:
  - Electric power requirements
  - Plasma plume and potential EMI

- Propulsion system trades performed to evaluate whether a given mission will benefit from the use of electric propulsion

Subsonic/Supersonic Propulsion Research

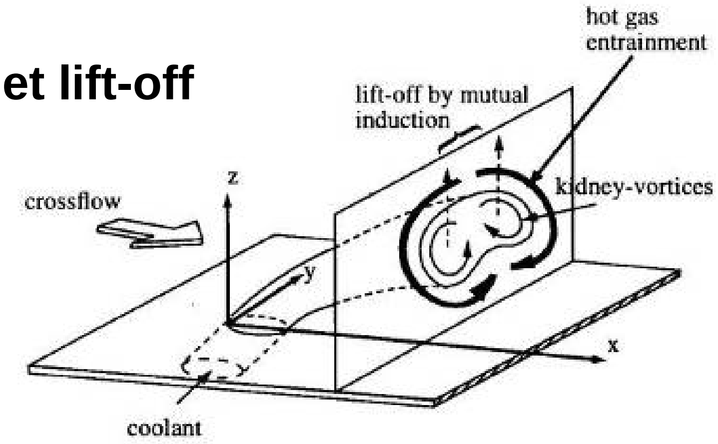
Collaboration Opportunities in the NASA Subsonic Fixed Wing Project

Subsonic and Supersonic Propulsion (Gas turbine research (new topics such as Weakly-ionized Plasmas to turbine blades), Exoskeletal Engine Concept, Embedded propulsion, Distributed Propulsion, Turboelectric Propulsion…

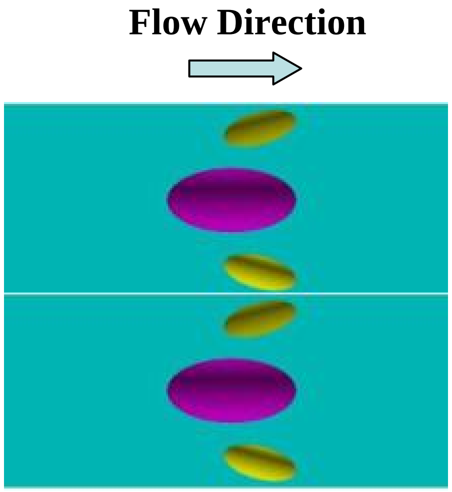
Application of Weakly-ionized Plasmas (plasmas in aero and space, plasma aero flow control, plasma-assisted ignition and combustion, fuel reforming by plasma,…

Advanced Turbine Cooling

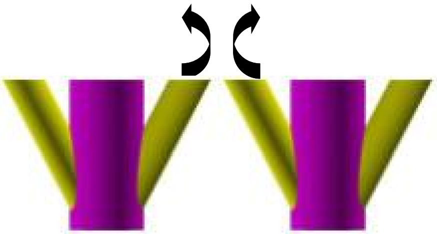
Jet lift-off



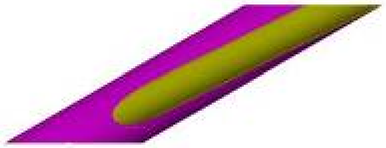
Anti-Vortex Film Cooling Concept



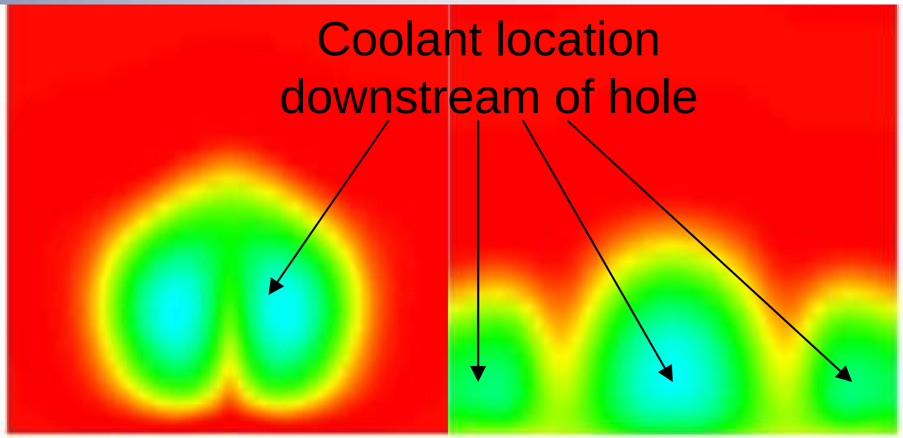
Top View



Front View



Side View



Baseline Coolant Coverage (hot wall)

Anti-Vortex Coolant Coverage (cool wall)

Objective

- High-performance engines demand increased turbine inlet temperature and reduced turbine cooling while maintaining durability
- At high blowing ratios, round film cooling holes become ineffective due to jet lift-off
- Proposed alternative to expensive shaped holes is the Anti-Vortex Concept
- Improved cooling effectiveness can reduce cooling required for given turbine inlet temp
- Computationally and experimentally develop and demonstrate improved turbine film cooling concepts, including Anti-Vortex Concept

FAP Hypersonic: Propulsion Technology Integration: TBCC Dual Integrated Inlet Mode Transition

Activities:

Develop multi-disciplinary technology critical to enable Turbine-Based Combined-Cycle (TBCC) propulsion systems for application to Highly Reusable, Reliable Launch Systems (HRRLS)

- TBCC propulsion system integration issues addressed by design and fab of proof of concept over/under TBCC propulsion system (Mach 7 design with transition from Mach 3-4) to be tested in GRC 10x10
- Database of TBCC dual-integrated inlet performance and operability including definition of engine inlet distortion for various bleed, ramp, cowl, and backpressure over the Mach range of 2-4.
- Controlled Inlet Mode Transition from Turbine to Scramjet Engine flowpaths
- Testbed for Integrated inlet/engine testing and mode transition controls development
- TBCC Integrated turbine engine technology/ database for start-up, shutdown, and re-light
- Engine design and analysis codes (inclusive of CFD w/ bleed models, engineering-level tools, and control models)

IMPACT

First full-scale inlet mode transition study

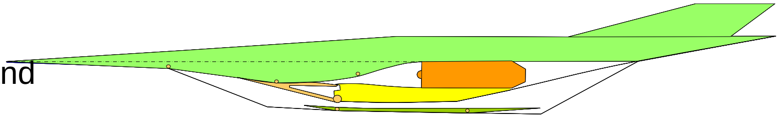
- engine inlet distortions quantified
- enables quantification of parametrics on bleed, performance, and distortion to validate tools

First TBCC mode transition w/ actual turbine engine installed

- engine and inlet operability addressed
- controlled mode transition studie

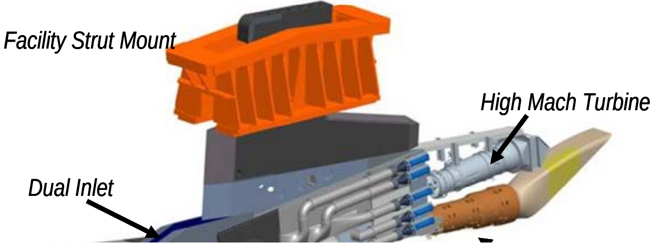
Schedule / Milestones:

✓ 2009 4th QTR: High Mach Turbine Engine SLS test w/ integrated nozzle
✓ 2009 4th QTR: Inlet Model installation into GRC 10x10 facilty
✓ 2010 1st QTR: Complete parametric inlet characterization
✓ 2010 3rd QTR: Complete inlet system ID tests (unsteady) for control models
✓ 2011 4th QTR: Demonstrate controlled mode transition w/ simulated engines
✓ 2012 3rd QTR: Demonstrate controlled mode transition w/ turbine engine



Test Approach (GRC 10x10 wind Tunnel)

1. Inlet w/ simulated Engine backpressure
2. Demonstrate mode transition control strategies and ability to recover from inlet unstart
3. Add engines/ nozzle for integrated system test



Glenn – Two Campuses Working Together to Achieve NASA's Mission

Plum Brook Station

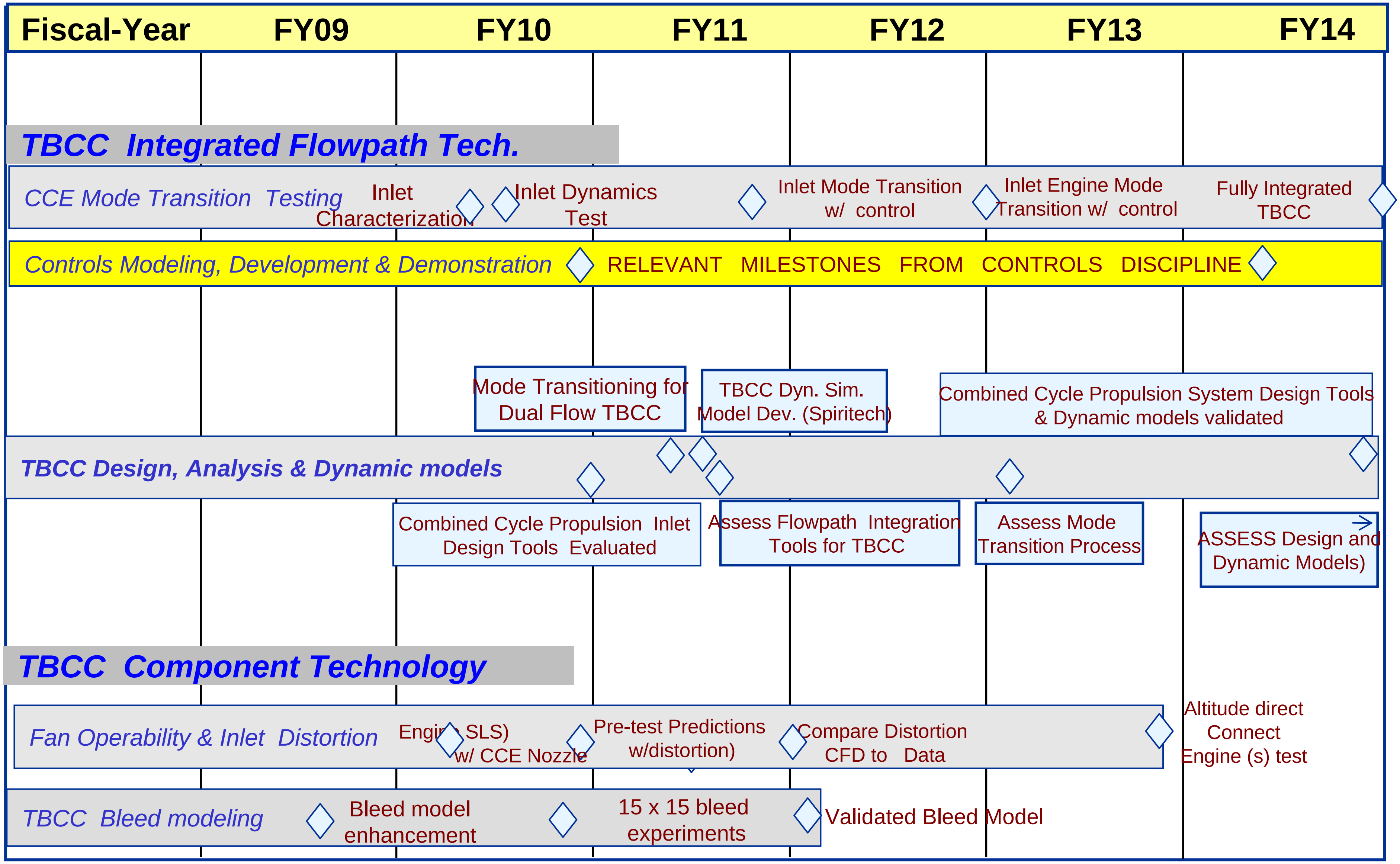
Location: Sandusky, Ohio
Civil Service FTE: 15
On-site Contractors: 75
Total Area: 6400 Acres

Location: Cleveland, Ohio
Civil Service FTE: o ~ (1750)
On-Site Contractors: o ~ (1200)
Total Area: 350 Acres

Lewis Field Main Campus

Combined current replacement value is $2 to $3 billion dollars

Hypersonic Project: TBCC Discipline Roadmap



Fiscal-Year FY09 FY10 FY11 FY12 FY13 FY14

TBCC Integrated Flowpath Tech.

CCE Mode Transition Testing

Inlet Characterization

Inlet Dynamics Test

Inlet Mode Transition w/ control

Inlet Engine Mode Transition w/ control

Fully Integrated TBCC

Controls Modeling, Development & Demonstration

RELEVANT MILESTONES FROM CONTROLS DISCIPLINE

Mode Transitioning for Dual Flow TBCC

TBCC Dyn. Sim. Model Dev. (Spiritech)

Combined Cycle Propulsion System Design Tools & Dynamic models validated

TBCC Design, Analysis & Dynamic models

Combined Cycle Propulsion Inlet Design Tools Evaluated

Assess Flowpath Integration Tools for TBCC

Assess Mode Transition Process

ASSESS Design and Dynamic Models)

TBCC Component Technology

Fan Operability & Inlet Distortion

Engine SLS) w/ CCE Nozzle

Pre-test Predictions w/distortion)

Compare Distortion CFD to Data

Altitude direct Connect Engine (s) test

TBCC Bleed modeling

Bleed model enhancement

15 x 15 bleed experiments

Validated Bleed Model

Interactive Analysis for Propulsion - Airframe Integration

Objective

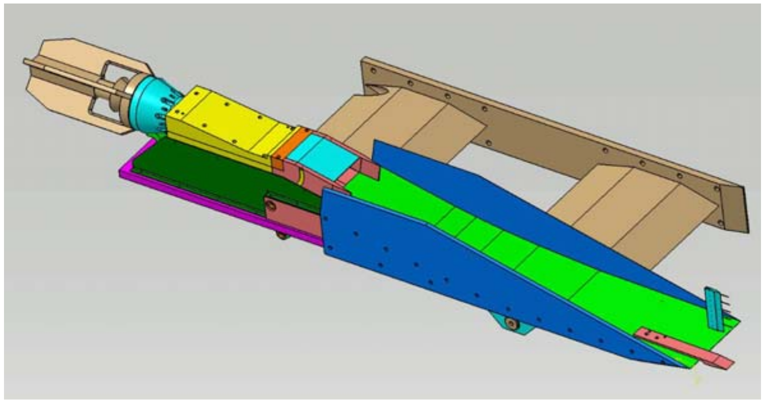
- Develop interactive computer program for preliminary design and analysis of 3-D forebody-inlet and 3-D integrated nozzle configurations
- Parabolized-Navier-Stokes (PNS) solver for parameterized geometry.

Technical Approach:

- Couple existing CAD, grid generation, 3D PNS solver, and graphics programs on a single Windows PC using a Matlab graphical user interface (GUI).
- Increase the accuracy of inlet/forebody design codes by including the effects of shock/boundary layer interactions using a high speed, 3D, PNS solver

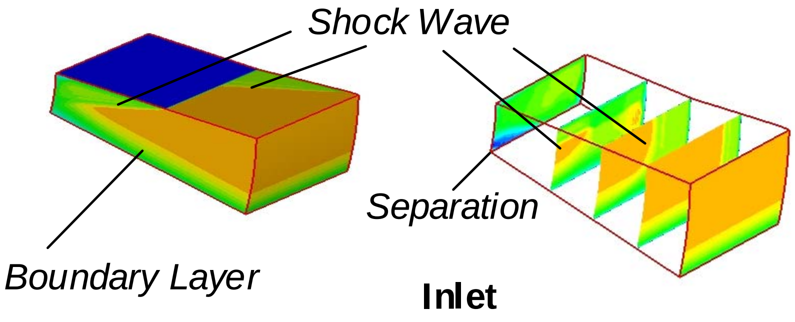
Status

- Preliminary GUI developed in Matlab, post-processing through Tecplot
- Preliminary version of system operational on single PC/ Windows XP : 1 million grid points in 2.5 minutes
- Codes being tested and validated against ¼ scale Round-to-Circular (RTC) Inlet Test at Langley



¼ Scale RTC (Round-to-Circular) Inlet Model

Computed Mach Contours



Utilize tool to Screen Bleed configurations on CCE Test - reduce test time

Bleed Modeling

- Bleed modeling is critical aspect of the CFD simulation of the low-speed flowpath.
- Objective is to be able to predict bleed rates and plenum pressures.
- Bleed model should capture the spatial variation of the bleed rates over the bleed region due to pressure variations.
- Bleed model should capture the variation of the bleed rates due to interaction of the terminal shock. This is especially important for the throat bleed regions.
- The variation in the bleed rate with back-pressure is what creates the “knee” in the inlet characteristic cane curve.
- Bleed model should be capable of simulating constant-pressure and fixed-exit bleed plenums.
- CFD simulations will explore the role of bleed and the need for control of bleed during inlet mode transition.