



Revolutionary Propulsion Research

**Presentation to
National Research Council
Independent Review of the
Pioneering Revolutionary Technologies Program**

June 12-17, 2002



Revolutionary Propulsion Research Project

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- Project Focus Area
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 - Advanced Chemical
 - Electromagnetics / Plasma Based
 - Advanced Nuclear
 - Advanced Sails and Interstellar Propulsion
 - Systems Analyses of Advanced Concepts
 - Breakthrough Propulsion Physics
 - Other



Revolutionary Propulsion Research Project: Organization and Management Structure

◆ Project Office

- Under Advanced Space Transportation Program Office at MSFC
- Manager, John Cole
- Deputy Manager, Ron Litchford

◆ NASA Center Task Managers

- | | | |
|--------|---|-----------------------------------|
| – ARC | – | Unmeel Mehta |
| – GRC | – | Craig Williams, Mark Millis (BPP) |
| – JPL | – | Ira Katz, Jay Polk |
| – MSFC | – | Jim Martin, Steve Rodgers |



Revolutionary Propulsion Research Project

◆ Goals & Objectives

- Look beyond current space transportation architectures and produce the science that might lead to low fuel fraction, low cost, revolutionary space access vehicles
- Contribute to fundamental advancement of in-space propulsion technologies that can ultimately enable short-duration, on-demand travel to any location in the solar system, as well as penetration of the interstellar medium
- Demonstrate scientific proof-of-principle of extremely energetic and enabling propulsion technologies
- Work closely with STLT/3rd Gen and In-Space programs as well as NEXT (NASA Exploration Team) to transfer and promote emerging propulsion technologies when appropriate
- Promote a culture of “*excellence in research*” – Demand Good Science

◆ Focus Area is Highly Energetic Propulsion

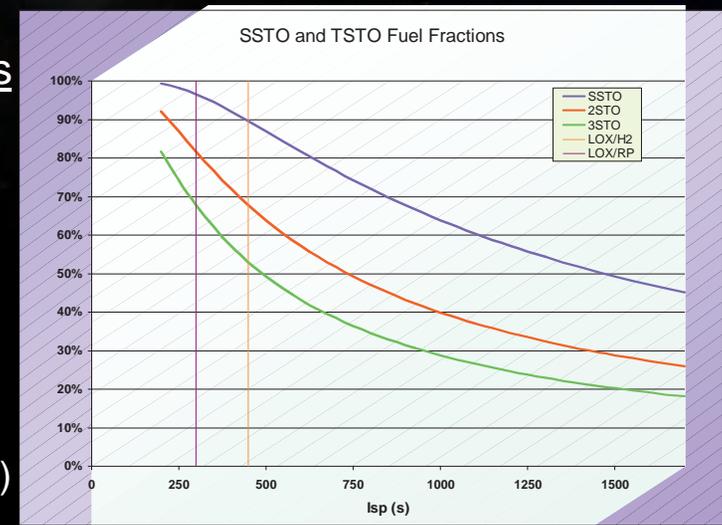
- High Specific Energy/Power
 - highly energetic reactions / off-board resources / ultra energy storage & power conversion
- High Temperatures & Electromagnetics
 - plasma sciences / high temperature technologies / plasma accelerators / MHD
- Non-Chemical Energy Sources
 - fission, fusion, antimatter, nuclear isomers
- Continued Support of Advanced Chemical Research
 - high energy density fuels / advanced cycles



Why is Propulsion Energetics Research Needed?

◆ Earth Orbit Access Technical Challenges

- The fundamental technical obstacles to routine space access are related to two basic parameters of Energetics
 - Specific Energy (reducing fuel fraction requires higher I_{sp})
 - Specific Power ($T/W > 1$ requires multi-GW power)
- Routine space access operations will ultimately require propulsion systems possessing robust performance margins
 - Adding features such as wings, landing gear, contingency fuel, operability, safety requirements, and more payload demands higher specific impulse (desired fuel fraction $< 70\%$)
 - Order of magnitude increase in I_{sp} with $1 < T/W < 3$
 - Implies order of magnitude increase in vehicle specific energy without sacrificing specific power
- Currently, No Technologies Exist that can significantly reduce fuel fraction while providing the specific energy/power needed to place a given mass in orbit
- Research Avenues Do Exist, however, that may enable the desired specific energy
 - High energy density propellants
 - Beamed energy from ground based power sources
 - Closed cycle nuclear systems (safe, very high specific power)
 - Ultra-high-density energy storage
- Research Avenues also exist for developing engines with the required specific power
 - Electromagnetic thrust augmentation, for example





Why is Propulsion Energetics Research Needed?

◆ In-Space Transportation Challenges

- The fundamental technical obstacles to deep space (beyond mars) transportation are also related to propulsion energetics

- Specific Energy
 - low IMLEO demands high Isp propulsion
- Specific Power
 - short trip times demand high Δv maneuvers (i.e., high jet power for high acceleration)

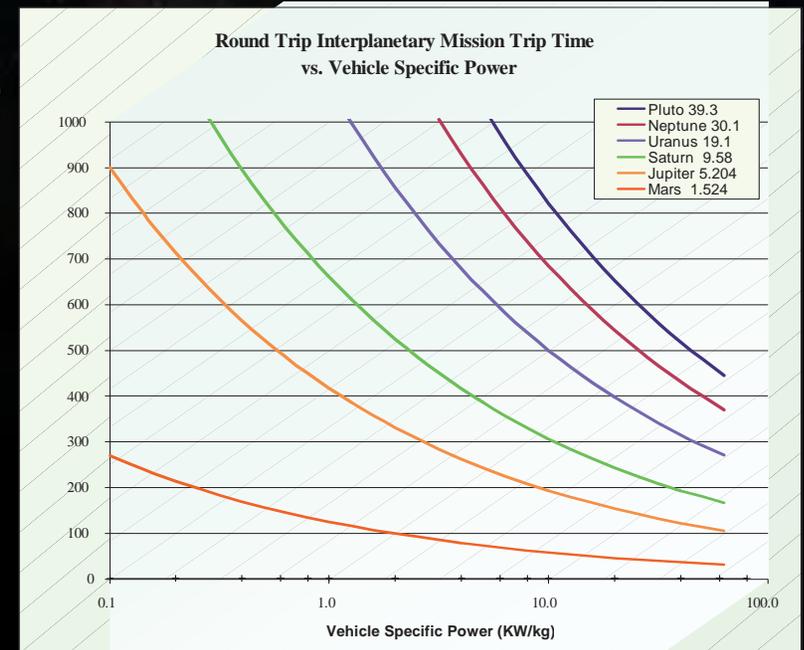
- Affordable, short-duration, on-demand travel beyond mars will require robust performance margins

- Order of magnitude increase in specific energy
 - delivered mass fraction > 50%
- Specific Power ~ 10 kW/kg
 - outer-planet round trips measured in days rather than years

- Requirements far beyond our current plans for Nuclear Electric Propulsion (~0.03 KW/kg)

- Potential research avenues

- Advanced closed-cycle nuclear electric propulsion best near-term prospect
- Fusion and antimatter good long-term prospects
- Beamed energy and sails may help
- Component research also needed (high-temperature radiators / flight-weight magnets)
- Breakthrough propulsion physics (new scientific discoveries)



... must break through 1 kW/kg barrier and ultimately approach ~ 10 kW/kg



Rationale for Propulsion Energetics Research

- ◆ **Push technology to enable commercial ventures and space voyages that are not currently feasible**
 - Propulsion is the key limiting factor in most "over the horizon" missions, such as:
 - Safe, low-cost, routine earth-to-orbit transportation
 - Rapid, safe, and affordable transportation of large payloads throughout the solar system
 - Penetration of the interstellar medium and timely return of scientific information

- ◆ **Propulsion energetics appears to be best plausible research strategy**
 - A strategic investment for advancing beyond today's planned space transportation technologies
 - NASA must make this investment, since there is no **current** commercial incentive or military need for this capability
 - Potential solutions are neither quick nor simple
 - Need to start developing the scientific underpinnings now rather than later



Research Investment Categories

- ◆ **Advanced Chemical**
- ◆ **Electromagnetics & Plasma-Based**
- ◆ **Advanced Nuclear (Fission, Fusion, & Antimatter)**
- ◆ **Advanced Sails and Interstellar Propulsion**
- ◆ **Systems Analysis**
- ◆ **Breakthrough Propulsion Physics**



Propulsion Research Approach for 2003

◆ Budget Split, preliminary

	FY03	FY04
– Assume a budget of, after taxes	\$6895 K	\$6916 K
– Allocated for NRA's		
• Breakthrough Propulsion Physics	650 K	650 K
• Propulsion Research	2000 K	2000 K
– Allocated for In-House	4245 K	4266 K
• JPL	1100 K	same
• GRC	1000 K	
• MSFC	1245 K	
• ARC	350 K	
• Project Management	550 K	
– 8 FTE for PO and managing NRA contracts	400 K	
– Workshops	50 K	
– Graphics Support	30 K	
– Other	70 K	



Programmatics

◆ Programmatic Approach

- Demonstrate scientific feasibility and, if possible, mature technologies to TRL 3
- Encourage widest possible dissemination of scientific results
- Enhance and develop NASA in-house capabilities
 - To perform world-class scientific research
 - To effectively manage advanced propulsion research activities across the agency
- Utilize unique external expertise and facilities (avoid duplication of existing capability)
 - DoD/DOE Laboratories (contracts & support of IPA's)
 - Universities (primarily grants)
 - Private Sector (contracts & SBIR's)
- Stimulate education and extend graduate research opportunities
- Release NRA's directed at selected emphasis areas – as funding permits



Investment Strategy

◆ Investment Strategy

- 50% of funds distributed broadly in relatively small efforts
- 50% of funds invested in three “focus areas”
- NRA’s released when budget permits
 - e.g., NRA 8-17 (launch assist / pulse detonation engines)
 - Unable to release NRA during past few years (insufficient funds)
 - Preferred approach for focus areas
- Selection criteria for in-house and external tasks.
 - Research addresses revolutionary propulsion and satisfies the project objectives
 - Research is reviewed and endorsed by appropriate management advisory team
 - Involves a low cost meaningful experiment
 - Provide some results each year and conclusive findings within 5 years
 - Constrained by available resources
- A few unsolicited proposals have been selected (< 1 in 10)
- Some augmented SBIR’s and University grants

◆ Customers

- Space Transportation and Launch Technology (Code R)
- In-Space Transportation (Code S)
- NEXT - NASA Exploration Team (Code M)



Management Strategy

- ◆ **Progress Evaluation / Assuring Technical Excellence**
 - Virtually all tasks are funded at level-of-effort (\$ and manpower)
 - Research progress depends on many intangible (non-quantitative) factors
 - Capability & enthusiasm of investigators
 - Leveraging of resources and expertise
 - Adequate resources and time for maturation of ideas
 - Task Planning & Review Cycle
 - Identify critical (make or break) issues at an early stage and focus research efforts
 - Stress proof-of-concept experiments (establish *scientific feasibility*)
 - Set realizable schedule/milestones consistent with budget constraints
 - Require annual publication of research results (deliverable)
 - Annual review cycle by appropriate NASA Task Managers
 - Graduate, continue, or terminate decision annually
 - Terminate for non-performance or technologically unfeasible (negative findings)
 - Anticipate 10 - 20 % annual washout (use freed funds to pick up new work)
 - However, should avoid punishing researchers for good science that leads to negative findings
 - Continual dialogue with customers



Investment Portfolio: Focus Areas

Emphasis on a few selected research areas leading to high-payoff propulsion technologies

◆ **Magnetohydrodynamics (MHD)**

- MHD Augmented Propulsion Experiment (MSFC/LyTec)
- MHD-Bypass Hypersonic Airbreathing Engine (ARC)
- MHD Slipstream Accelerator (RPI)
- High Power Nuclear MHD Space Propulsion (INSPI/University of Florida)

◆ **Fusion**

- Magnetic Nozzle Simulator for Fusion Plasma Conditions (GRC/OSU)
- Coaxial Helicity Injection Experiment (GRC/Princeton University)
- Magnetized Target Fusion (MSFC/LANL)
- Magnetic Nozzle Technology for Pulsed Micro-Fusion (MSFC)

◆ **High Power (MW-Class) Electric Thrusters for Deep Space NEP**

- 500 kW Lithium-Fed Lorentz Force Accelerator (JPL)
- 1 MW Bismuth Anode Layer Thruster (JPL)
- 1-MW Ion Engine Feasibility (JPL)
- FRC Thruster (MSFC/ University of Washington)



Summary of Investment Portfolio

◆ Advanced Chemical

- Realities of Chemical Propulsion
 - Will never provide ultimate desired capabilities
 - All we have for now and for some time to come
 - Some performance improvements possible
- High Energy Density Fuels
 - Advanced hydrocarbons (AFRL/MSFC)
 - $\Delta I_{sp} = 20$ sec / specific gravity = 1.1
 - AFRL-Edwards provided MSFC with several advanced hydrocarbon fuels
 - Initial screening of these fuels completed in 2001
 - Recombination energy fuels (GRC)
 - High risk monopropellant ($I_{sp} = 550 - 700$ sec)
 - Experiments on formation of solid hydrogen snow completed in 2001
 - Video-based analysis of particle formation and design of next phase of experiment during 2002
 - Metallic Hydrogen (Harvard University)
 - Analysis of metallic hydrogen existence at megabar pressures
 - Td N₄, Tetrahedral Nitrogen (ARC)
 - Synthesis paths explored using numerical chemistry in 2001
 - Negotiations with AFRL to attempt synthesis (difficulties with low funds)
- Many other promising fuels and cycles can no longer be pursued at this time



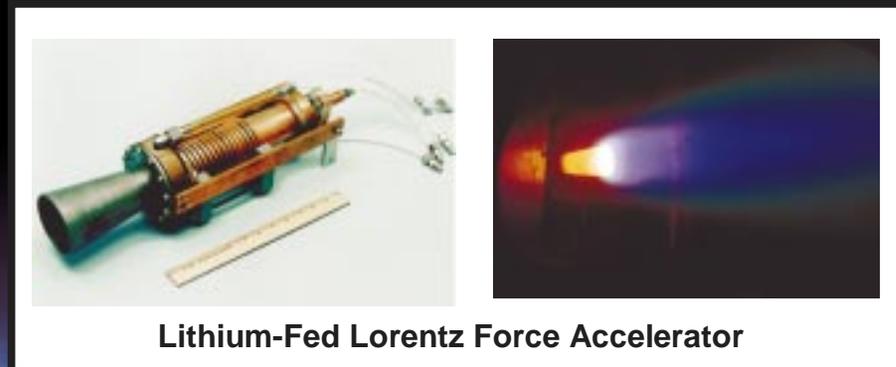
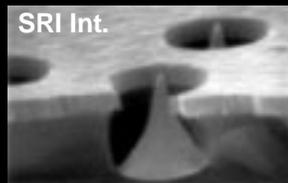
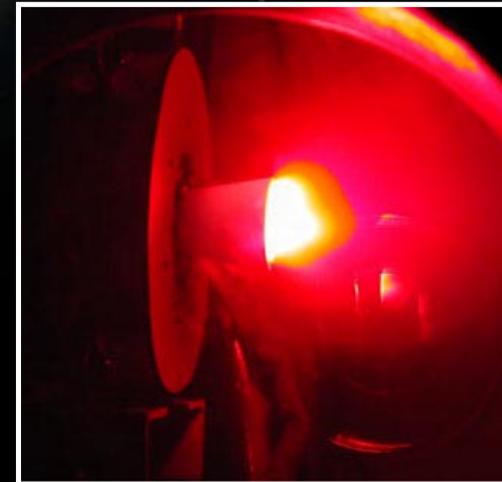
Solid molecular hydrogen particles (H₂ matrix) formed on the surface of the liquid helium (circled)



Summary of Investment Portfolio

◆ Electromagnetics / Plasma Based

- Electromagnetics is a path for bypassing thermal limits
 - Aim is conversion of electromagnetic energy to momentum
 - Mainly oriented toward plasma based concepts
- Megawatt-Class Electric Thrusters (JPL)
 - Li-fueled LFA test facility constructed
 - 500 KW LFA thruster in assembly (initial testing in 2002)
 - Contract with TsNIIMASH to design a subscale 200 kW-class bismuth anode layer thruster
 - 1 Megawatt ion engine design feasibility assessment underway
 - Several field emitter concepts built and tested in 2001 and 2002 (tests ongoing)



Lithium-Fed Lorentz Force Accelerator



Summary of Investment Portfolio

◆ Electromagnetics / Plasma Based (cont'd)

- MHD Accelerators (ARC/MSFC/LyTec/AFRL)
 - Small-scale MHD accelerator built and in-test at Ames Electric Arc Shock Tunnel
 - to support MHD bypass hypersonic engine research
 - 1 MW steady flow MHD accelerator experiment using 1-MW arcjet driver at MSFC
 - support electrically augmented rocket research
 - analysis and design complete / fabrication and assembly ongoing
 - Planning continues for development of a 20-MW accelerator experiment at ARC
 - MHD slipstream accelerator experiment at RPI
 - Development of comprehensive CFD code for high-temperature plasma/MHD flows (ARC/Stanford/MSFC)

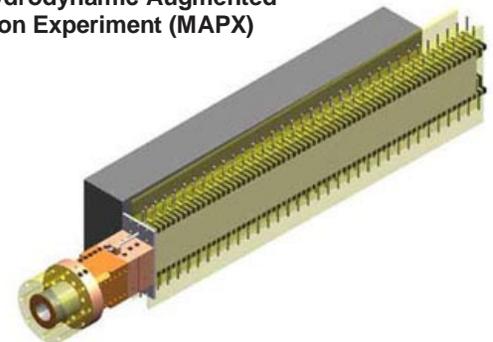
MHD Slipstream Accelerator



ARC MHD Accelerator Assembly



Magnetohydrodynamic Augmented Propulsion Experiment (MAPX)





Summary of Investment Portfolio

◆ Electromagnetics / Plasma Based (cont'd)

- Beamed Energy
 - Microwave Lightcraft rectenna testing at Rensselaer Polytechnic Institute
 - Laser Lightcraft CFD analyses at MSFC in support of AFRL-Edwards research
- Flight Weight Magnets
 - High-purity aluminum magnet completed and tested in 2001 by LSU
 - Development of low-weight superconductor magnet flux pump continues at LSU
- MagLev Launch Assist
 - Army and PRT conducting flywheel and drone launch studies into 2002





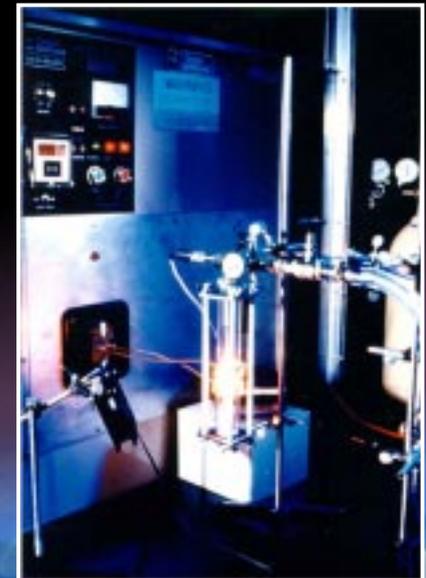
Summary of Investment Portfolio

◆ Nuclear - Advanced Fission

- Chemical systems already pushed to limit
- Nuclear offers a new growth path
 - Potential for 10^6 factor of improvement in specific energy
 - Best near-term prospect (relatively high TRL)
 - Potential to achieve specific power > 1 kW/kg with high-temperature reactor
 - Would also like to start exploring possible utilization of isomers as funding levels permit
- LOX Augmented NTR
 - First series of LOX injection testing of simulated NTR completed by GRC in 2001
 - Planning and experiment design for next series of tests will continue into 2002
- High Temperature Nuclear Fuels
 - Effort focuses on cermet and carbide fuels potentially capable of enabling high performance (>0.1 kW/kg) nuclear electric propulsion system as well as nuclear thermal rockets with mission averaged specific impulse >850 secs
 - Significant progress made by INSPI/ University of Florida in fuel characterization and fabrication methodologies (effort continuing into 2002)



Aerojet Corp Test Rig
LANTR hot fire test
(25:1 area ratio)



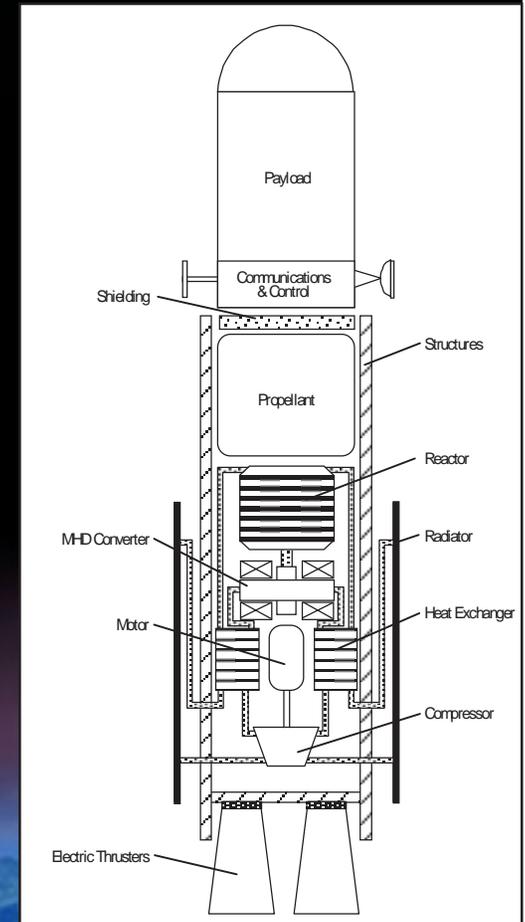
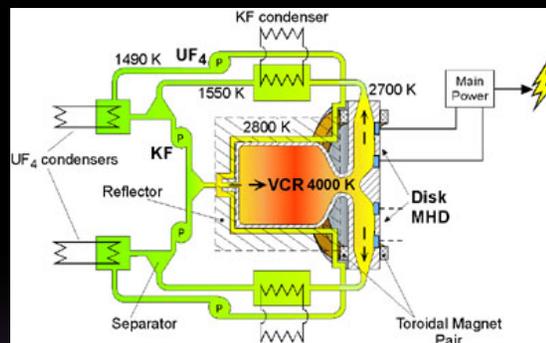


Summary of Investment Portfolio

◆ Nuclear - Advanced Fission (cont'd)

– Nuclear Electric MHD Systems ($P_{sp} > 1 \text{ KW/kg}$)

- University of Florida analysis and assessment of vapor core reactor with MHD energy conversion for deep space NEP is continuing
- Neutron ionization enhancement experiment at MSFC temporarily halted (lack of adequate resources)
 - Fundamental data obtained using electron gun to simulate neutron flux
 - Planned research includes in-pile experimentation to confirm predictions based on modeling and electron-gun results
 - May be able to restart research through an NRA solicitation

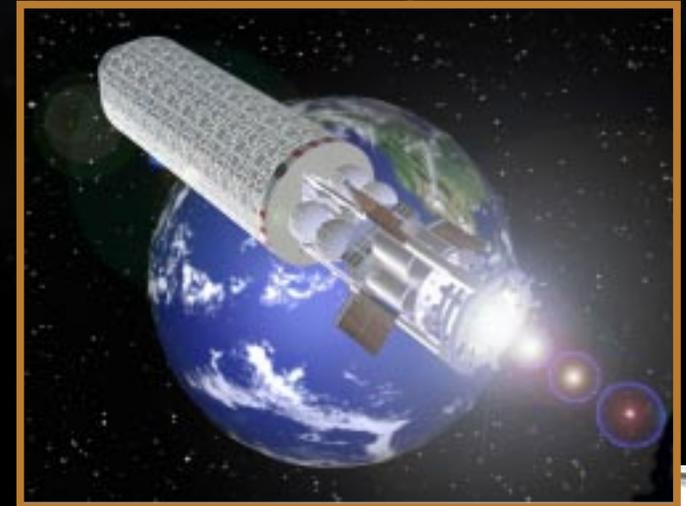




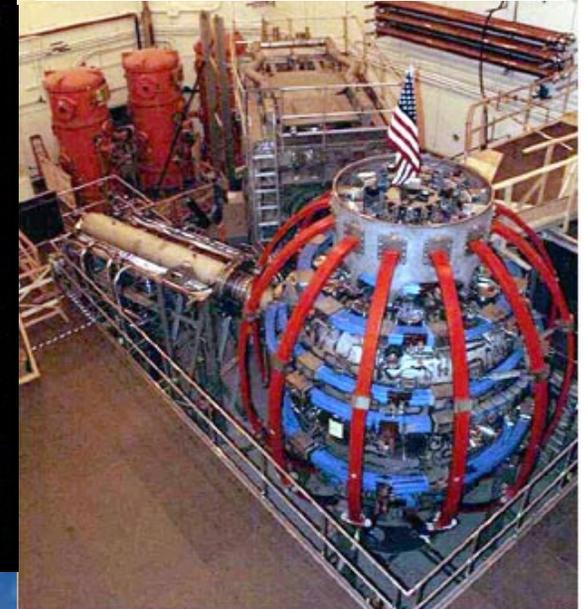
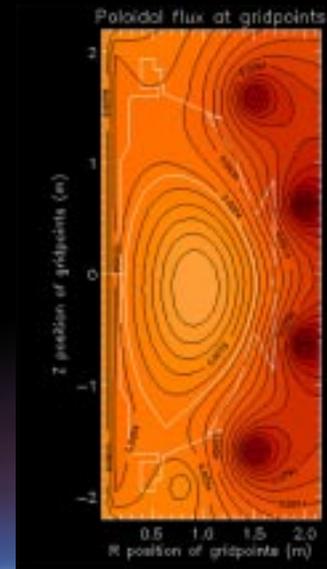
Summary of Investment Portfolio

◆ Nuclear - Fusion

- Very high energy density reactions
 - Theoretical $I_{sp} \approx 10^6$ sec (with low neutron yield reactions)
 - Benefits from energy conversion process inside the plasma
 - May require innovative confinement schemes
- High payoff but high risk
 - Controlled fusion breakeven power never demonstrated
 - Serious research requires major fiscal investments (distraction?)
 - Envisioned systems tend to be big (high IMLEO)
- Potential benefits demand we start now
 - Payoff would be immense (~ 10 kW/kg)
 - Frontline researchers confident of success
 - DOE has made significant progress
 - NASA can pursue only with substantial DOE help



Spherical Torus Experiment

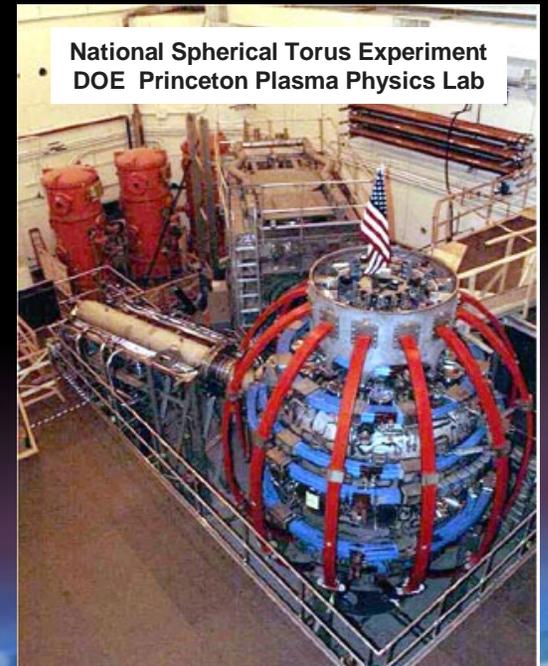




Summary of Investment Portfolio

- ◆ **Nuclear - Fusion (con't)**
 - Magnetic Nozzle Simulator (GRC/OSU)
 - Final report on plasma/propellant boundary layer
 - Coil hardware fabricated, test cell configured for test
 - Initial attempt at low power test

 - Helicity Injection (GRC/Princeton University)
 - Defined experimental campaign with NSTX research plan
 - CHE theory development and plasma modeling
 - Small reactor study (ORNL)





Summary of Investment Portfolio

◆ Nuclear - Fusion (cont'd)

- Magnetized Target Fusion (MSFC/LANL)
 - Completed Mark-1 Marshall gun experiment demonstrating low jitter (<10 ns) and launching of 0.2 mg plasma at 62km/s
 - Initiated design of Mark-2 gun
 - Development of 2-D MHD simulation code
 - 75% design completion for FRC target generator
- Gas Dynamic Mirror (MSFC)
 - Brought up system and demonstrated first plasma
- IEC Fusion Reactor (MSFC)
 - Placed into operation with deuterium plasma and demonstrated neutron production
 - Applying advanced plasma diagnostics to reveal underlying physical processes
- University Efforts
 - Z-Pinch (U. Nevada at Reno)
 - FRC (U. Washington)
 - Computational Analysis (UAH, U. Tenn.)





Summary of Investment Portfolio

◆ Nuclear - Antimatter

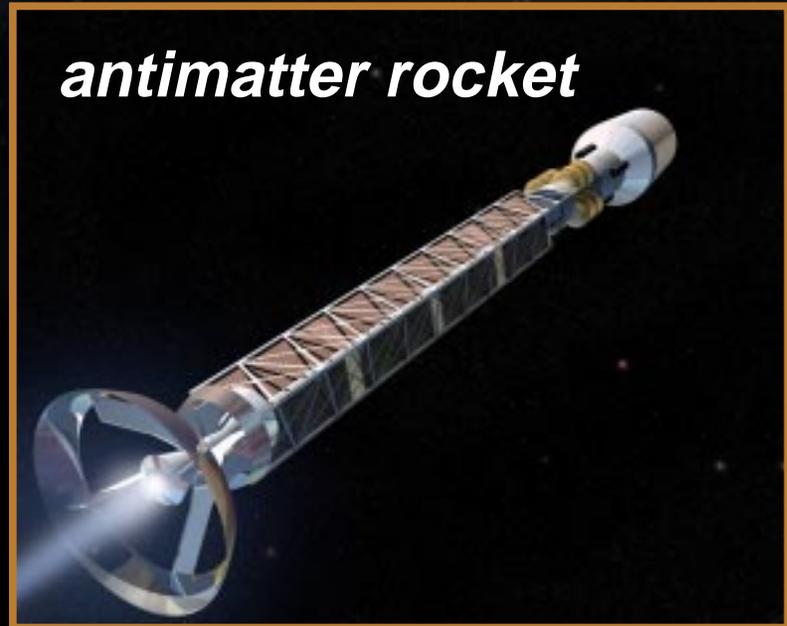
- Ultra-high energy density reaction
 - Potential for $I_{sp} > 2 \times 10^6$ sec
 - May be useful as catalyst for micro-fusion detonations as well
- Major issues at this stage are production & storage
- High potential for commercial spin-offs
- Research team includes MSFC, Industry, Universities, and DOE Laboratories

◆ Storage Research

- High Performance Antiproton Trap (HiPAT)
 - One-trillion antiproton storage capacity
 - 18-day half-life
- Transportability
 - Fill trap at Fermi Lab
 - Transport to MSFC for utilization experiments
 - To date, only tested with normal matter

◆ Antimatter Catalyzed Micro-Fusion

- ICAN & MICF target concepts
- Reduce stand-off driver mass
- Antimatter usage rate less demanding





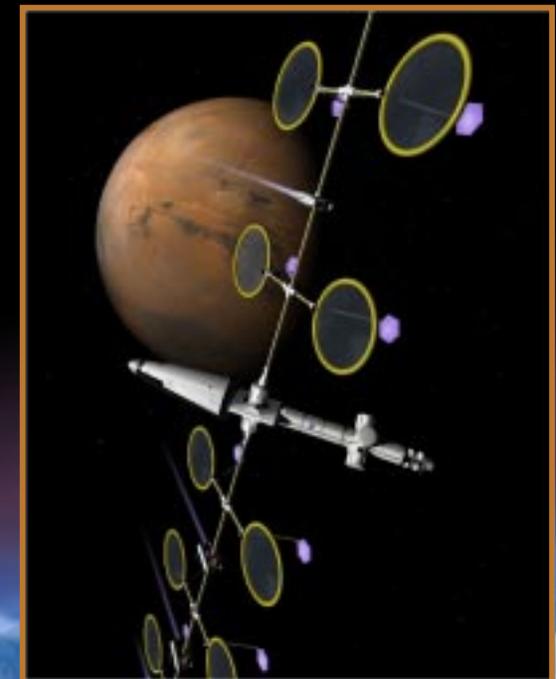
Summary of Investment Portfolio

◆ Interstellar Option

- Specific energy requirements beyond 10^9 MJ/kg
- May ultimately depend upon some unforeseen breakthrough
- Limited penetration of interstellar medium is possible
 - Utilization of insitu or off-board resources
 - Solar, dust, laser, and magnetic sails

◆ Other Propulsion Options

- Micropropulsion technology
- Tethers
- Very large solar electric

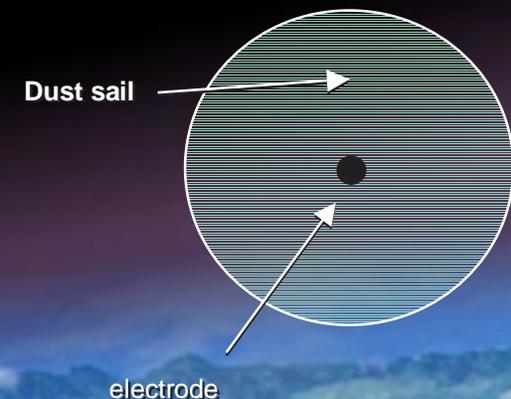




Summary of Investment Portfolio

◆ Interstellar - Advanced Sails

- Reinforced metal film sails
 - Tasks underway include concept feasibility evaluation, bonding, film assembly, and reflectivity measurements
- KC-135 self deploying sail experiment
 - Hoop sail experiment completed in FY01
 - Vacuum deployment tests and KC-135 tests planned for FY02
- Electrostatic dust solar sail
 - Completed preliminary assessment of cloud coupling to spacecraft
 - Vacuum deployment test planned soon

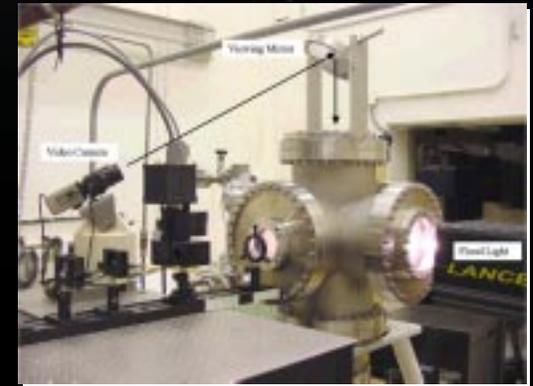




Summary of Investment Portfolio

◆ Interstellar - Advanced Sails (cont'd)

- Laser ablated sails
 - Test performed to measure coupling coefficients. Initial results in FY01
 - Final results to be presented in FY02
- Laser sail photon measurements
 - Completed force measurements in agreement with theory to within 5%
 - Preliminary results to be presented in FY02





Summary of Investment Portfolio

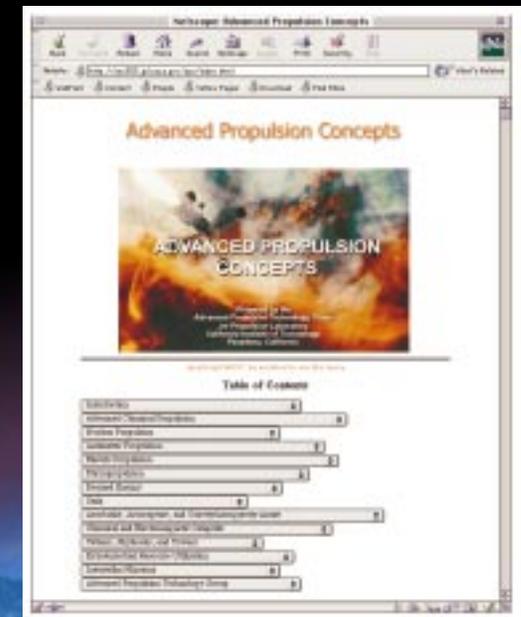
◆ Advanced Concepts Mission and Systems Analysis

- Piloted outer planet missions
 - Completed analysis of Neptune piloted mission using Multi-MW NEP
 - Completing analysis of chemical, fission, and fusion options for Neptune
- Analysis of Jupiter and Saturn missions during FY02
- Team X; Completed initial assessment of evolutionary approach to NEP



◆ Workshop and Data Base

- 13th Advanced Propulsion Concepts Workshop hosted by JPL in June 2002
- Advanced Concepts Database is being modified to ensure compatibility with ITAR guidelines





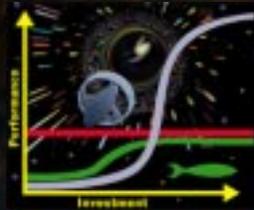
Summary of Investment Portfolio

Breakthrough Propulsion Physics (GRC)

Objectives & Goals

Objective

- ◆ Produce advances on physics to revolutionize spaceflight and enable interstellar voyages
 - Look beyond Newtonian mechanics to provide new scientific foundations for breakthrough technology.
 - Ensure that such research is conducted in credible and productive manner.



Technical Challenges (Goals)

- ◆ **Mass:** Discover new propulsion methods that eliminate or dramatically reduce the need for propellant.
- ◆ **Speed:** Discover how to circumvent existing limits to dramatically reduce transit times.
- ◆ **Energy:** Discover new methods to power these propulsion devices.

Research Tasks

Interim results presented at the 2001 Joint Propulsion Conference
http://www.grc.nasa.gov/WWW/bpp/2001_JPC_Paper_List_test.htm

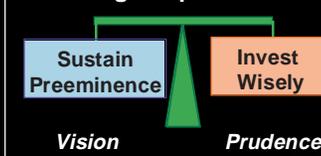
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 BPP NRA Mojahedi, Univ NM QM Tunneling	 WV Earmark Koeck, Inst Software Heaviside Force	 DAI Grant Deck, U. Toledo, OH Deep Dirac Energy	 GRC In-House Fralic, GRC, OH Thrusting Antenna

Implementation

Project Approach

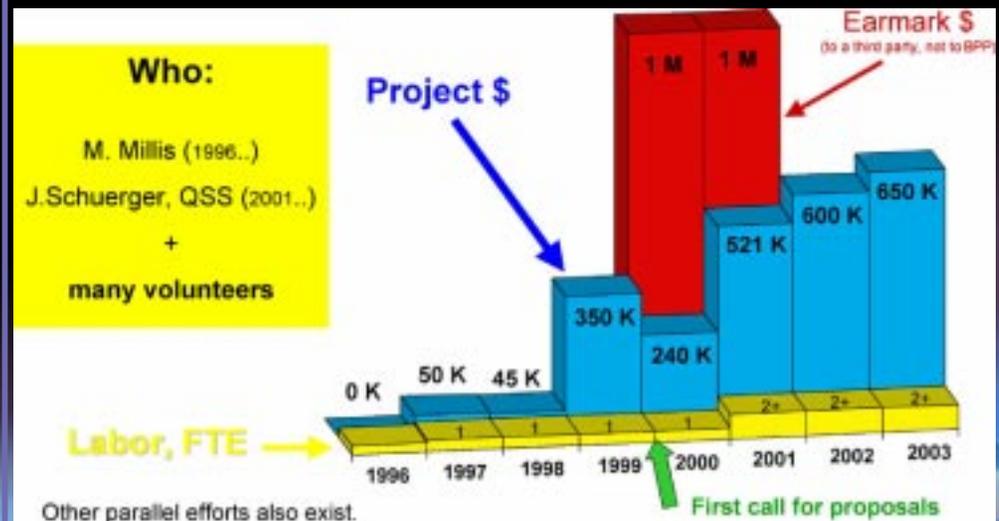
- ◆ “Success” defined as “acquiring reliable knowledge” (rather than “achieving a breakthrough”).
- ◆ Focus on *immediate* make-or-break issues, unknowns, or curious effects.
- ◆ Explore **multiple, divergent** research topics simultaneously.

Balancing Responsibilities



- ◆ Sustain progress as a **series** of short-term, **incremental** tasks.
- ◆ Measure progress using the **scientific method**.
- ◆ Consider **visionary** specifications, yet tempered with **credible** methods and foundations (**reviews judge reliability of results, not feasibility of concept**).

Budget / FTE

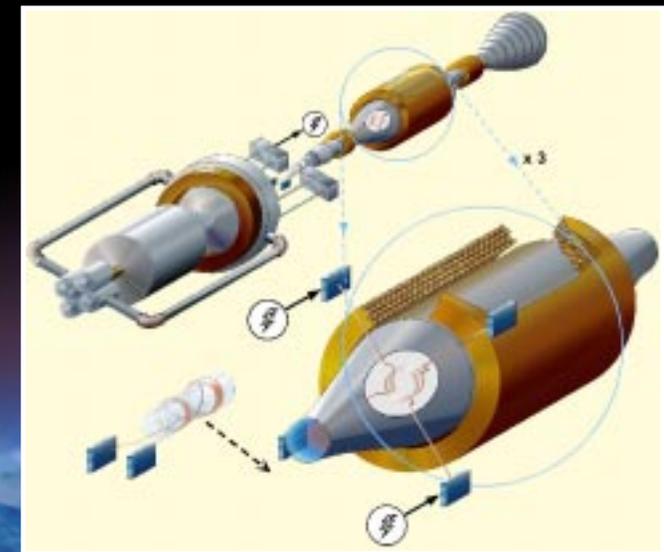
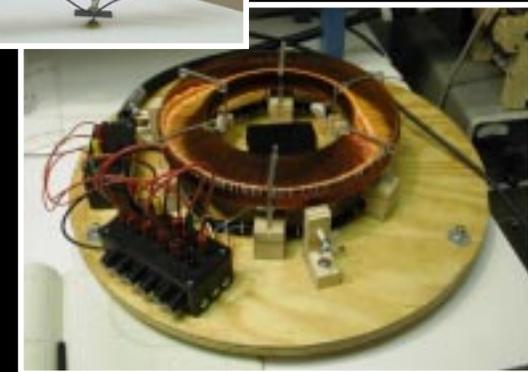
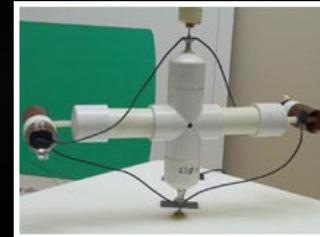




Summary of Investment Portfolio

◆ Other

- Congressional Earmark to W. Virginia Institute for Software Research
 - Asymmetric Capacitor
 - experiments to date indicate that Trichel Pulses are part of the operation
 - Liquid Metal Flywheel
 - A generator mode has been built and demonstrated using a gallium-Indium eutectic
 - Fissioning Plasma Core Reactor Analysis
 - Analysis in support of INSPI/UF research
 - A significant number of core calculations have been run using U235 and Pu239
 - A kinetics code has been developed specifically for the analysis of the FPCR and preliminary results obtained





Funding Plans for FY03

- ◆ **Two NRAs, some basic support, and a few close out tasks continuing into FY03**
 - 60% for NRA for Revolutionary Propulsion Research and contract administration
 - 10% for NRA for Breakthrough Propulsion Physics and contract administration
 - 30% for NASA Centers basic support and completing critical experiments
 - **GRC**
 - Recombination Energy Fuels, needs one more year to get data from experiment
 - **JPL**
 - Li LFA thruster test facility completed, engine assembly underway, and testing will continue into 2003
 - Systems analyses and evaluation support
 - Database maintenance and Workshop Management
 - **ARC**
 - MHD accelerator tests and virtual inlet tests need to continue into 2003 somewhat.
 - **MSFC**
 - Antimatter trap experiment needs to travel to Fermi Lab to test filling
 - MHD accelerator tests with LyTec unit will continue into 2003 somewhat
 - Project Management support



Concluding Remarks

- ◆ Space transportation challenges are daunting but avenues of research exist which promise tremendous potential
- ◆ We must look beyond conventional technologies to ever make any real progress toward our ultimate goals
 - Scaling-up existing systems will never satisfy our ultimate desires*
- ◆ Fundamentally, it is a problem of energy storage density and energy-to-thrust conversion efficiency – Energetics
- ◆ A comprehensive investment strategy has been developed which addresses the fundamental technical challenges while insuring scientific excellence and accountability to the customer
- ◆ This research strategy has been implemented over the course of several years with participation by NASA in-house staff, universities, government labs, and the private sector and has built a solid record of return on investment