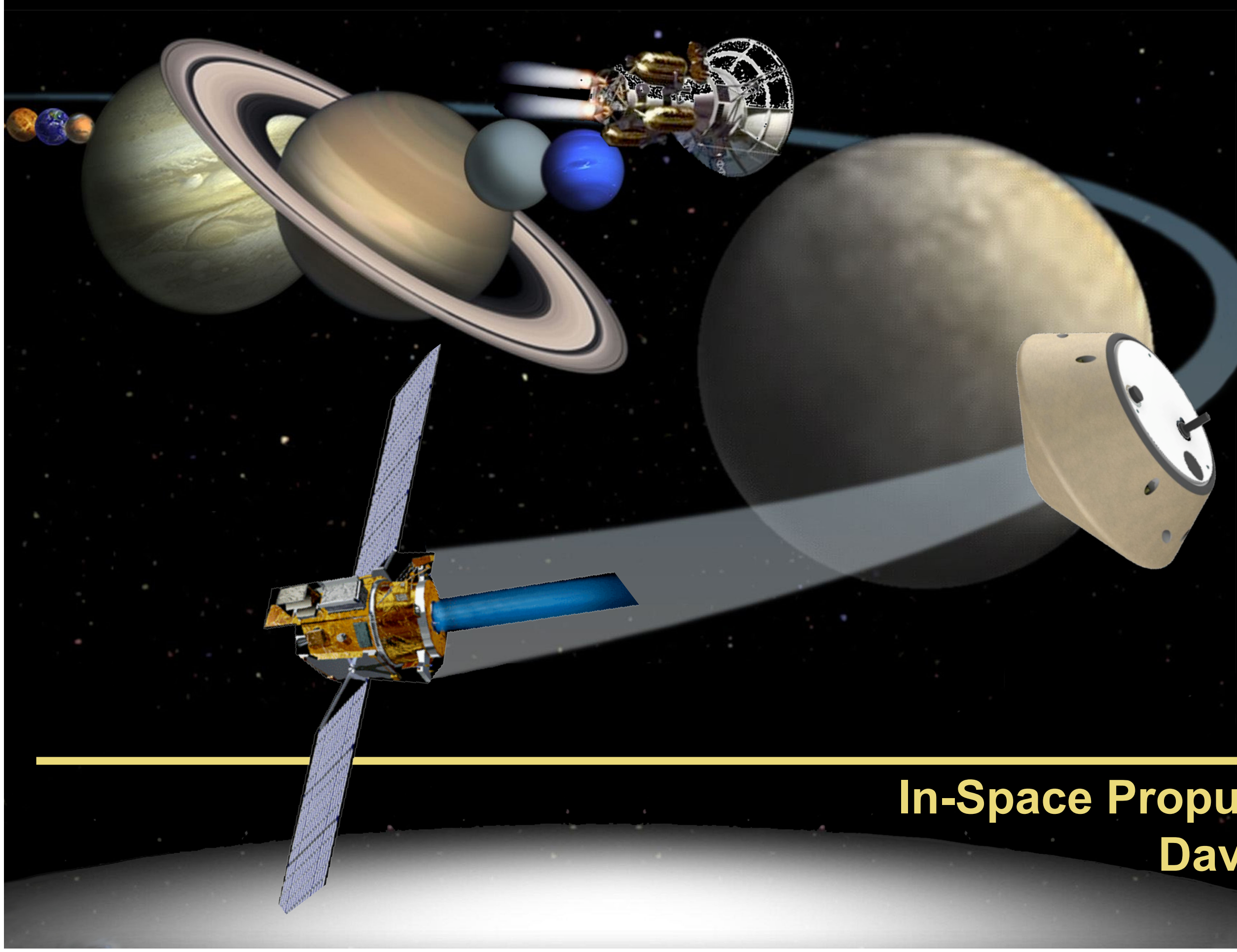
National Aeronautics and Space Administration

July 1, 2010



Discovery

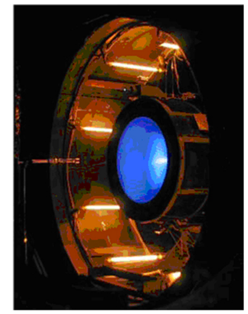
In-Space Propulsion Technology Infusion

David Anderson, NASA Glenn

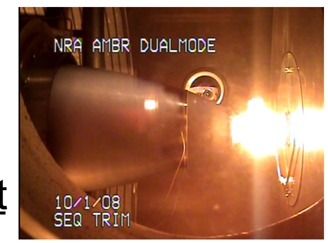
Propulsion Technology Infusion

Discovery Program

- SMD's In–Space Propulsion Technology (ISPT) program has developed several technologies that are nearing TRL 6 and that are therefore potentially applicable to Discovery missions
- Three of these technologies are:
  - Electric propulsion technologies include completing **NEXT (NASA's Evolutionary Xenon Thruster)**, a 0.6-7kW throttle-able gridded ion propulsion system
  - Chemical propulsion technologies include **AMBR (Advanced Material Bi-propellant Rocket)**, a high-temperature storable bi-propellant rocket engine providing higher performance for lower cost
  - **Aerocapture technologies** include a family of efficient thermal protection system (TPS) materials and structures; aerothermal effect models; atmospheric models which include Titan, Neptune, Mars, and Venus; GN&C algorithms for blunt-body rigid aeroshells; and GN&C hardware in the loop ground testing



NEXT



AMBR

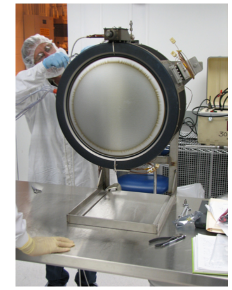
Aerocapture

(AO pg41)

Propulsion Technology Infusion

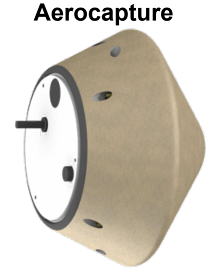
- NASA is providing an incentive to encourage the infusion of the NEXT system, the AMBR engine, or the Aerocapture maneuver or hardware elements
- NASA would share in the flight development costs
- The PI-Managed Mission Cost cap would be raised by:
  - $19M (FY 2010) for missions that utilize NEXT
  - $5M (FY 2010) for missions that utilize AMBR
  - $10M (FY 2010) for lander missions that utilize Aerocapture elements
  - $20M (FY 2010) for orbiter missions that utilize Aerocapture maneuver
- To qualify for the incentive, a proposed mission must meet minimum demonstration requirements for its chosen technology.
  - These requirements are contained in the document *In-Space Propulsion Technologies Minimum Demonstration Requirements located in the Discovery Program* Library.

NEXT gridded ion thruster



AMBR engine

Aerocapture

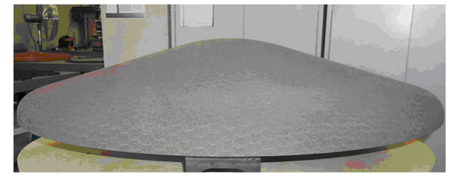


(AO pg42-43)

Propulsion Technology Infusion Requirements

Discovery Program

- Proposers will be responsible for the required NEXT, AMBR, or Aerocapture flight hardware development and integration, including the flight hardware development schedule
  - Clearly describe the application of NEXT, AMBR, or Aerocapture in the proposed investigation (Req. 89) (including how the proposed use meets the minimum demonstration guidelines for the chosen technology)
  - Identify costs associated with NEXT, AMBR, or Aerocapture (Req. 90)
- The application and development of flight hardware from the applicable technology will be evaluated as described in Section 7.2.4.



1-m Ablative Aeroshell

AMBR Vibe Test

Xenon Feed System Integration On the Dawn Spacecraft

(AO pg43)

New Technologies/Advanced Developments

- Guidelines for infusion of the NASA-developed technologies
  - NASA SMD assumes the responsibility for maturing these technologies to TRL-6
  - As these are technology development projects, NASA cannot guarantee the anticipated performance under conditions different than those for which they have been designed and tested
  - It is the responsibility of proposers to assess any risk inherent in application of these technologies beyond the design envelope
  - Proposals that include utilization of one of these NASA-developed technologies would not be required to include a maturation plan for them
  - Proposals would be required to include a plan for the infusion of these technologies (Appendix B, Section J.13)

(AO pg 18 and 44)

Technology Infusion Plan

In a 5 page appendix, describe any proposed utilization of the NASA-developed technology if not addressed in the proposal body. (Req. B-72) At a minimum, address the following (expands on Req. 89 and 90) if not addressed in main body:

1) Demonstrate your understanding of the chosen NASA-developed technology
   - Also describe understanding of any inherent risks associated with the technology
2) Describe technology infusion implementation plan w.r.t. use of that technology
   - Description of any required flight hardware development and integration plans for producing flight-qualified hardware/software
   - If any fallbacks/alternatives exist and are planned, describe cost, schedule, and performance liens imposed on the baseline design and decision milestones for their implementation
3) Description of the application, appropriate use, and benefits of NEXT or technology in the proposed investigation
   - Including how this technology would enhance/enable the proposed investigation's science return
4) Description of how you would engage with the relevant program office
   - Desires insight into the flight hardware development, IV&V testing and results, flight development lessons learned, and performance data obtained during flight for the chosen technology.

(AO pg B-29)

NEXT Incentives for Discovery

Discovery Program

- ***The minimum required hardware set for a flight demonstration of the NEXT system is comprised of the NEXT thruster and its accompanying PPU*.**
  – The **NEXT Prototype Model (PM) ion thruster** is a 6.9 kW ion thruster design @TRL6
    - The NEXT Prototype Model (PM) ion thruster design baseline is a required component of any demonstration, although minor design changes of the type commonly associated with the normal evolution in transitioning a PM design to a flight design are acceptable.
    - NASA GRC led development, and fabricated by Aerojet.
  – The **NEXT Engineering Model (EM) PPU** is a 7kW PPU design that operates the NEXT ion thruster.
    - TRL 6 will be achieved after successful conclusion of an on-going part failure investigation and associated re-work, and completion of system integration (SIT) and environmental testing.
    - The NEXT EM PPU circuit design baseline is a required component of any demonstration, although NASA recognizes that substantive hardware design changes may be desired, or required, to transition NEXT EM PPU to a flight design.
    - NASA GRC led development and fabricated by L-3 Communications.
- Also Available: The remainder of the NEXT ion propulsion system may be used for flight demonstrations but is not required.
  – NEXT Propellant Management System (PMS) design. @TRL 6. GRC/Aerojet developed.
  – Digital Control Interface Unit (DCIU). <TRL 6. JPL developed.
  – The gimbal. TRL 4-5. JPL/ATK developed

(Min Req'mnts Doc)

AMBR Incentives for Discovery

Discovery Program

- ***The minimum required hardware to be demonstrated is a combustion chamber fabricated using this process***.
  - A major goal of AMBR was to develop **the iridium/rhenium El-form fabrication process**
- Acceptable Alternatives/modifications
  - Alternate injector designs, which would improve performance over the existing AMBR injector design, would be considered acceptable.
    - However, the additional development, cost, schedule, and technical risks to bring this alternate injector design to TRL 6 would be borne by the proposer.
  - It would be acceptable to modify the AMBR engine to use the alternate fuel/oxidizer combination of monomethylhydrazine/nitrogen tetraoxide (MMH/NTO).
    - The AMBR engine was designed for the baseline fuel/oxidizer combination of hydrazine/ nitrogen tetraoxide (N_2H_4/NTO)
    - However, the additional development, cost, schedule and technical risks to bring this alternate fuel/oxidizer option to TRL 6 would be borne by the proposer.

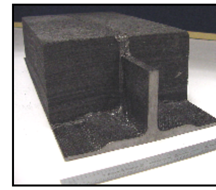
(Min Req'mnts Doc)

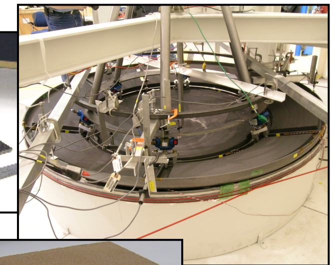
Aerocapture Technology Development Products

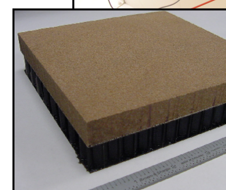
Elements at TRL6 and Ready to Infuse

Discovery Program

- Rigid aeroshell and TPS products
  - Carbon-Carbon hot structure from Lockheed Martin:
    - 2-meter rib-stiffened 70-deg aeroshell tested and finite element validated
    - Capable up to 700 W/cm^2, <u>30% lighter</u> than Genesis capsule equivalent
  - High-temperature aeroshell structures (composite and honeycomb sandwich):
    - Lockheed Martin
      - Composite honeycomb and modified adhesives raise TPS bondline by 65˚C, structurally and thermally tested
      - System (with SLA-561V) stagnation tested to over 300 W/cm^2, <u>15% lighter than MER</u>
    - ATK-Composite Optics
      - Titanium honeycomb and modified facesheet resins and fibers, coupon tested and manufactured at 2.65-meter scale
      - Raises bondline by 150˚C, <u>reducing system mass up to 30%</u> over traditional
  - Ablative Thermal Protection System Materials from Applied Research Associates
    - “Family system” approach provides range of densities and robustness levels for wide range of applications: 50 to 1,100 W/cm^2
    - Extensive arcjet testing, application at flat-panel, 1-meter, and 2.65-meter (pending) scales
    - Most mature material is SRAM-20, applicable up to 260 W/cm^2







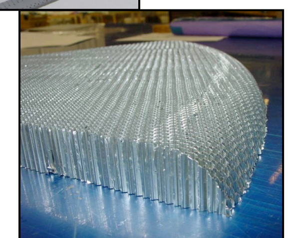


Figure 6 – Posttest Sample 3540 with 18.0-Deg Seam

Aerocapture-Related Incentives for Discovery

Discovery Program

- $10M incentive for landers using aerocapture elements
- ***Missions performing a complete atmospheric entry must demonstrate one or more rigid heat shield materials matured by the ISPT program under conditions specified*** *(in the minimum requirements document).*
  - Although termed the “lander” option in the AO, a probe, penetrator, hopper, atmospheric sampler, Earth return entry vehicle, or delivery device to mid-altitudes are acceptable.
  - The materials (@TRL6) and the required demonstration conditions are:
  - **A carbon-carbon “hot structure” with Calcarb bonded to the structure interior.**
    - ***To be considered an acceptable demonstration, these materials need to be applied in a relevant heating environment (over 300 W/cm^2 heat flux) and the C-C and Calcarb construction must be employed. Using C-C as a secondary structure is not an acceptable modification.*** (the structure will need to be instrumented with thermocouples)
  - **A honeycomb “warm structure”.**
    - ***To be considered an acceptable demonstration, the ISPT-developed adhesives and core material would be employed.*** (the structure will need to be instrumented with thermocouples)
  - **A honeycomb “warm structure” with an ablator.**
    - ***To be considered an acceptable demonstration, these materials must be used in a forebody heat shield application, although the maximum bondline temperature need not be achieved.*** (the structure will need to be instrumented with thermocouples)

(Min Req’mnts Doc)

Aerocapture-Related Incentives for Discovery

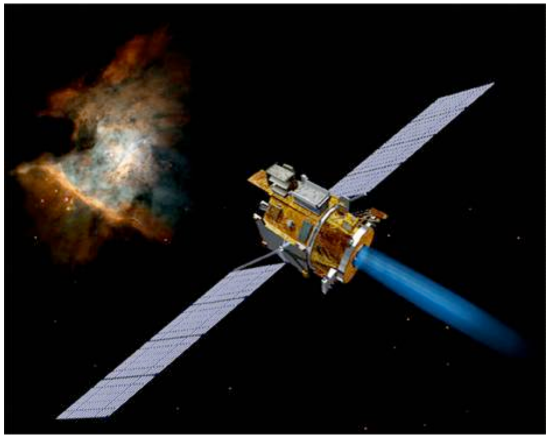
Discovery Program

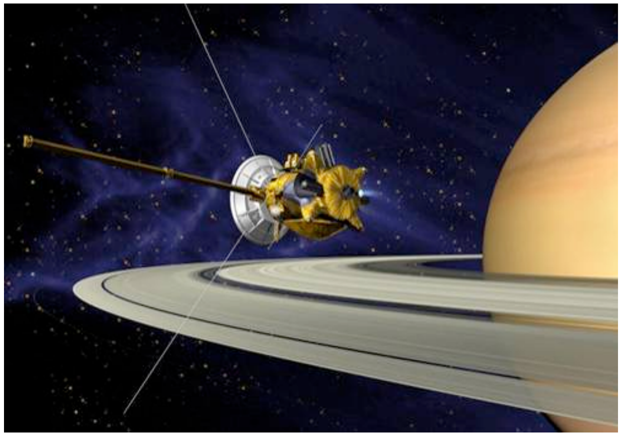
- $20M incentive for orbiters using aerocapture
- ***The minimum acceptable demonstration uses the aerocapture maneuver to decelerate by at least 2km/s in the atmosphere of a planetary body and then completely exit the atmosphere after this atmospheric passage. The vehicle must also contain some minimum instrumentation suite that will validate the Aerocapture maneuver was performed within the expected parameters.***
  - Missions not performing a complete atmospheric entry — termed the “orbiter” option in the AO
  - The post-aeropass vehicle is not limited to being an orbiter; it could perform a subsequent planetary entry, or some other function.
- The following is available upon request, but not required
  - ISPT Program has matured the Analytical Predictor-Corrector (APC) guidance
  - A hardware-in-the-loop simulation of the Guidance, Navigation and Control (GN&C) system has been assembled and tested, with the APC algorithm coded in flight software. @TRL6 Developed by Ball Aerospace.

(Min Req’mnts Doc)

Questions?

Discovery Program





Please see the Discovery Program Library (http://discovery.larc.nasa.gov/dpl.html) for more resources on the ISPT project, the 3 technologies, and other supporting information

Anyone requiring further information should contact David J. Anderson, ISTP Project Manager, NASA's Glenn Research Center (Telephone: 216-433-8709; E-mail: david.j.anderson@nasa.gov).

Back-Up

Discovery Program Library

- *NASA's In-Space Propulsion Technology Project Overview, Near-Term Products, and Mission Applicability - provides an overview of ISPT*
- In-depth reference documents and briefing packages of the NEXT ion propulsion system, the AMBR rocket engine, and aerocapture are provided in the following documents:
  - *NASA's Evolutionary Xenon Thruster (NEXT) Ion Propulsion System Information Summary for Discovery Missions* - in-depth description of the technology
  - *NEXT Ion Propulsion System for Discovery Missions* - standard briefing package
  - *Advanced Materials Bi-propellant Rocket (AMBR) Information Summary for Discovery Missions* - in-depth description of the technology
  - *AMBR Engine for Discovery Missions* - standard briefing package
  - *Aerocapture Information Summary for Discovery Missions* - in-depth description of the technology
  - *Aerocapture for Discovery Missions* - standard briefing package
- *In-Space Propulsion Technology Project Low-Thrust Trajectory Tool Suite* -describes trajectory tools developed by the ISPT program that would be useful for determining mission trajectories if NEXT is utilized
- *Electric Propulsion Thruster Lifetime Qualification Standard* – ISPT's recommendation regarding a standard approach for electric propulsion thruster lifetime qualification
- *In-Space Propulsion Technologies Minimum Demonstration Requirements*

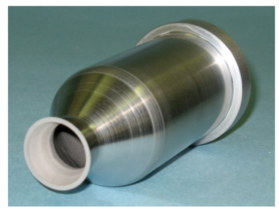
(AO pg42)

Advance Materials Bipropellant Rocket (AMBR)

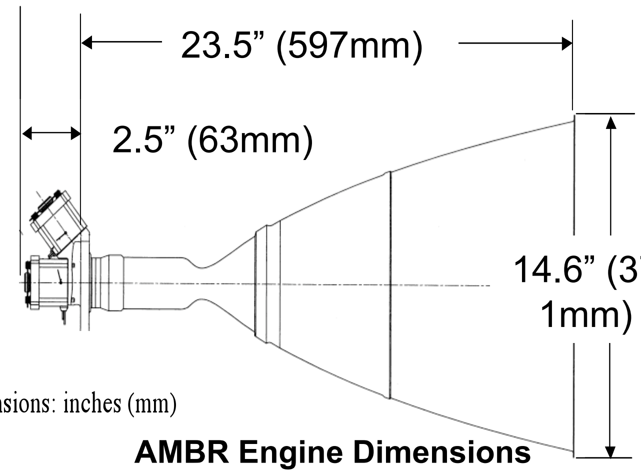
- Improve the HiPAT bipropellant engine Isp performance by fully exploiting the benefits of advanced thrust chamber materials
- Performance
  - * 333 seconds Isp with NTO/N2H4
  - * Over 1 hour operating (firing) time
  - * 140 lbf thrust
  - * 3-10 years mission life (goal)
  - * Lower cost (up to 30% savings on the chamber)

Primary Partners

- Aerojet Corp.: Lead
- PPI, MSFC, JPL



Completed EL-Form Ir/Re Chamber



AMBR Engine Dimensions

Total Propulsion System Mass Reduction (Kg)					
Isp (sec)	320	325	330	**332.5**	335
GTO to GEO	0	16	30	**37**	45
Europa Orbiter	NA	0	12	**16**	24
Mars Orbiter	N/A	0	14	**22**	29
T-E Orbiter	N/A	0	29	**45**	60

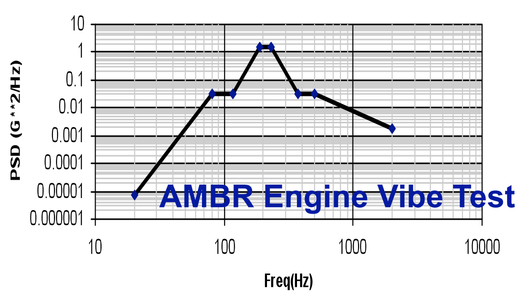
The AMBR technology is an improvement upon the existing HiPAT™ engine

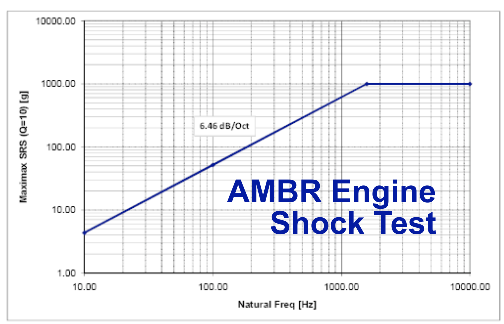
- The HiPAT™ engine is one of the Aerojet Corporation’s R-4D Family of thrusters
- The R-4D family of thrusters carries the heritage: >1000 engines delivered, >650 flown, 100% success

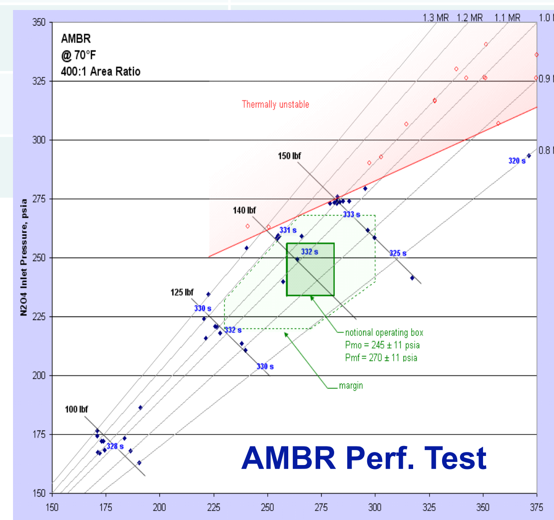
AMBR: a Proven Design for Higher Performance

Discovery Program

Design Characteristics	HiPAT DM	AMBR Design	AMBR Test Results 10/1/08	AMBR Test Results 6/25/09
Trust (lbf) (N2H4/NTO)	100		150	141
Specific Impulse (sec)	326/329		333.5	333
Inlet Pressure (psia)	250		275	250
Chamber Temperature (F)	3100	4000	≥3900	3900
Oxidizer/Fuel Ratio	0.85		1.1	1.1
Expansion Ratio	300:1 / 375:1	400:1		
Engine Mass (lbm)	11.5 / 12	12		
Physical Envelope		(Within existing HiPAT envelope (R4D-15-DM))		
Length (inch)	24.72 / 28.57	25.97		
Nozzle Exit Dia (in.)	12.8 / 14.25	14.6		
Propellant Valves	R-4D Valves	R-4D Valves		







Electric Propulsion

EP uses electrical power to provide kinetic energy to a gas propellant

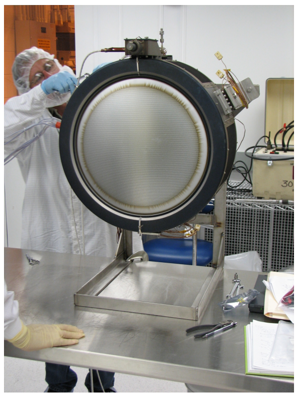
- Provides higher exhaust velocities than chemical engines
  - Reduces propellant mass needed to provide a given impulse
  - Allows reduction in launch mass or increase in payload/margin; can provide substantial benefits in mission cost
- Opens launch window over chemical systems in certain scenarios
- 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 science missions such as
    - DAWN (asteroid fly-by)
    - Hayabusa (asteroid sample return)
    - SMART-1 (lunar imaging)
    - DS-1 (comet fly-by)

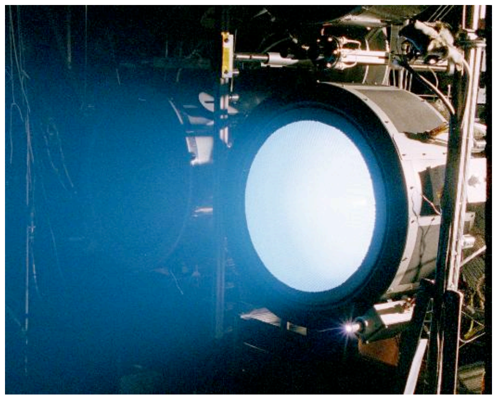
Additional considerations…

- 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

NEXT: Expanding SEP Applications For SMD Missions

Objective: Improve the performance and life of gridded ion engines to reduce user costs and enhance/enable a broad range of NASA SMD missions


NEXT gridded ion thruster


NEXT PM ion thruster operation at NASA GRC

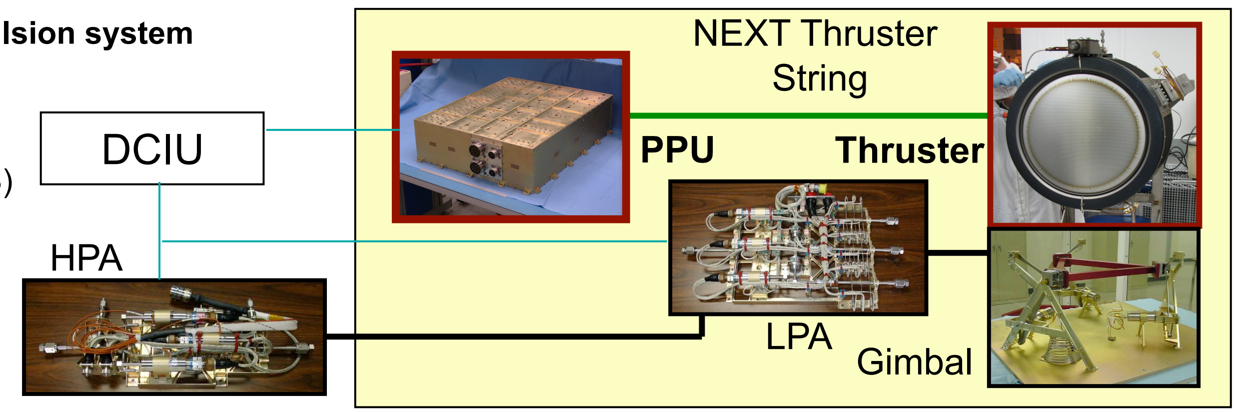
Thruster Attribute	
Thruster power range, kW	**0.5 - 6.9**
Max. Specific Impulse, s	**4,190**
Thrust range, mN	**26 - 236**
Propellant Throughput, kg	**450***
Mass (with harness), kg	**13.5**
Envelope dimensions, cm	**43.5 x 58.0**
Power Processing Unit Attribute	
Power Processing Unit mass, kg	**33.9**
Envelope dimensions, cm	**42 x 53 x 14**
Input voltage range, V	**80 - 160**
Feed System Attribute	
High Pressure Assembly mass, kg	**1.9**
Low Pressure Assembly mass, kg	**3.1**

NEXT addresses the entire ion propulsion system

- Gridded ion thruster
- Power processing unit (PPU)
- Propellant management system (PMS)
- System integration (including gimbal and control functions)

Primary Partners

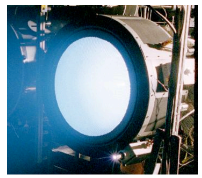
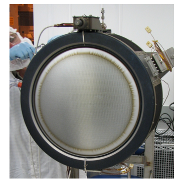
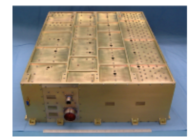
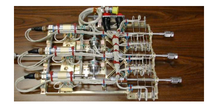
- NASA Glenn Research Center: Lead
- JPL, Aerojet Corp., L3 Comm.

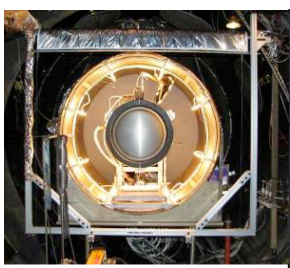


* Rated Capability Goal 300Kg → Design/Qualification Goal (1.5x Rated) 450Kg
Projected 1st Failure >750Kg → Potential Rated Capability 500Kg

NEXT is Nearing TRL6 Validation

Discovery Program

• Critical tests have been completed, or are imminent, on high fidelity hardware	PM1 	PM1R 	PPU 	Feed System 	Gimbal 
Functional & Performance Testing	**Complete**	**Complete**	**Complete**	**Complete**	**Complete**
Qual-Level Vibration Test	**Complete***	**Complete**	**FY10**	**Complete**	**Complete**
Qual-Level Thermal/ Vacuum Test	**Complete**	**Complete**	**FY10**	**Complete**	**Not planned**

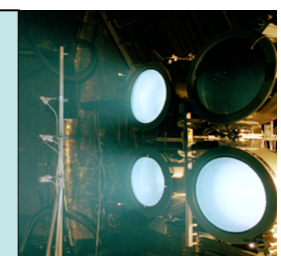


Single-String System Integration Test: **Complete**

Multi-String System Integration Test: **Complete**

Thruster Life Test: **Completed** goal of 450Kg throughput

- ***>26,450 hours and >450 kg of xenon processed as of 12/31/09***
- Life Test will continue through 750Kg or first failure



NEXT Benefit chart

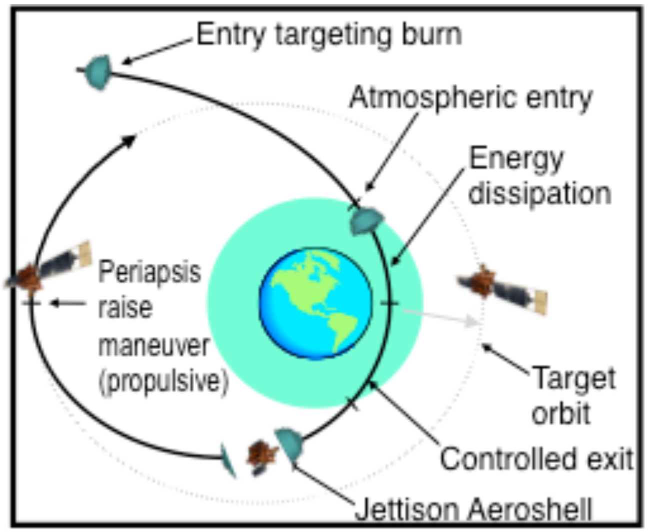
CHARACTERISTIC 	NSTAR (SOA)	NEXT	Improve-ment	NEXT BENEFIT
Max. Thruster Power (kW)	**2.3**	**6.9**	**3x**	**Enables high power missions with fewer thruster strings**
Max. Thrust (mN)	**91**	**236**	**2.6x**	
Throttling Range (Max./Min. Thrust)	**4.9**	**13.8**	**3x**	**Allows use over broader range of distances from Sun**
Max. Specific Impulse (sec)	**3120**	**4190**	**32%**	**Reduces propellant mass, enabling more payload and/or lighter spacecraft**
Total Impulse (10^6 N-sec)	**4.6**	**>18**	**>3.9x**	**Enables low power, high ΔV Discovery-class missions with a single thruster**
Propellant Throughput (kg)	**150**	**450**	**3x**	

Mission	Performance Finding
Discovery - Small Body Missions	**Higher net payload mass with fewer thrusters** than NSTAR system
New Frontiers - • Comet Surface Sample Return • Titan Direct Lander	CSSR: **Higher net payload mass** than NSTAR, with, **simpler EP System**: 2+1 NEXT vs 4+1 NSTAR thrusters Titan: > 700 kg entry package with 1+1 NEXT system
Flagship - Saturn System Missions • Titan • Enceladus	> 2400 kg to Saturn Orbit Insertion with 1+1 NEXT system, EGA + Atlas V EELV - **Doubles delivered mass of chemical/JGA approach** > 4000 kg to Saturn Orbit Insertion with 3+1 NEXT system, EGA + Delta IV Heavy

Aerocapture Overview and Benefits

Description

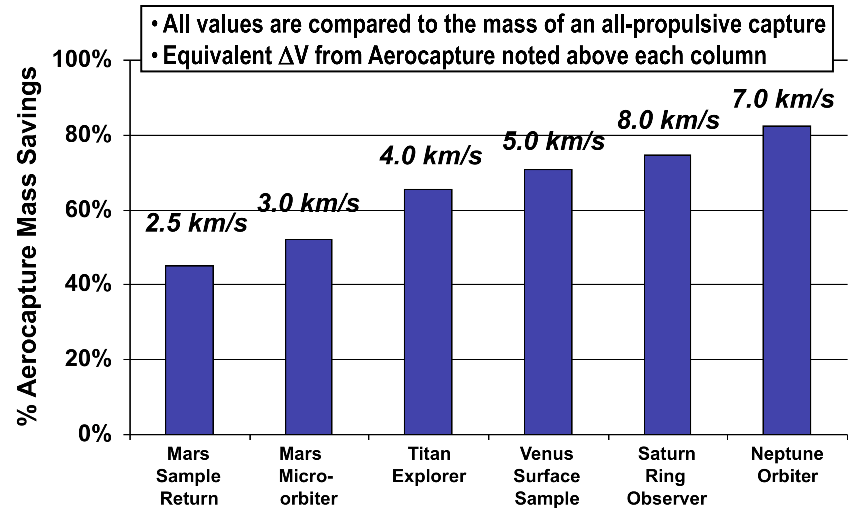
Aerocapture is a spaceflight maneuver executed upon arrival at a body in which atmospheric drag, instead of propulsive fuel, is used to decelerate the spacecraft into a specific orbit. Aerocapture is a natural extension of other commonly-used flight maneuvers using atmospheres: aeroentry and aerobraking.



Objective

- To develop Aerocapture systems for exploration of the Solar System and to validate those systems in their relevant environments
- Raise Aerocapture propulsion to TRL 6+ through the development of subsystems, operations tools, and system level validation and verification

Benefits



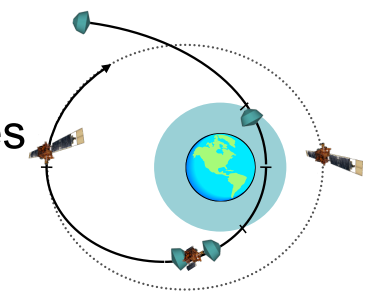
Discipline Areas

- Aerocapture builds upon well established entry system design processes and tools:
  - Atmospheric modeling
  - GN&C algorithm advancement
  - Materials development
  - Aerodynamics
  - Aerothermodynamic modeling
  - Systems engineering and integration
  - Rigid aeroshell technology including: TPS, structures, adhesives and sensors
  - Inflatable deceleration system concepts

Aerocapture Technology Development Products

Supporting Software, Tools and Analysis - Ready to Infuse

- Aerocapture Guidance and Control Hardware-in-the-Loop Testbed (Ball):
  - Real-Time simulation testbench written in flight software code, hosted on flight space computer with flight or flight-like interfaces
  - Demonstrates execution within flight-like avionics system, verifies communication paths and the absence of timing issues
  - Brings Analytic Predictor-Corrector Algorithm to TRL6



- Aerothermal and atmospheric codes
  - Extensive work completed over the past 7 years to improve aerothermal prediction capability, particularly by validating codes through ground test of fundamental physics—over 50 published papers (led by ARC)
  - Engineering-level atmospheric models developed and improved for nearly every destination in the Solar System; incorporated directly into high-fidelity flight dynamics simulations (led by MSFC)
- Aerocapture Quick-Look Tool
  - End-to-end engineering-level conceptual design and trade tool for assessing aerocapture concepts
  - Available through LaRC software request process