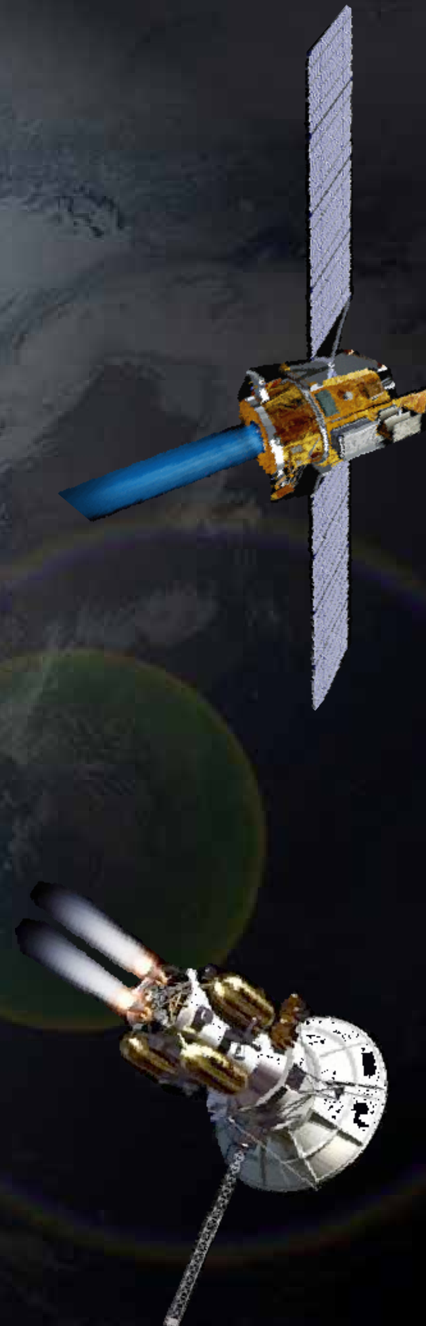
In-Space Propulsion Technology (ISPT) Project Overview



Planetary Science Subcommittee Meeting, October 3, 2008

David Anderson
ISPT Project Manager (Acting)

The What and Why of ISPT

- ISPT Objective: "*develop in-space propulsion technologies that can enable or benefit near to mid-term NASA science missions by significantly reducing travel times required for transit to distant bodies, increasing scientific payload capability or reducing mission costs*"

- The ISPT project is the only NASA project that addresses the primary propulsion technology needs for the agency's future robotic science missions.
  - Development occurs in the TRL 3-6+ range.

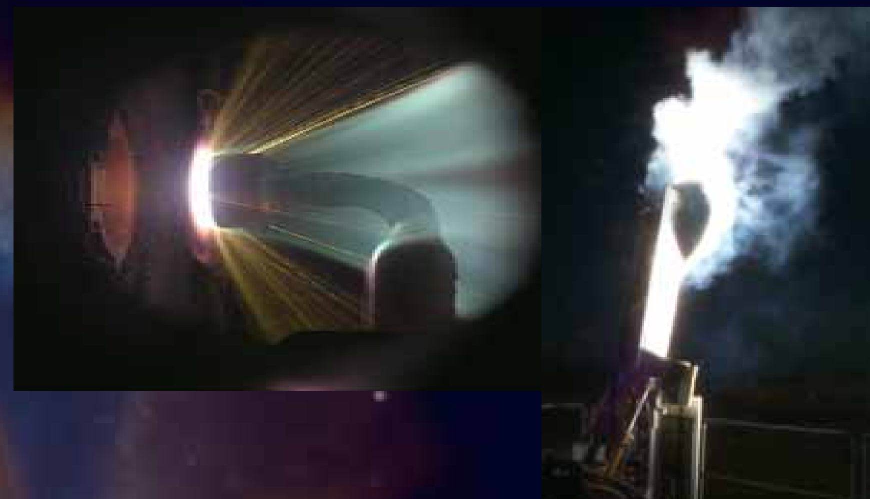
The current ISPT project focus is on completing our near TRL6 products

Technology Products At or Nearing TRL 6

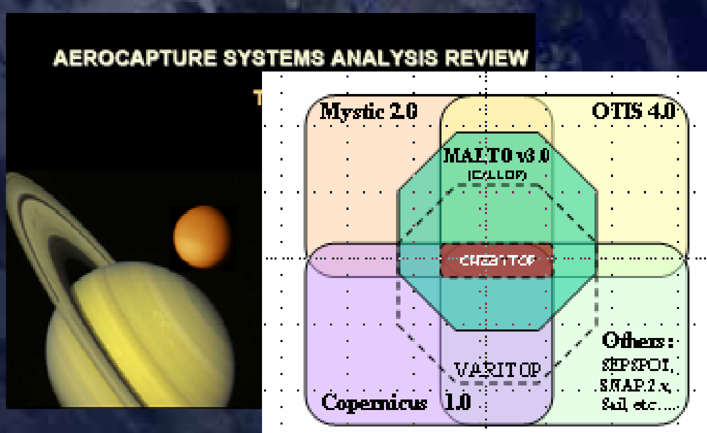
NEXT Electric Propulsion System

HiVHAC Hall Thruster

Aerocapture Technologies



Systems Analysis Tools



AMBR High Temperature Rocket

Advanced Chemical Propulsion

Advanced Materials Bi-propellant Rocket (AMBR)

Approach: Enhancing a proven commercial product (Aerojet's HiPAT engine)

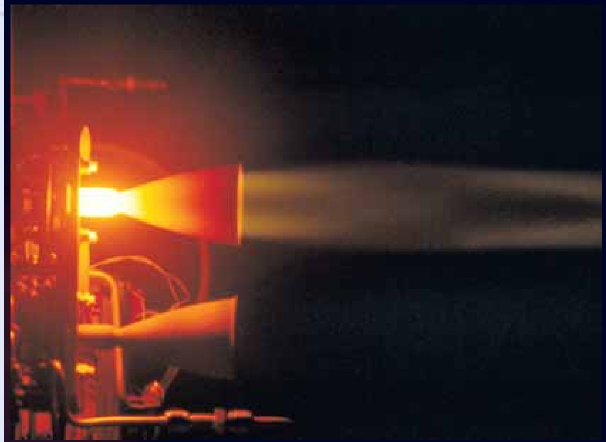
AMBR: a high temperature bi-propellant Ir/Re engine

- Benefit: Mass saving 60 Kg for a conceptual high-energy mission over SOA chemical engine, lower cost, advanced manufacturing and materials
  - Attain TRL 6 for storable bi-propellant, Ir/Re, apogee class engine in by early FY09
    - Including life, vibe and shock testing
  - Achieve the objective by increasing engine performance by increasing operating temperature and thereby (I_{sp})

Advance Materials Bipropellant Rocket (AMBR)

Objective

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



Approach

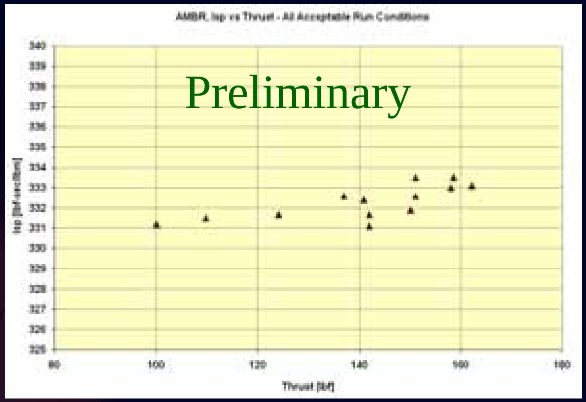
- Adopt operating conditions to allow the thruster to run at higher temperatures and pressures
- Test a baseline engine for model development
- Evaluate materials and fabrication processes
- Develop advanced injector and chamber design
- Fabricate and test a prototype engine
- Perform environmental testing: life hotfire, vibe, and shock tests

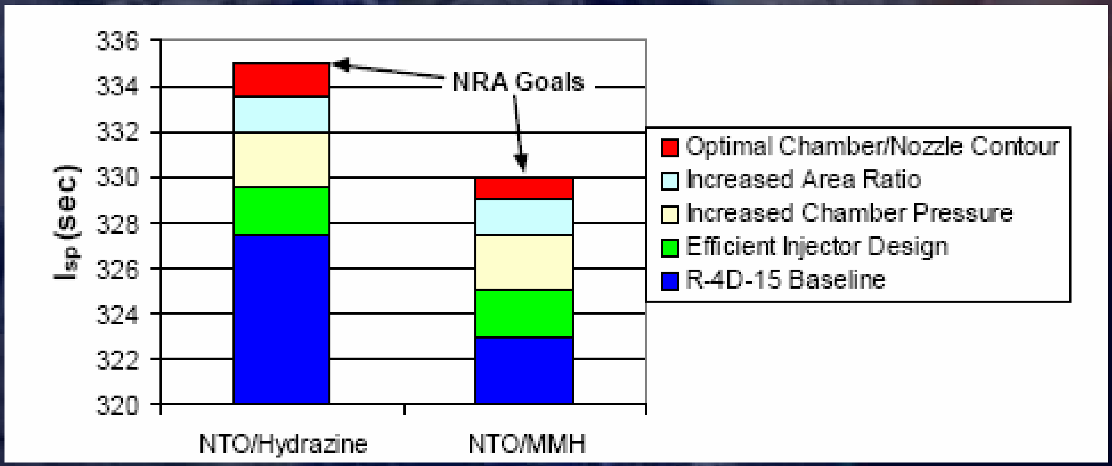
Remaining Tasks

- Completing AMBR prototype fabrication (3rd Quarter 2008)
  - Injector assembly, combustion chamber, nozzle, and nozzle extension
- Testing AMBR prototype to verify performance (4th Quarter 2008)
- Carrying out environmental tests (2008/2009)
  - Vibration (Aerojet)
  - Shock (JPL)
  - Hotfire life test (Aerojet)

Proven Design for Higher Performance

Design Characteristics	AMBR	HiPAT DM	AMBR Test Results
• Trust (lbf) (N2H4/NTO)	200	100	150
• Specific Impulse (sec)	335	328	333.5
• Inlet Pressure (psia)	400	250	275
• Chamber Temperature (F)	4000	3100	3900
• Oxidizer/Fuel Ratio	1.2	1.0	1.1
• Expansion Ratio	400:1	300:1	400:1
• Physical Envelope	Within existing HiPAT envelope (R4D-15-DM)		
• Propellant Valves	Existing R-4D valves		





- 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 rate

Mission and System Studies Show Benefit

- Conducted mission and system studies to identify propulsion technology requirements and impacts

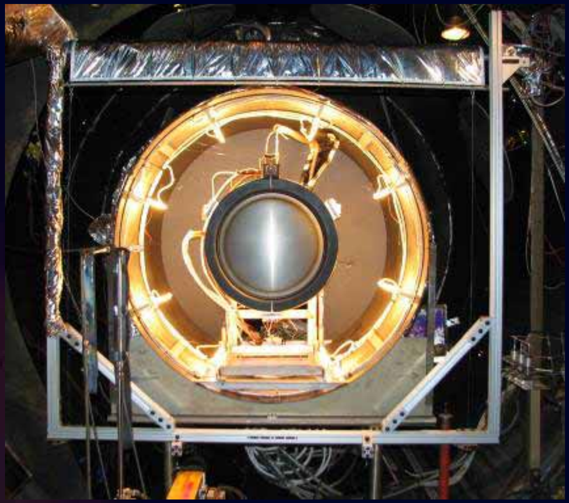
AMBR Engine potential mass reduction (payload gain) for various missions

- Results show increased performance can reduce the propellant required to perform spacecraft maneuvers.
- Propellant reduction implies increase of payload or margin

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

Broad mission applicability. Lowers cost and increases performance. TRL 6 in 2009!

Electric Propulsion



Technology Development Highlights

- NEXT (NASA's Evolutionary Xenon Thruster) Ion Propulsion System
- Benefit: specific impulse increased 32%, >2x increase in throughput, throttle range increased 3x, specific mass decreased 50% over SOA Ion
  - Improve performance/life of ion propulsion system (IPS)
  - Demonstrate TRL6 system readiness through operation of a system integration test (SIT) system of prototype model components (thruster, power processing unit (PPU), feed system)

- HiVHAC (High Voltage Hall Accelerator) Thruster
- Benefit: Total system cost reduction relative to SOA IPS, specific impulse increased 68% and xenon throughput increased 2x over SOA Hall
  - Specifically developing a low cost, high reliability product for cost-limited missions
  - Develop low power, long-life Hall thruster for Discovery missions

- Standardization and components
- Benefit: Total system cost reduction relative to SOA IPS, specific mass and other improvements over SOA
  - Feed system, Distributed Control Interface Unit, …

NEXT Ion Propulsion System

NASA's Evolutionary Xenon Thruster (NEXT)

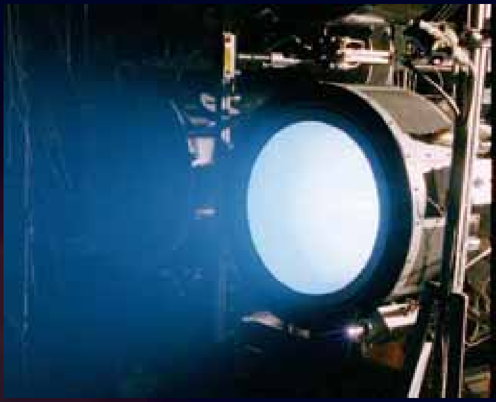
Objective

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

Thruster Attribute	SOA	NEXT
Max. Input Power (kW)	2.3	Up to 6.9
Throttle Range	4:1	>12:1
Max. Specific Impulse (s)	3,170	4,190
Efficiency @ Full Power	62%	71%
Propellant Throughput (kg)	235	>300 (design)
Specific Mass (kg/kW)	3.6	1.8

A high performance EP system with broad applicability. System demonstrated in relevant environment in FY08

NEXT gridded ion thruster



NEXT PM ion thruster operation at NASA GRC

Key Milestones / Accomplishments

- **Multi-thruster array test** of 3 operating engineering model (EM) thrusters and 1 instrumented spare completed at GRC Dec 2005
- **EM thruster extended duration test** initiated June 2005, has exceeded 17,450 hours and 355-kg throughput as of 09/04/08 (DS-1 <80-kg)
- **Prototype model (PM-1) thruster passed qual level environmental testing** at JPL in 2007.
- **PM-1 single string test** completed.
- **Demonstration of system TRL 6 except completion of life testing**

NEXT is Nearing TRL 6 Validation

- 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	2008	Complete	Complete
Qual-Level Thermal/ Vacuum Test	Complete	Complete	2008	Complete	Not Applicable

- Single-String System Integration Test: March 2008 - September 2008
- Multi-Thruster Integration Test: Completed September 2008
- Thruster Life Test: In progress & continuing through FY2010

NEXT – Mission Benefits

	Discovery (<10 kW)			New Frontiers (< 20kW)			Flagship	
	Dawn	Near Earth Asteroid Sample	Comet Rendezvous	Titan Lander	CSSR	JPOP	Titan	Neptune
Single NSTAR	X	X						
Multi-NSTAR		X	X	?				
HiVHAC	XX	XX	XX	?	XX			
NEXT	X	X	X	X	X		X	X

X= Applicable
XX= Possibly Cost Enabling
?= Not Evaluated
Not Applicable

NSTAR: NASA Solar Electric Propulsion Technology Application Readiness
NEXT: NASA's Evolutionary Xenon Thruster
HIVHAC: High Voltage Hall Accelerator

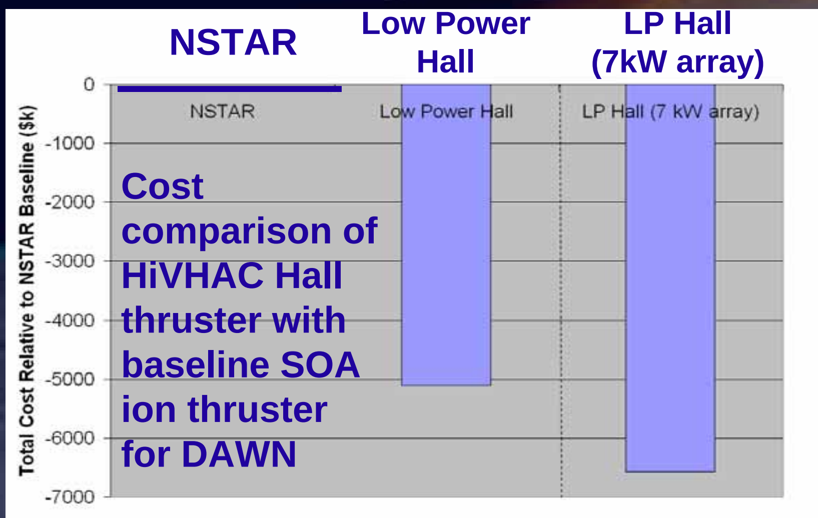
Mission	Performance Finding
Discovery- Small Body Missions • Near Earth Asteroid Rendezvous • Vesta-Ceres Rendezvous (Dawn) • Comet Rendezvous • Deimos Sample Return	Higher net payload mass with fewer thrusters than NSTAR system
New Frontiers - Comet Surface Sample Return	Higher net payload mass than NSTAR, with, Simpler EP System: 2+1 NEXT vs 4+1 NSTAR thrusters
New Frontiers - Titan Direct Lander	>700 kg entry package with 1+1 NEXT system, potentially within New Frontiers cost cap
Flagship - Saturn System Missions • Titan • Enceladus	> 2400 kg to Saturn Orbit Insertion with 1+1 NEXT system, Earth Gravity Assist and Atlas 5 EELV (2x delivered mass of chemical/JGA approach) > 4000 kg to Saturn Orbit Insertion with 3+1 NEXT system, Earth Gravity Assist and Delta IV Heavy

NEXT provides mission benefits across *all* planetary science mission classes

High Voltage Hall Accelerator (HiVHAC) Thruster

Objective

Develop low power, long-life Hall thruster to reduce the cost of Discovery-class EP



A low power, low cost, high reliability EP thruster for future science missions.

NASA-77M

NASA-94M (SOA)

NASA-103M (ASOA)

Key Milestones/Accomplishments

- **NASA-103M (ASOA) hall thruster fabrication and assembly** in August 2006
- **NASA-103M wear test** (>4630 hours of life and 97 kg throughput accumulated as of 8/31/08)
- **Full EM Thruster design and fabrication** based on validated life tests completed in FY08
- **Advanced Hall thruster erosion modeling** ongoing at the University of Michigan and JPL

Aerocapture System

Technology Development Highlights

- Advanced lightweight ablators & high-temp & sensors
- Benefit: Decreases mass 20-30% over SOA heatshield
  - Attain TRL6 for lightweight heatshield systems at 1-meter scale by manufacturing 3 aeroshells, testing at solar tower, and developing finite element models
  - Manufacture full-scale (2.65m) lightweight, high-temperature aeroshell and perform standard qualification testing on it (Vibro-acoustic, thermal-vac, mechanical loading, etc.)
- Rib-stiffened Carbon-Carbon (C-C) aeroshell
- Benefit: Decreases mass 30+% over Genesis heatshield
  - Manufactured 2m demo article and mechanically tested to representative loads – ready for infusion
- Simulations and Modeling
- Benefit: Reduces risk for infusion and minimizes TPS margin
  - Develop Hardware In-The-Loop simulation for Guidance, Navigation, and Control (GN&C) software to raise to TRL6 for aerocapture at all destinations
  - Continue modeling of aerothermal environments to allow reduction in TPS margin, risk assessment
  - Continue atmospheric model development to incorporate most recent scientific data

Studies and Tools

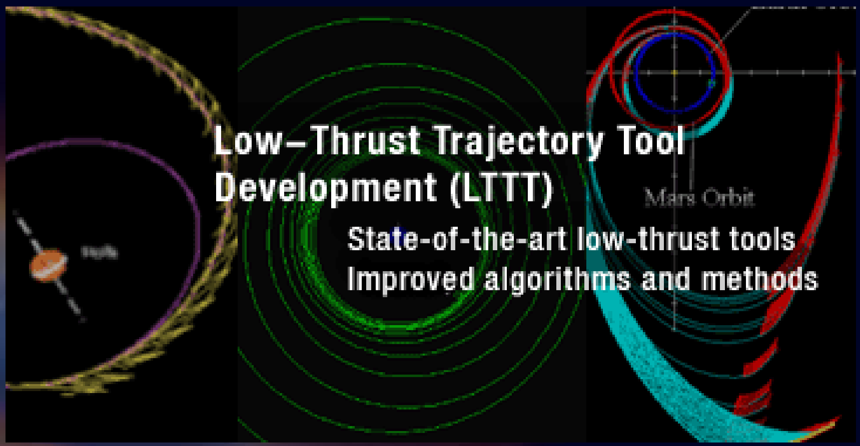
Objective

- To enhance NASA and industry mission analysis capabilities and consistency by providing trajectory generation/ optimization tools for low thrust propulsion technologies.
- Inform decisions and infuse products
- To enable mission trajectory analysts to produce uniform results across all NASA centers

Recent efforts

- Aerocapture Quicklook tool
- Life qualification approach for EP systems
- Chemical propulsion trades
- EP parameters for a radioisotope powered mission

– Provide expertise or training to proposers, evaluators or others as requested



Recent Products

- Suite of Low-Thrust Tools delivered March 2006
  - **Copernicus** v3/28/06
  - **SNAP** v2.3 (Spacecraft N-Body Analysis Program)
  - **MALTO** v4.4 (Mission Analysis Low-Thrust Optimization)
  - **Mystic** v9.0
  - **OTIS** v4.0 (Optimal Trajectory by Implicit Simulation)
- LTTT website on-line April 2006 http://www.inspacepropulsion.com/LTTT/
- Numerous abstracts of papers for the AIAA/AAS Astrodynamics Specialist Conference (ASC) accepted for presentation

Product Infusion

Commitment to Product Infusion by the ISPT Project & SMD

- SMD has stated that it desires that ISPT products be utilized and proposed on missions and is committed to encouraging proposers to do that on upcoming missions
- The upcoming New Frontiers 3 AO will provide an incentive to infuse NEXT or AMBR into the proposed missions
- ISPT is dedicated to completing the propulsion products and assisting in their infusion onto future NASA science missions
- The project can confidentially assist potential users with information and other support *

ISPT products nearing infusion readiness into NASA science missions.

* To discuss options please contact: David Anderson, ISPT Project Manager (Acting) 216/433-8709 or David.J.Anderson@nasa.gov

Back-up

Why Does ISPT Exist

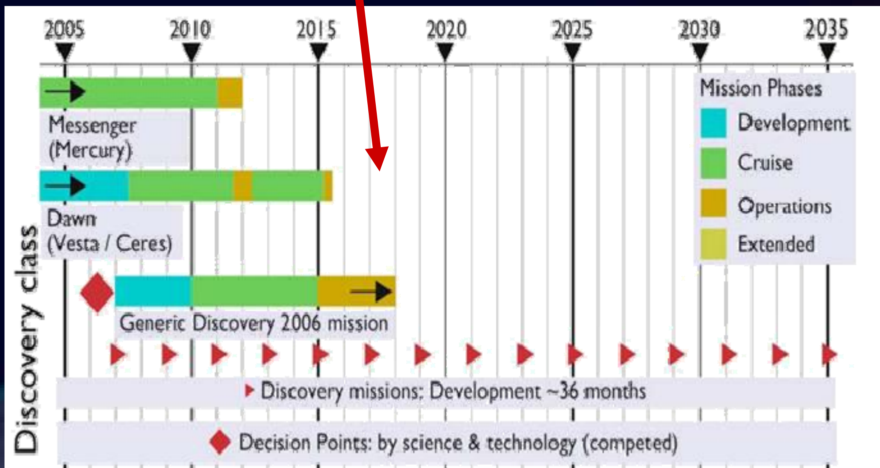
The NASA Science Missions of greatest interest (as as defined by the Decadal Survey, The Solar System Exploration Roadmap, Heliophysics Roadmap,…) identify in-space transportation technologies that need to be development if these missions are to be successfully implemented.

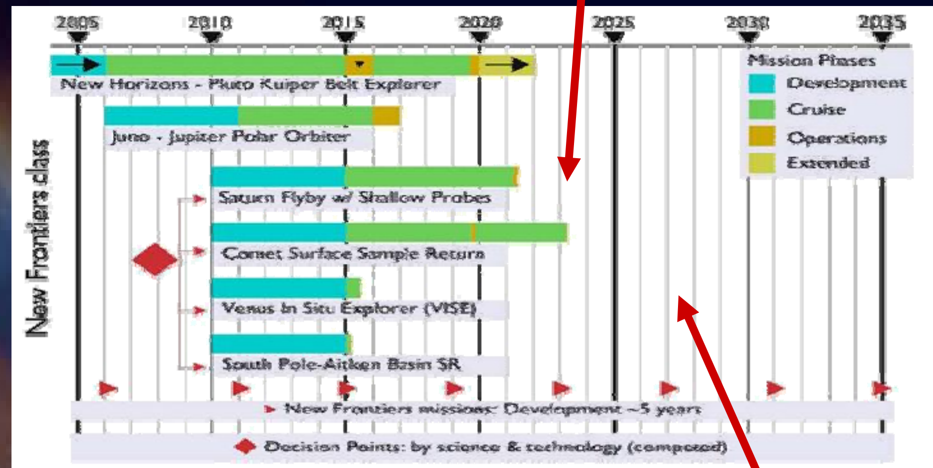
The ISPT project exists because its technology products are pulled by NASA Science Missions.

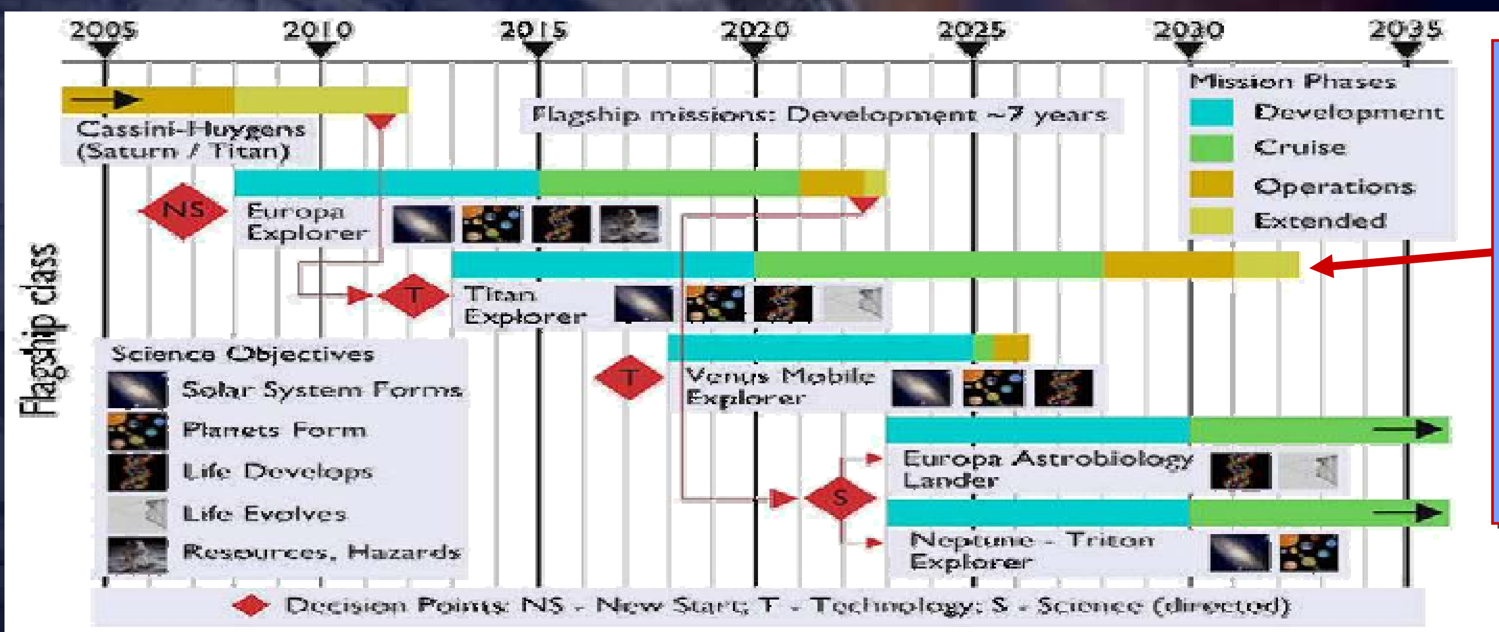
National Aeronautics and Space Administration

Solar System Exploration (SSE) Missions of Interest

Competed missions keep cost a priority and pull the broadly applicable high performing technologies







Flagship and directed missions pull specific technologies and define performance needs

Needed Transportation Technologies for SSE

- *SSE Table 4.1: Technology Priorities for Solar System Exploration*

Technology	Priority	Comments
SPACECRAFT SYSTEMS		
Transportation	●	▹ Aerocapture technologies could enable two proposed Flagship missions, and solar electric propulsion could be strongly enhancing for most missions. These technologies provide rapid access, or increased mass, to the outer Solar System.
Power	●	▹ Radioisotope power systems are needed for all five proposed Flagship missions, requiring a sufficient supply of plutonium. Advances in power conversion efficiencies would reduce the need for plutonium for a given power requirement, while the mass savings could be traded against payload, or increase mass margin on the spacecraft.
Communications	●	▹ The science return from every mission would benefit from improvements in direct–to–Earth communications infrastructure. In situ exploration with orbital assets would be strongly enhanced by improved proximity links.
Planetary protection	▲	▹ New planetary protection technologies will be needed to meet the anticipated requirements for in situ exploration to targets of interest for astrobiology.
Autonomy and software	▲	▹ Autonomous systems strongly enhance most missions by providing for more robust operations. New methodologies for software verification and validation and fault protection will substantially reduce the associated risks.
IN SITU EXPLORATION SYSTEMS		
Extreme environments	●	▹ The proposed Flagship mission set spans a number of diverse extreme environments, requiring technology advances in fields ranging from extremes in temperature and pressure, to high radiation and high heat flux during atmospheric entry. These technologies could also enhance the operational capabilities of the Discovery and New Frontiers missions facing temperature extremes or those with returned samples.
Entry, descent, and landing	▲	▹ New propulsive landing systems would enable operations on small bodies and satellites without atmospheres. Entry, descent, landing, and aerial operations on bodies with atmospheres (such as Titan and Venus) would be possible with the associated advances in technologies for extreme environments.
Planetary mobility	▲	▹ Access is critical to the in situ exploration central to the later Flagship mission concepts, making various types of mobility systems enabling for those missions. Advances in mobility technologies could also provide alternatives for various New Frontiers mission concepts.
SCIENCE INSTRUMENTS		
In situ sensing	●	▹ New technologies and instruments will be required for improved science return to targets of astrobiological interest, enabling several of the proposed Flagship missions. The instrument technologies will require associated development in sample acquisition and handling systems.
Components and miniaturization	●	▹ Every mission is either strongly enhanced or enabled by improvements in miniaturization and advanced component design. Missions with systems requiring isolation from the ambient environment will be particularly improved by lighter instrumentation.
Remote sensing	▲	▹ Flagship missions with orbital or extended aerial operations would be strongly enhanced by improved technologies for passive and active remote sensing, and smaller missions would benefit from these technologies, as well.

● Highest priority — new developments are required for all or most roadmap missions
▲ High priority — either applications are more limited or can leverage existing work effectively

Aerocapture and Electric Propulsion are the highest priority technologies

Another application/need for Advanced Chemical technologies?

Tracing Missions to SMD Objectives and Science Questions

SMD objectives and science questions drive missions

SSE Table 3.1: Traceability Matrix – Scientific Questions, Objectives, and Missions

Major Questions	R&A		Discovery				New Frontiers						Flagship (Small/Large)							
Objectives	Expt.‡	Theory	SB	Moon	Venus	Mercury	NH	Juno	SPABSR	VISE	CSSR	SP	C–H	EE	TE	VME	EAL	NTE	*CCSR**	*VSSR**
How did the Sun's family of planets and minor bodies originate?																				
Understand the initial stages of planetary and satellite formation	●	●	●	●	▲	▲	●	●	●		▲	●	▲	▲	▲	▲		●	●	●
Study the processes that determine the original characteristics of bodies in the Solar System	●	●	●	●		▲	▲	●	▲		●	●	▲	▲	▲			●	●	●
How did the Solar System evolve to its current diverse state?																				
Determine how the processes that shape planetary bodies operate and interact	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	●	●	●	●	●	●	●	●
Understand why the terrestrial planets are so different from one another	▲	▲			●	▲			▲	●						●				●
Learn what our Solar System can tell us about extrasolar planetary systems	▲	▲					▲	▲				▲	●	▲	▲	●		▲		●
What are the characteristics of the Solar System that led to the origin of life?																				
Determine the nature, history, and distribution of volatile and organic compounds in the Solar System	▲	▲	▲				●	●		▲	●	●	●	●	●	●	●	●	●	●
Determine evidence for a past ocean on the surface of Venus	▲	▲			▲					▲						●				●
Identify the habitable zones in the outer Solar System	▲	▲											●	●	●		●	●		
How did life begin and evolve on Earth and has it evolved elsewhere in the Solar System?																				
Identify the sources of simple chemicals important to prebiotic evolution and the emergence of life	●	▲	▲				▲						●	▲	●		●	▲	●	
Evidence for life on Europa, Enceladus, and Titan	▲	▲											▲	▲	●		●			
Evidence for past life on Venus	▲	▲														▲				●
Study Earth's geologic and biologic record to determine the historical relationship between Earth and its biosphere	●	▲																		
Identify environmental hazards and resources enabling human presence in space																				
Determine the inventory and dynamics of objects that may pose an impact hazard to Earth	●	▲	●				▲													
Inventory and characterize planetary resources that can sustain and protect human explorers	▲	▲	●						▲		●									

Convention: ● Major or Unique Contribution; ▲ Support Contribution

SB — small bodies; NH — New Horizons; SPABSR — South Pole–Aitken Basin Sample Return; VISE — Venus In Situ Explorer; CSSR — Comet Surface Sample Return; SP — Saturn Flyby with Shallow Probes; C–H — Cassini–Huygens; EE — Europa Explorer; TE — Titan / Enceladus Exp.; VME — Venus Mobile Exp.; EAL — Europa Astrobiology Lander; NTE — Neptune–Triton Explorer

*CCSR — Cryogenic Comet Surface Sample Return; VSSR — Venus Surface Sample Return * — beyond the 8 proposed Flagship missions*

‡ — "Expt" includes ground– and space–based observations with a range of NASA facilities including the Hubble and Spitzer Space Telescopes and, in the next decade, the proposed James Webb Space Telescope.

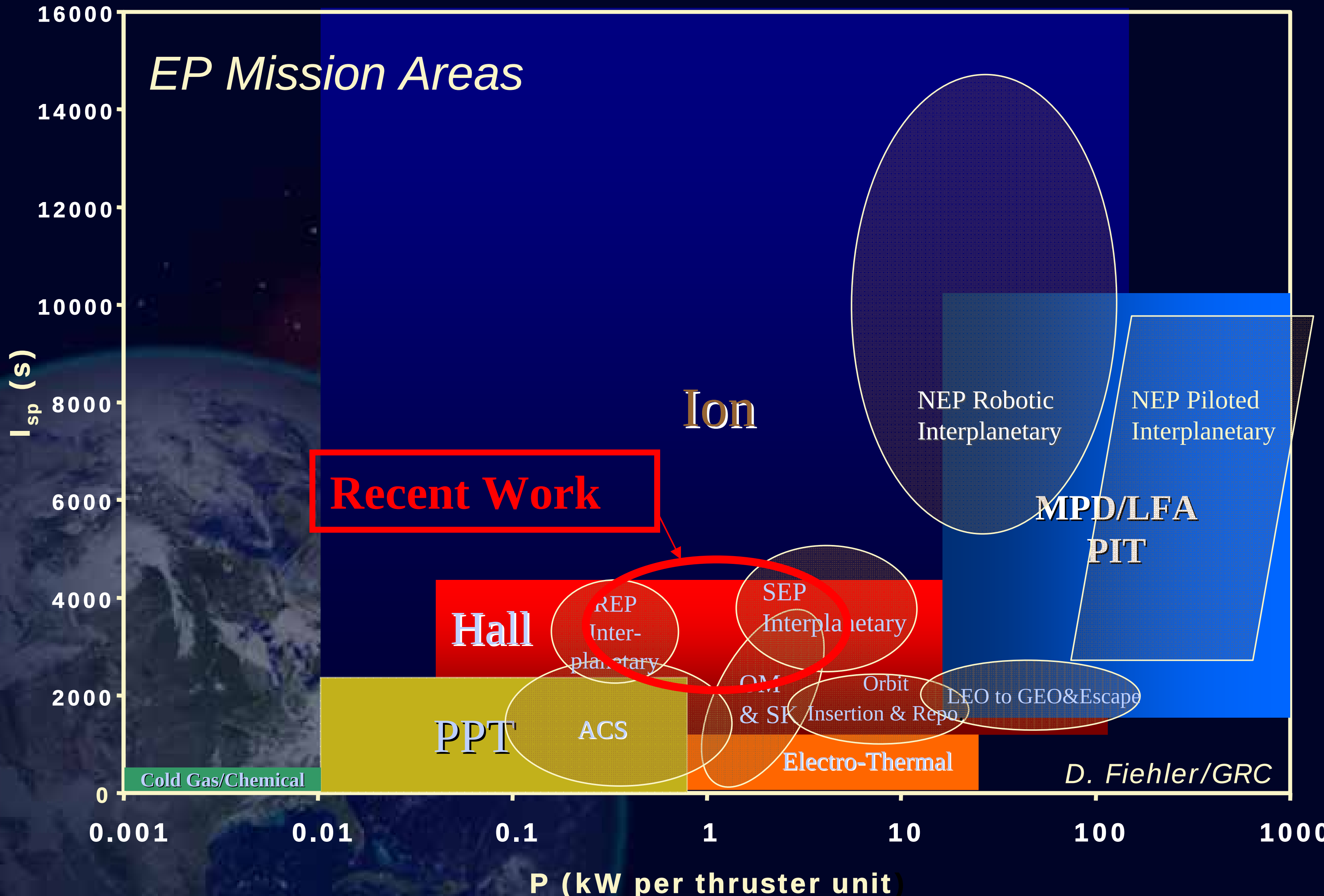
Needed Transportation Technologies per Roadmaps

ISPT investments trace to SMD objectives and science questions through missions

Major Questions	Discovery				New Frontiers						Flagship (Small/Large)									LWS			MIDEX
Objectives	SB	MOON	VENUS	MERCURY	NH	JUNO	SPABSR	VISE	CSSR	SP	C-H	EE	TE	VME	EAL	NTE	CCSR*	VSSR*	INTERSTELLAR PROBE	HELIOSTORM	SPI	DBC (+)	
Spacecraft Systems Technologies																							
Transportation																							
Access to Space					⊖	⊖					⊖				■	■							
Solar Electric Propulsion	■	■	■	■	⊖	⊖			■	■	⊖		■		■	■	■	■					
NEXT	●			■					●	■			●		■	●	●	■					
Hall	●	■	■	■					●	■													
Standard Architecture	Pending final definition of products.																						
Aerocapture / Aeroassist			■		⊖	⊖	■				⊖		■	■		●		■					
TPS			■				■						●	■		●		■					
Sensors			■				■						●	■		●		■					
Inflatable Decelerators													●	■		■							
GNC			■										●	■		●							
Modeling			■				■						●	■		●		■					
Advanced Chemical Propulsion		■		■	⊖	⊖				■	⊖	■		■	●			■					
High-Temp Thrust		■		■						■		■		■	●			■					
Light-Weight Components		■		■						■		■		■	●			■					
Solar Sails																							
Inflation Deployed, Tip-Vane Controlled, Mylar Sail Material																			■	●	●	●	■
Coilable/Rigid Boom, CM/CP Shift Control, CP1 Sail Material																			■	●	●	●	■
Advanced Materials (Higher temperature, reflectivity and emissivity)																			●				■

● *Major Contribution* ■ *Support Contribution* ⊖ *On-Going Mission*

EP Description

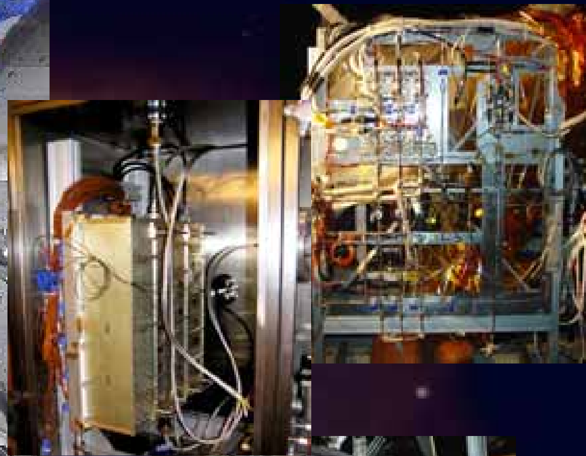


NEXT Hardware

EM PPU

EM3 wear test

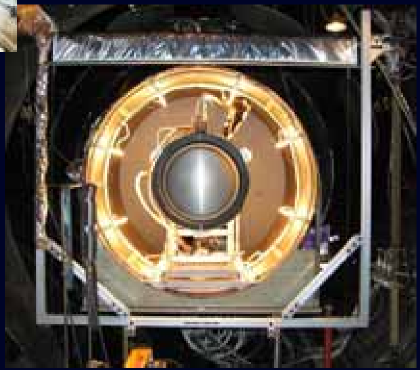
System Integration
Test Set-Up



PM Thruster

NEXT Multi-Thruster Array

Gimbal vibe test



Thermal cycle

EP Technical Approach

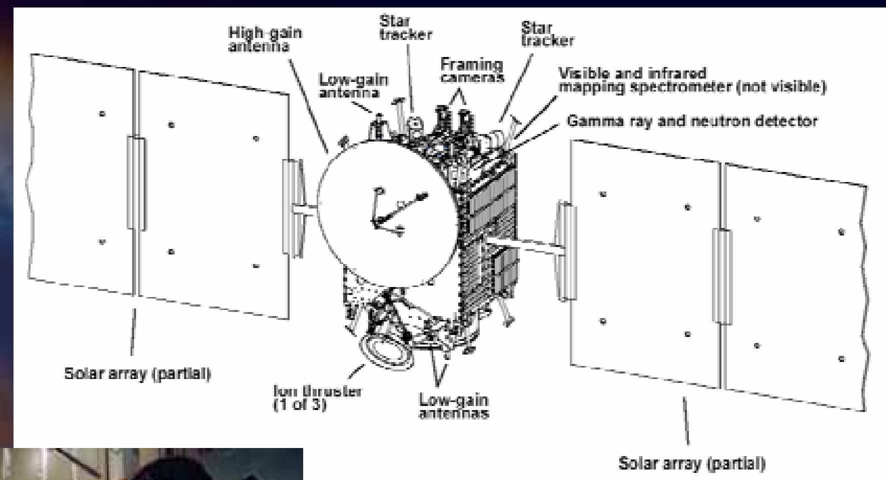
Technology Performance Parameter		SOA	Projection (Status)	Goal (Target Metric)
NEXT		(NSTAR)		
Thruster	Efficiency	0.60η & 3100 sec at 2300 w	0.71η at > 4190 sec Demonstrated - PM test	0.68η & 4050 sec at 6850 w
	Efficiency	0.38η & 1780 sec at 430 w	0.32η at > 1400 sec Demonstrated - PM test	0.32η & 1400 sec at 540 w
	Mass	150 kg Xe throughput	266 kg on EM3 - 11/13/07	> 300 kg Xe throughput
	Mass	8.3 kg	12.7 kg PM actual	< 14 kg
PPU	Mass	14.8 kg (6.4 kg/kw)	< 33.9 kg, EM actual (4.9 kg/kw)	< 26 kg (< 3.8 kg/kw)
	Temperature	20-50 deg C baseplate	25-60 deg C baseplate, design projection	25-60 deg C baseplate
	Efficiency	0.89 - 0.92η eff over power range	> 0.94η eff at full power, > 0.85η high voltage power eff over power range, in benchtop unit tests	> 0.95η eff at full power, > 0.89η eff over power range
PMS	Mass	< 10.9 kg (single string primary components)	5 kg EM actual (single string assemblies)	< 6.7 kg (single string assemblies)
	Accuracy	control flows to +/- 3%	+/- 3% demonstrated EM test	control flows to 3%
HIVHAC		(SPT-100)	(NASA-103M.XL)	
Thruster	Efficiency	0.50η & 1450 sec at 1400 w	0.30η & 1200 sec at 300 w, test	0.30η & 1200 sec at 300 w
	Efficiency	0.50η & 1450 sec at 1400 w	0.54η & 2700 sec at 3.5 kw, test	0.54η & 2700 sec at 3.5 kw
	Mass	5.6 kg (4 kg/kw)	7.2 kg (2.1 kg/kw) (lab model)	< 7.2 kg (2.1 kg/kw)
	Mass	150 kg Xe throughput	300 kg Xe throughput projected by test and analysis	300 kg Xe throughput
VACCO AXFS		NSTAR		
PMS (Chems)	Mass	14.5 kg	2.6 kg (3 FCM actual + 1 PCM projected); 0.7 kg single string	< 2.3 kg (single string)
	Accuracy	control flows to +/- 3%	<1% demo in FCM acceptance test	control flows to +/- 3%

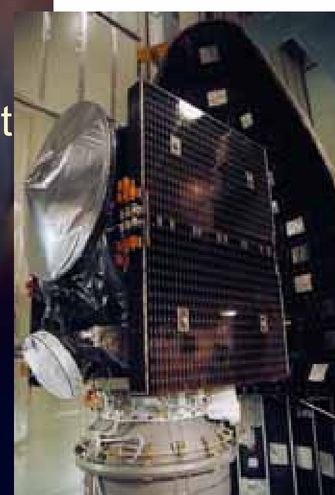
Technology Infusion

- Infusion of IPS into Dawn mission

ISPT supported EP technology development for a SMD mission

- **NSTAR thruster Extended Life Test (ELT)**
  - ISPT agreed to make the ELT a test-to-failure
  - ELT data established IPS throughput capability to reach both Vesta and Ceres
  - Required by NASA HQ to approve flight implementation
- **Post ELT engine analysis**
- **Understanding of thruster wear-out modes**
- **Low-thrust trajectory tool development**





ISPT support enabled Dawn mission

National Aeronautics and Space Administration

Aerocapture Technology Subsystem Readiness

Subsystem \ Destination	Venus	Earth	Mars	Titan	Neptune
Atmosphere Goal: Capture Physics	Venus-GRAM based on world-wide VIRA.	Earth-GRAM validated by Space Shuttle	Mars-GRAM continuously updated with latest mission data.	Titan-GRAM based on Yelle atmosp. Accepted worldwide and updated with Cassini-Huygens data	Neptune-GRAM developed from Voyager, other observations
Aerodynamics Goal: Errors ≤ 2%	Heritage shape, well understood aerodynamics	Heritage shape, well understood aerodynamics	Heritage shape, well understood aerodynamics	Heritage shape, well understood aerodynamics	New shape; aerodynamics to be established.
GN&C Goal: Robust performance for 4-6 DOF simulations	APC algorithm captures 96% of corridor	Small delivery errors. APC algorithm captures 97% of corridor	APC algorithm captures 99% of corridor	APC algorithm captures 98% of corridor	APC algorithm with α control captures 95% of corridor.
TPS Goal: Reduce SOA by 30%+, expand TPS choices	More testing needed on efficient mid-density TPS. Combined convective and radiative facility needed.	Technology ready for ST9. LMA hot structure ready for arrivals up to 10.5 km/s.	ISPT investments have provided more materials ready for application to slow arrivals, and new ones for faster entries.	ISPT investments have provided more materials ready for application.	Zoned approach for mass efficiency. Needs more investment.
Structures Goal: Reduce SOA mass by 25%	High-temp systems will reduce mass by 31%.	High-temp systems will reduce mass by 14%-30%.	High-temp systems will reduce mass by 14%-30%.	High-temp systems will reduce mass by 14%-30%.	Complex shape, large scale. Extraction difficult.
Aerothermal Goal: Models match within 15%	Convective models match within 20% laminar, 45% with turbulence. Radiative models agree within 50%	Environment fairly well-known from Apollo, Shuttle. Models match within 15%	Convective models agree within 15%. Radiative: predict models will agree within 50% where radiation is a factor.	Convective models agree within 15%. Radiative models agree within 35-300%	Conditions cannot be duplicated on Earth in existing facilities. More work on models needed.
System Goal: Robust performance with ready technology	Accomplishes 97.7% of ΔV to achieve 300 x 300 km orbit. No known technology gaps.	Accomplishes 97.2% of ΔV to achieve 300 x 130 km orbit. No known technology gaps.	Accomplishes 97.8% of ΔV to achieve 1400 x 165 km orbit. No known technology gaps.	Accomplishes 95.8% of ΔV to achieve 1700 x 1700 km orbit. No known tech gaps. ENABLING	Accomplishes 96.9% of ΔV to achieve Triton observer. orbit ENABLING

Ready for Infusion | Some Investment Needed | Significant Investment Needed

National Aeronautics and Space Administration

Example of Aerocapture Benefits to Missions

Prop System/ Orbit Insertion System / Mission	Launch Vehicle	All Chemical Mass Delivered	All Chemical Trip Time	Chemical/ Aerocapture Mass Delivered	Chemical/ Aerocapture Trip Time	SEP/ Aerocapture Mass Delivered	SEP/ Aerocapture Trip Time
Titan (1700 km circ orbit)	Delta IV H*	466 kg (1.00)	9.1 yrs (1.00)	2225 kg (4.80x)	7.1 yrs (0.78x)*-	4488 kg (9.60x)	6.1 yrs (0.67x)
Neptune (3986 x 430,000 km orbit)	Delta IV H**	1416 kg (1.00)	15 yrs (1.00)	3709 kg (2.60x)	10.8 yrs (0.72x)	4173 kg (2.9x)	10.3 yrs (0.68x)
Venus (300 km circ orbit)	Delta 2925H-10	112 kg (1.00)	0.44 yrs 159 days (1.00)	687 kg (6.10x)	0.44 yrs 159 days (1.00x)		
Venus – Aerobraking (300 km circ orbit)	Delta 2925H-10	374 kg (1.00)	0.77 yrs 281 days (1.00)	687 kg (1.80x)	0.44 yrs 159 days (0.57x)		
Mars* – Sample Return (500 km circ orbit, opposition class)**	Delta IV H	Not Possible	Not Possible	8279 kg	0.58 yrs 213 days		

* Titan Explorer mission can be accomplished on Delta 4450 using Chemical or SEP with Aerocapture

** Neptune Orbiter mission can be accomplished on Atlas 551 using SEP/Aerocapture

*** MEP requested study (MEP also provided mission parameters)

Significant mass savings. TPS and other subsystems have broad applicability. Ground development complete in FY09