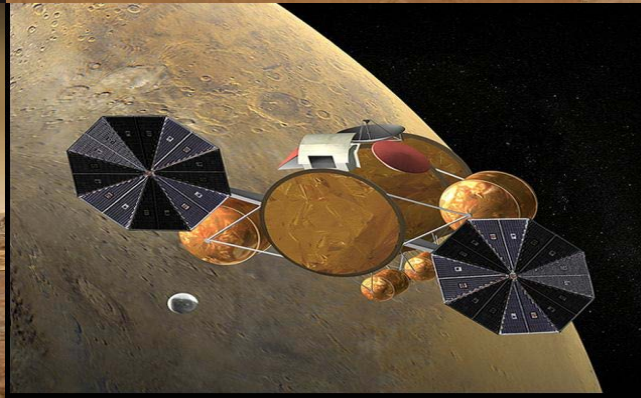
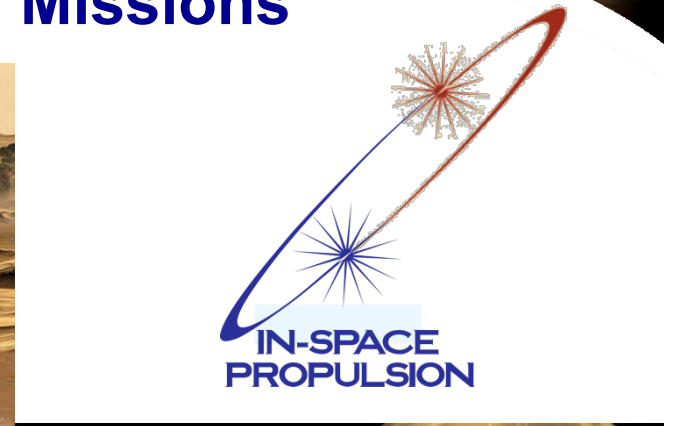




# Overview of NASA's In-Space Propulsion Technology Program for Future Science Missions



David Anderson, Michelle Munk, John Dankanich, Lou Glaab, Eric Pencil, and Todd Peterson

Presented by: John Dankanich

Space Propulsion 2012 Conference, May 7-10, 2012

# NASA's In-Space Propulsion Technology (ISPT) Program

NASA's ISPT Program develops critical propulsion, entry vehicle, and other spacecraft and platform subsystem technologies to enable or significantly enhance future planetary science missions. The current ISPT focus is TRL 3-6+ product development.

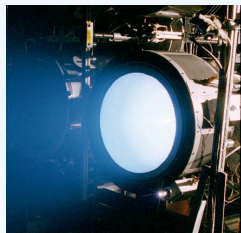
*•Develop technologies that enable access to more challenging and interesting science destinations or benefit the agency's future robotic science missions by significantly reducing travel times to distant bodies, increasing scientific payload capability, or reducing mission cost and risk.*

## Propulsion System Technologies

**AMBR High-Temp Rocket Engine**



**7 kW NEXT Ion Propulsion System**



**4 kW HIVHAC Thruster & Hall Propulsion System**

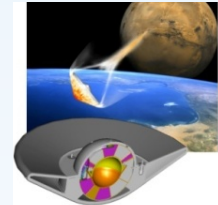


## Entry Vehicle Technologies

**Aerocapture**



**Multi-Mission Earth Entry Vehicle**

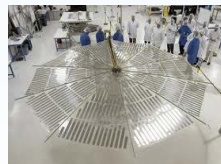


## Spacecraft Bus & Sample Return Technologies

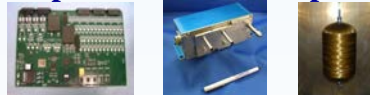
**Mars Ascent Vehicle**



**PV Array Systems for planetary missions**



**Spacecraft Bus Components**

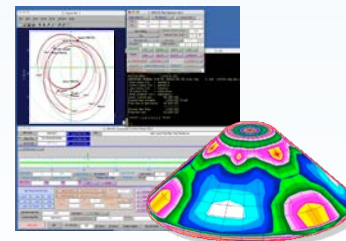


**Extreme Environments**

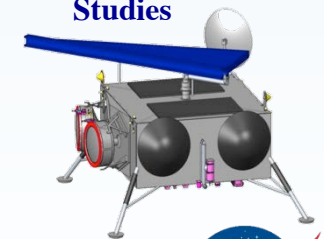


## Systems & Mission Studies

**Mission Analysis Tools**



**Mission and System Studies**

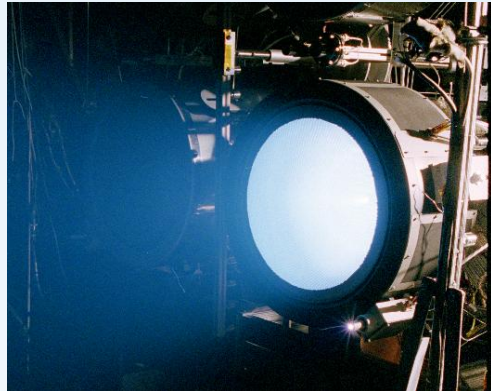


# NASA's Evolutionary Xenon Thruster (NEXT) Expanding SEP Applications For Science Missions

**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

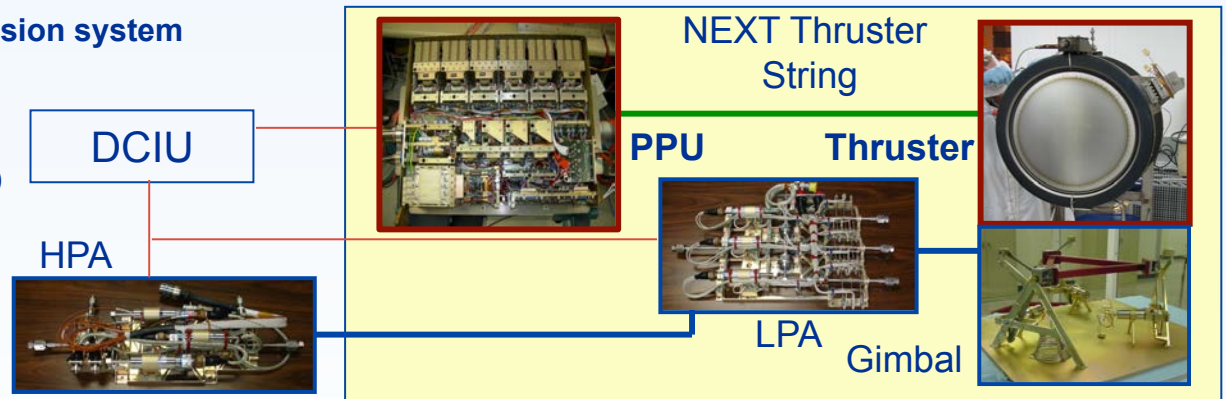
Thruster Attribute	
Thruster power range, kW	0.5 - 6.9
Max. Specific Impulse, s	4,190
Thrust range, mN	26 - 236
Propellant Throughput, kg	450*
Mass (with harness), kg	13.5
Envelope dimensions, cm	43.5 x 58.0
Power Processing Unit Attribute	
Power Processing Unit mass, kg	33.9
Envelope dimensions, cm	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.

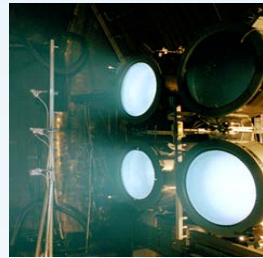
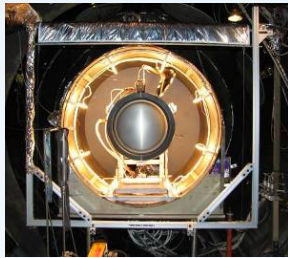


\* Rated Capability Goal 300Kg → Design/Qualification Goal (1.5x Rated) 450Kg  
Projected Life Limit >800Kg → Potential Rated Capability >530Kg

# NEXT TRL6 Status and Mission Benefits

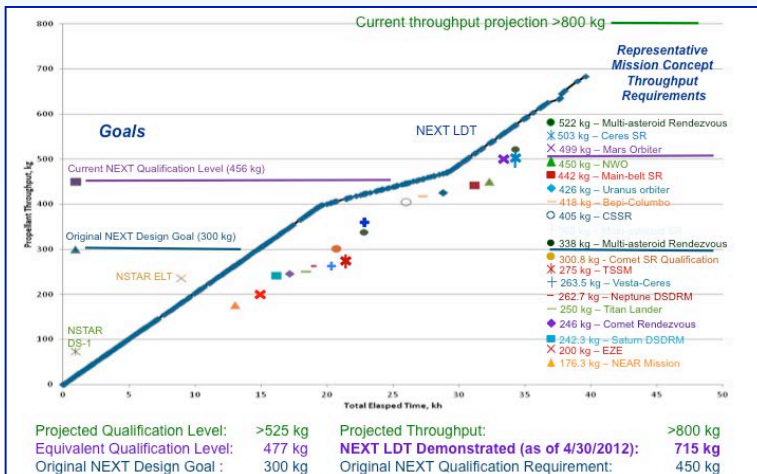
## NEXT is Ready for Infusion

- Single-String System Integration Test: **Complete**
- Multi-String System Integration Test: **Complete**
- Thruster Life Test: **Completed** 450Kg throughput goal
  - As of April 30, 2012, the LDT has achieved >715kg xenon throughput, >41,096 hours of operation and >27.2 MN-sec of total impulse
  - Life Test will continue through FY13 or demonstrate thruster life limit



## NEXT Mission Benefits & Applicability

CHARACTERISTIC	NSTAR (SOA)	NEXT	Improvement	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 <sup>6</sup> 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	



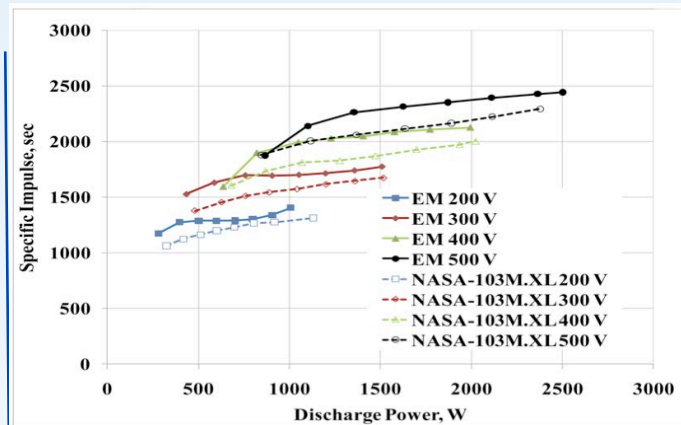
Critical tests have been completed, or are imminent, on high fidelity hardware	PM1	PM1R	PPU	Feed System	Gimbal
Functional & Performance Testing	Complete	Complete	Complete	Complete	Complete
Qual-Level Vibe Test & Analysis	Complete	Complete	Not planned	Complete	Complete
Qual-Level Thermal / Vacuum Test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

# High Voltage Hall Accelerator (HIVHAC) for low cost Discovery-class and Sample Return Missions

## Objective

Develop low power, long-life Hall thrusters to reduce the cost of Discovery-class missions compared to SOA ion and hall thrusters

Input Power	0.3 – 3.9 kW
Specific Impulse	860 - 2700 s
Max Efficiency	62%
Thrust	20 – 207 mN
Propellant Throughput	> 300 kg
Specific Mass	2.4 kg/kW
Operational Life	> 10,000 hrs



HIVHAC EM

## Approach

### Hall thruster numerical erosion models

- Implement advanced numerical simulations of Hall thruster channel erosion, and evaluate against experimental data

### Thruster fabrication and extended life test

- NASA-103M (ASOA) Hall thruster with in-situ replacement of channel ceramic walls to improve Xenon throughput to 300-kg
- Incorporate lessons-learned from NASA-103M.XL wear test into the design of an EM 3.5 kW HIVHAC thruster

### Primary Partners

- NASA Glenn Research Center: Lead
- Aerojet Corp.

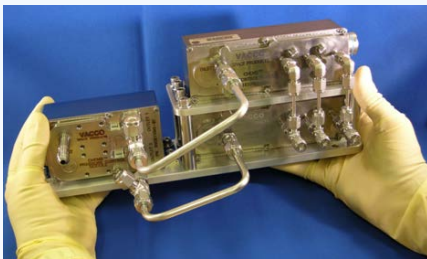
## Key Milestones/Accomplishments

- **NASA-103M wear test** started at GRC Sept 2006 with >100 kg and >4750 hours of life accumulated (34% of goal)
  - Novel channel replacement mechanism demo'ed in FY07-08
  - Thermal environment characterized over throttle table and used in design of EM thruster in FY08
- **Preliminary Design Review** of EM thruster completed August 2008.
- **Fabrication of Engineering Model** unit thruster was completed 2009. EM Thruster rework completed November 2011.
- **Performance Acceptance Test** completed December 2011.
- **Environmental testing** (vibration and thermal vacuum) are scheduled in March-May 2012. Long-duration wear tests will start late 2012.

# Advanced Xenon Feed System (AXFS)

## OBJECTIVE

- ISPT award a contract with VACCO industries to develop a modular Advanced Xenon Flow System (AXFS) with significant reductions in mass, cost, and volume over SOA while increasing system reliability.
  - Flow control accuracy error < 3% EOL
  - System designed to operate NEXT
  - Complete feed system and controller
  - TRL 6 testing
  - Award for two FCMs, 1 PCM, 1 controller with LabVIEW software



VACCO AXFS



Dawn Feed System

## STATUS

- The ISPT project has invested in an AXFS, developed by VACCO Industries:
- Completed limited qualification level environmental testing
  - Demonstrated hot-fire operation
  - Pressure control
  - Current control
- Demonstrated 70% reduction in Mass,
- 50% reduction in footprint, and
- Expected 50% cost reduction over NEXT SOA PMS.
- **The VACCO AXFS is ready for technology infusion.**

	NSTAR	NEXT	AXFS	XFCM
Mass, kg	11.4	5.0	1.5	1.25
Estimate Footprint, cm <sup>2</sup>	1,900*	1,654	800	115
# Channels Controlled	2	3	3	2
Duration to Throttle, min	45	<1	<1	<1
Average Power (Max), W		7.9(81)	<0.01	<0.01

\* Does not include plenum tanks

The AXFS was a small investment on feed system technology independent of NEXT to leverage commercial investments and push the limits of technology without adding risk to the NEXT project.

# Ultra Lightweight Tank Technology (ULTT) for future planetary missions

## Description

- This effort aims to develop the Composite Overwrapped Pressure Vessel (COPV) tanks for propellants and pressurants for Mars Sample Return (MSR) mission
- Tanks are most often the heaviest component on a spacecraft
- Currently component technologies are maturing and ready to be “harvested”

## Objective

- To develop and qualify ultra-lightweight propellant and pressurant tanks sized for MSL/MSR Skycrane
- Goal: Achieve highest mass saving with reliability

## Benefits

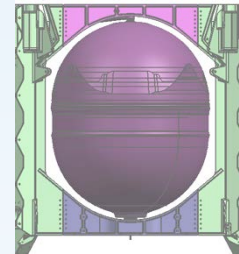
- 20-30 kg mass savings are achievable for 3 tanks sized for the Skycrane
  - Mass savings can be passed on to the scientific payload or increase mass margin
- Broad impact to virtually ALL space missions as most use liquid propellants or pressurant
  - Europa Explorer tank mass can be reduced by 60 kg

## Baseline Approach

- To build and test three (3) Skycrane size tanks
- To ready the tanks for 2018 flight demonstration

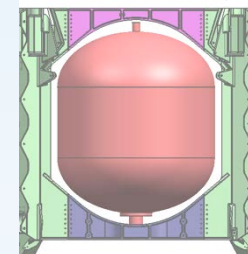
### **Descent Stage Propellant Tanks**

Existing MSL Titanium Tank

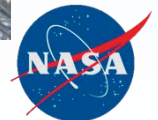
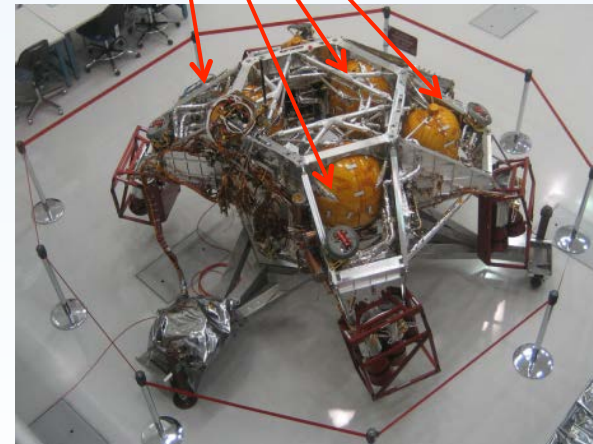


594mm Diameter,  
~720mm Tall

Drop in replacement ultralight tank



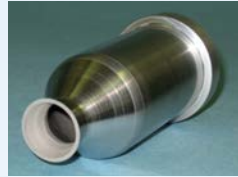
594mm Diameter,  
684mm Tall



# Advanced Materials Bipropellant Rocket (AMBR)

## Objective

- Improve the HiPAT bipropellant engine Isp performance by fully exploiting the benefits of advanced thrust chamber materials
- Performance
  - \* 333 seconds Isp with NTO/N<sub>2</sub>H<sub>4</sub>
  - \* Over 1 hour operating (firing) time
  - \* 140 lbf thrust
  - \* 3-10 years mission life (goal)
  - \* Lower cost (up to 30% savings on the chamber)



Completed EL-Form Ir/Re Chamber



## • Performance Tests

- Completed 89 engine starts
- 9,138s of total firing time (152.3 minutes)
  - 2,700s (45 minutes) longest single burn duration
- 3,935°F (2,160°C) steady state chamber temperature
- 99 – 289 psia operating chamber pressure
- 333.5 seconds maximum specific impulse
- Defined complete operational range

## • Environmental Tests

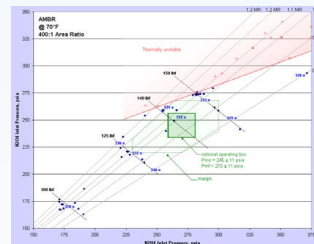
- Passed qualification level vibration test
- Passed shock test

## • Future Use

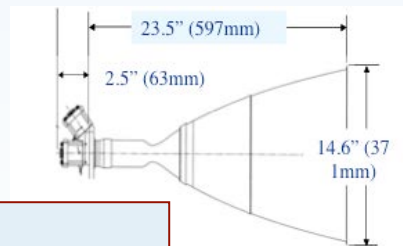
- Commercial interest, DoD interest, constellation interest, and decadal studies



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

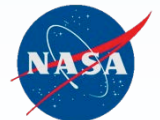


## AMBR Engine Dimensions



**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

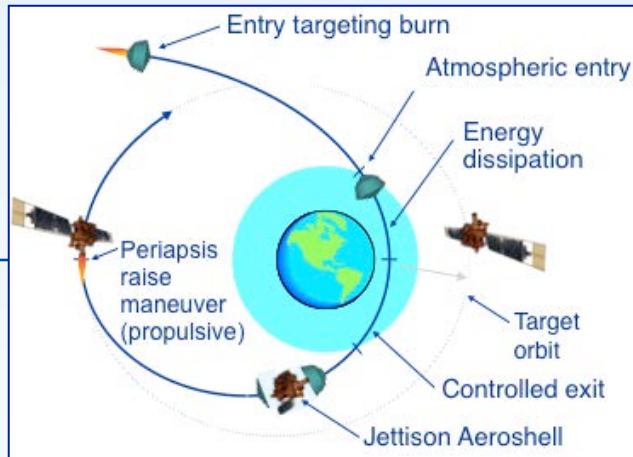




# Aerocapture Overview and Benefits

## 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.

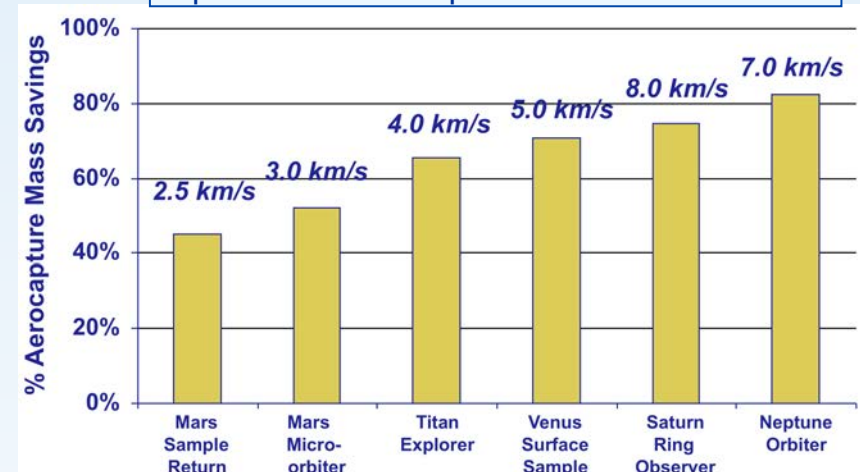


## Objective

- 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

- All values are compared to the mass of an all-propulsive capture
- Equivalent  $\Delta V$  from Aerocapture noted above each column



## 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



# Multi-Mission Earth Entry Vehicle (MMEEV) Technology

## Description

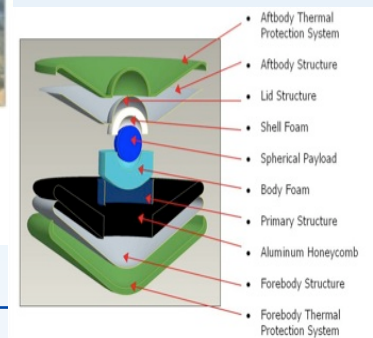
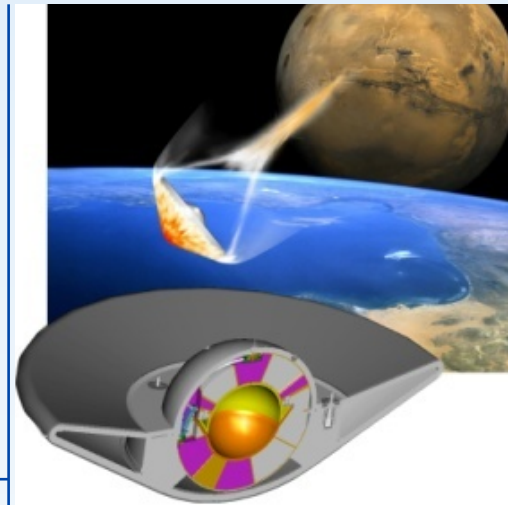
- Earth Entry Vehicles (EEVs) are necessary for bringing samples of material from our Solar System safely back to Earth's surface.
- The Multi-Mission EEV approach seeks to develop and implement common design principles on multiple missions such as New Frontiers, Discovery, and eventual planetary sample returns.

## Objective

- To develop technologies that enable new sample return missions
- To apply common design features to multiple flights, to improve reliability to the  $10^{-6}$  level

## Benefits

- Maximize efficient use of technology investments, saving Agency costs over the long term
- Establish validation data for risk reduction on future missions that require extremely high probabilities of success.

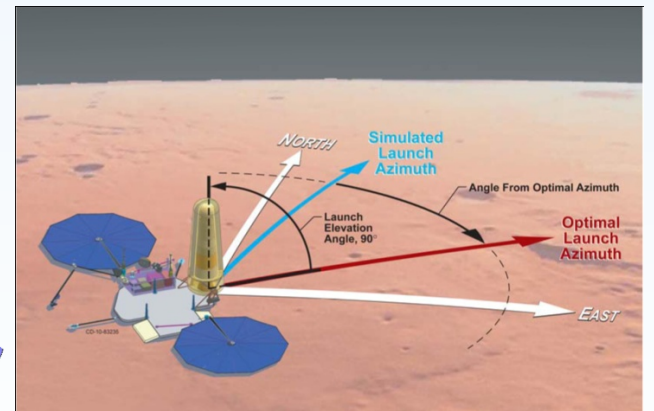
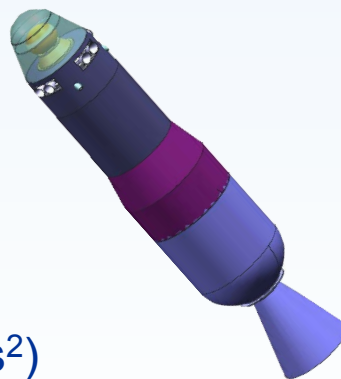
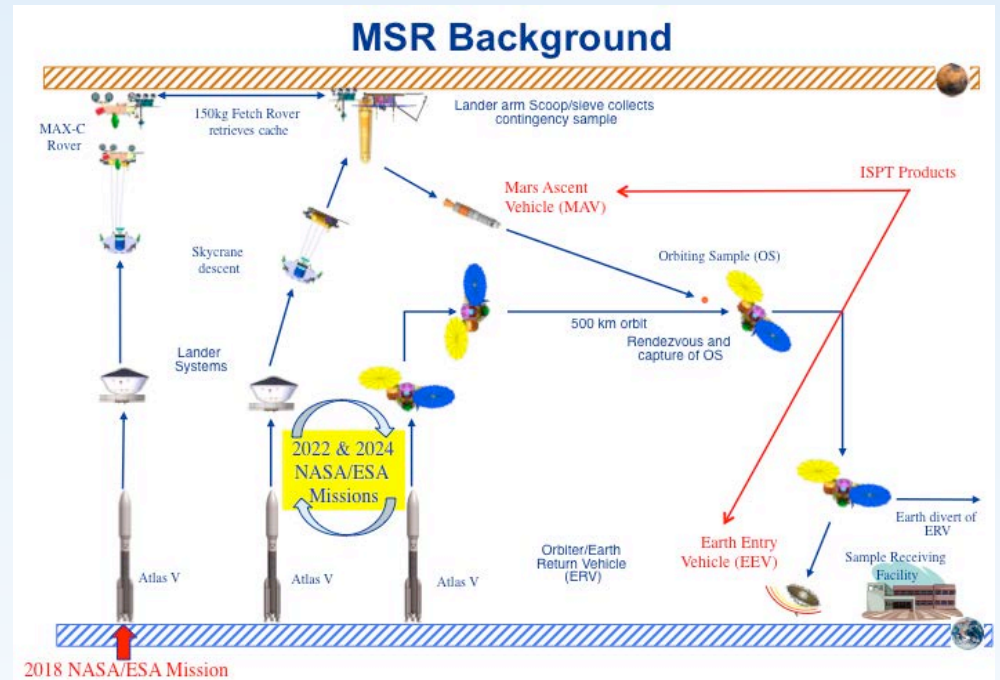


## Discipline Areas

- Materials development
- Aerodynamics
- Aerothermodynamic modeling
- Systems engineering and integration
- Advanced materials for TPS, structures, and impact protection
- Thermal control
- Mechanical Design/Packaging
- Systems Engineering

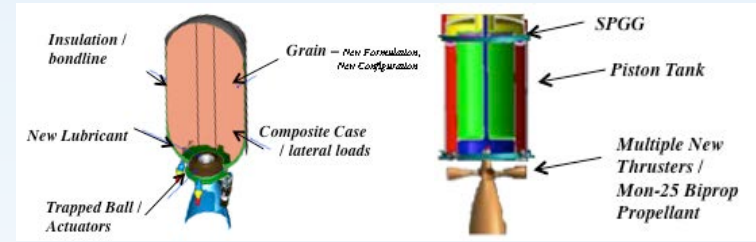
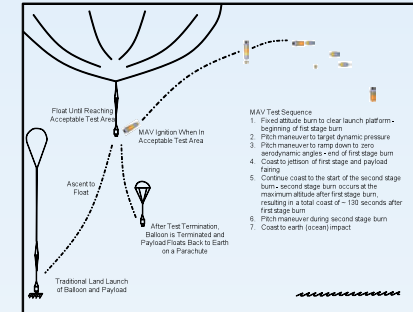
# Mars Ascent Vehicle (MAV) Top Level Requirements

- Launch to Mars orbit
  - 500 km  $\pm$ 100 km
  - 45° latitude
  - Delta V > 3.3 km/s
- MAV spends 90 + sols on Martian surface
- 5 kg Orbiting Sample (OS), with 0.5-1.0 kg of samples
- Single-fault tolerant avionics & thermal control
- Telemetry system operational through payload separation
- Adequate data link margin to orbiter at 4400 km altitude
- Desire to meet interface requirements of MSL EDL
- EDL produces  $\geq 20$  g's (200 m/s<sup>2</sup>)

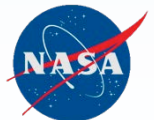
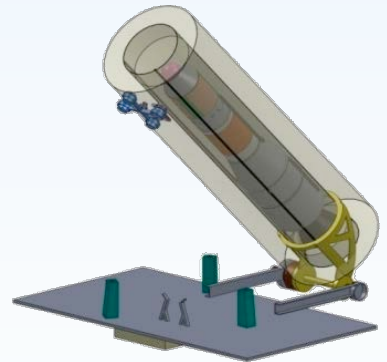
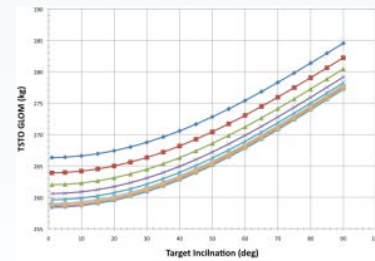


# MAV Component Technology Development

- Phase 1: Early investment
- Published MAV study guidelines
- System definition and development studies (~6 months)
  - Awarded three study contracts to Lockheed Martin, ATK, and Northrop Grumman
- Completed Multiple Team-X and COMPASS studies
- Completed High Altitude Balloon MAV Flight Test Study
- NRA Phase 2 Awards were not implemented
  - On hold until joint Mars Program Planning Group (MPPG) architecture clarifies options



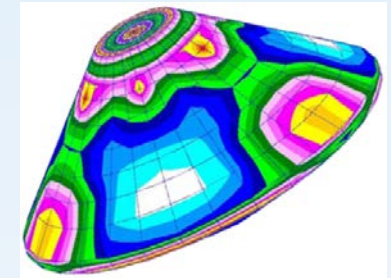
WBS Number	Description	Basic Mass (kg)	Orbital (kg)	Orbital (kg)	Total Mass (kg)
MAV	MAV Launch Vehicle (MAV) - April 2010	803.99	2.23	0.99	807.21
MAV.1.1	Attitude Determination and Control	3.68	0.75	0.68	5.11
MAV.1.2	Autonomous Navigation & Control	1.38	2.23	0.88	4.49
MAV.1.3	Control	2.88	30.23	2.18	35.29
MAV.1.4	Command & Data Handling	5.38	30.23	3.32	38.93
MAV.1.5	Instrumentation & Wiring	3.48	30.23	0.98	34.69
MAV.1.6	Launch Vehicle System	5.23	30.23	0.83	36.29
MAV.1.7	Medical Gas Airline	1.23	0.13	0.12	1.48
MAV.1.8	Comprehensive Instrumentation	5.93	30.23	0.93	37.09
MAV.1.9	Electrical Power Subsystems	0.88	30.23	1.43	6.54
MAV.1.10	Autonomy System	1.23	30.23	1.13	32.59
MAV.1.11	Power Management & Distribution	1.23	30.23	1.23	32.74
MAV.1.12	Power Cells and Sensors Subsystems (3 and 10)	2.23	30.23	1.23	33.74
MAV.1.13	Weight	2.23	30.23	1.23	33.74
MAV.1.14	Thermal Control (Non-Propellant)	0.33	15.23	0.98	16.54
MAV.1.15	Active Thermal Control	0.33	15.23	0.98	16.54
MAV.1.16	Passive Thermal Control	0.33	15.23	0.98	16.54
MAV.1.17	Propulsion (1st Stage)	28.33	3.23	3.33	34.89
MAV.1.18	Reentry/Parachute Thermal Control	10.47	7.23	3.33	21.03
MAV.1.19	Second Stage Propulsion System	12.13	1.23	0.23	13.59
MAV.1.20	Propulsion	38.88	4.46	0.88	44.22
MAV.1.21	First Stage Propellant	147.13	1.23	0.23	148.59
MAV.1.22	Second Stage Propellant	22.23	0.23	0.23	22.74
MAV.1.23	Structures and Mechanisms	10.65	17.23	3.27	31.15
MAV.1.24	Mechanisms	7.23	14.23	1.23	22.74
MAV.1.25	Mechanisms	34.23	14.23	3.23	51.74



# Systems and Mission Analysis

## Objectives:

- 1) Conduct systems and mission studies to prioritize and guide investments and quantify mission benefit of ISPT products.
  - NEXT throttle table, HIVHAC power and life requirements, etc.
- 2) Develop tools for the user community to assist in ISPT product infusion.
  - Low Thrust Trajectory Tool (LTTT) suite
  - Aerocapture Quicklook Tool (a.k.a. SAPE)
  - Advanced Chemical Propulsion System (ACPS) tool



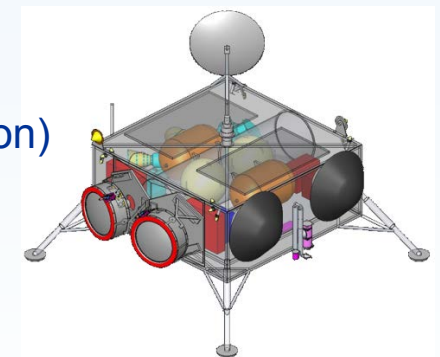
## Recent Studies:

- 1) Barbara SR, Ceres SR, Mars Moons' SR, NEARER, Discovery Cost Viability, etc.
- 2) Supported 1/2 of all decadal studies: Uranus, Neptune, Chiron, Trojans, Vesta and Hebe, and Mercury
  - While performing the mission design, infused ISPT products as baseline for every mission!



## Tool Success:

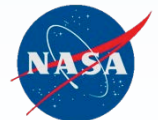
- 1) Agency point-of-contact for trajectory analyses (e.g. HILTOP Validation)
- 2) Provided tool training for MALTO, OTIS, and Copernicus
  - 100s from all NASA centers, academia and industry
  - Copernicus baseline tool for exploration (Constellation)
  - OTIS (GRC Led) NASA Software of the year
- 3) Mystic used for Dawn mission operations, and tools used in Discovery proposals



# ISPT Technology Infusion

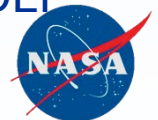
- **ISPT is pursuing opportunities to take technologies beyond TRL6**
  - NEXT and AMBR incentivized on the last New Frontiers Announcement of Opportunity
  - NEXT, AMBR, and Aerocapture incentivized on the last Discovery AO
  - Conducting and participating on systems and mission studies looking at technology applicability to future mission concepts/DRM's
  - Developing tools to aid the use of new technologies
  - Developed HEAT sensors for Mars Science Laboratory (MSL) as part of MSL Entry, Descent, and Landing Instrumentation (MEDLI)
  - Working to develop and fabricate 2 flight qualified AXFS. Interest has increased due to pursuing the flight qualification step!
  - Ultra-Light Weight Propellant Tanks
    - 2002 - Mars Exploration Rover, ISP funds Qualified MER tank design
    - Developing flight-qualified ultra-light weight propellant tanks as a drop-in replacement for Skycrane. Assessing other mission opportunities.
      - Mission pull/applicability important to get the technology qualified. Once this tank design has been qualified, the “validated” technology will be broadly applicable to most spacecraft.

- ISPT has several technologies which are ready for infusion
- ISPT has several more technologies which will be ready tech infusion in the next several years
- ISPT is assessing the next set of technologies to enable future planetary science missions



## In-Space Propulsion Technology Summary Infusion Ready Products

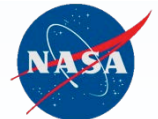
- The In-Space Propulsion Technology (ISPT) portfolio continues to invest in high-priority technology areas such as the Electric Propulsion and Aerocapture
  - ISPT technologies are identified in the 2011 Planetary Decadal Survey
- The ISP Project is completing development of several propulsion technologies (products) in support of future Flagship, Discovery, and New Frontiers missions.
  - The **AMBR high-temperature chemical thruster** development task has been completed (2009)
  - High-priority **aerocapture ground-development** activities are nearing completion
    - 2.65M aeroshell manufacturing demonstration, Space Environmental Effects (SEE) testing, and GN&C hardware-in-the-loop testing
  - **NASA's Evolutionary Xenon Thruster (NEXT)** ion system development are nearing completion
    - Achieved >715Kg Xe throughput. Completing PPU refurbishment and will resume performance and environmental testing.
  - Other recent products include an Advanced Xenon Flow Control System (AXFS), Mixture Ratio Control Balanced Flow Meter (BFM), and the MEDLI sensor which will be used on MSL entry at Mars



# In-Space Propulsion Technology Summary

## Future Products

- ISP increasing emphasis on sample return propulsion technology developments. Studies and technology development activities have been initiated.
- **Planetary Ascent Vehicles (PAV)**
  - Completing studies and developing requirements to initiate technology development for Mars Ascent Vehicles (MAV), with the MAV studies were completed in Jan 2011.
- **Multi-mission Earth Entry Vehicles (MMEEV)**
  - Completing trade studies and requirements development to kick off technology development for multi-mission Earth Entry Vehicles (MMEEV), and initiating some low levels of technology development
- Low-cost Hall systems for Discovery-class missions, and Chemical and Electric propulsion for Earth Return Vehicles (ERV)
  - Complete **High Voltage Hall Accelerator (HiVHAC)** thruster EM Thruster development, and initiate other subsystem technology developments
    - HiVHAC applicable to ERV, transfer stages, and Discovery-class missions.
  - Continuing advanced chemical propulsion technology development as funds allow
- **System and Mission analysis and tool development**
  - Are conducted to guide investments, quantify benefits, and support technology infusion and application





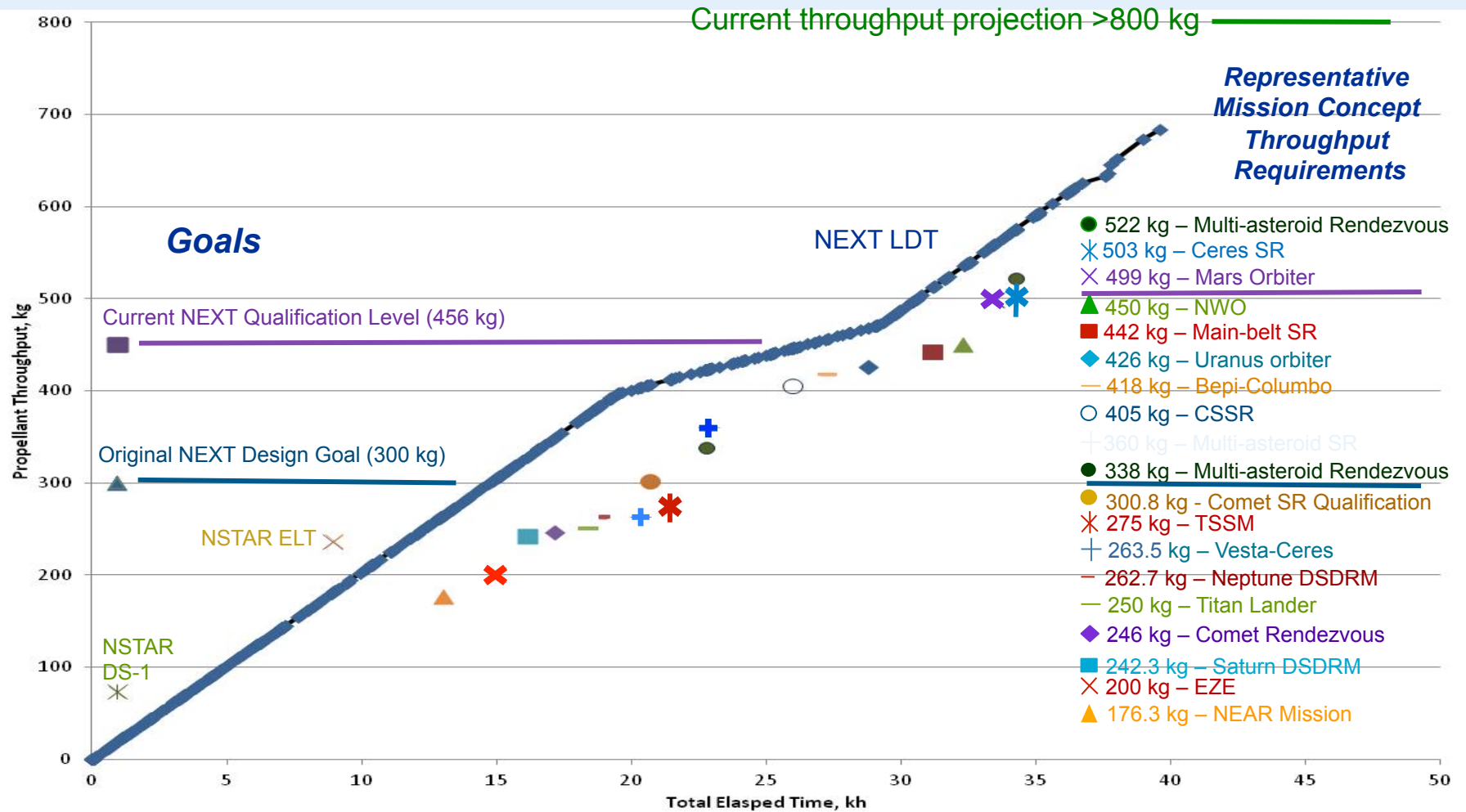


# Questions?

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# NEXT LDT Propellant Throughput



Projected Qualification Level: >525 kg  
 Equivalent Qualification Level: 477 kg  
 Original NEXT Design Goal : 300 kg

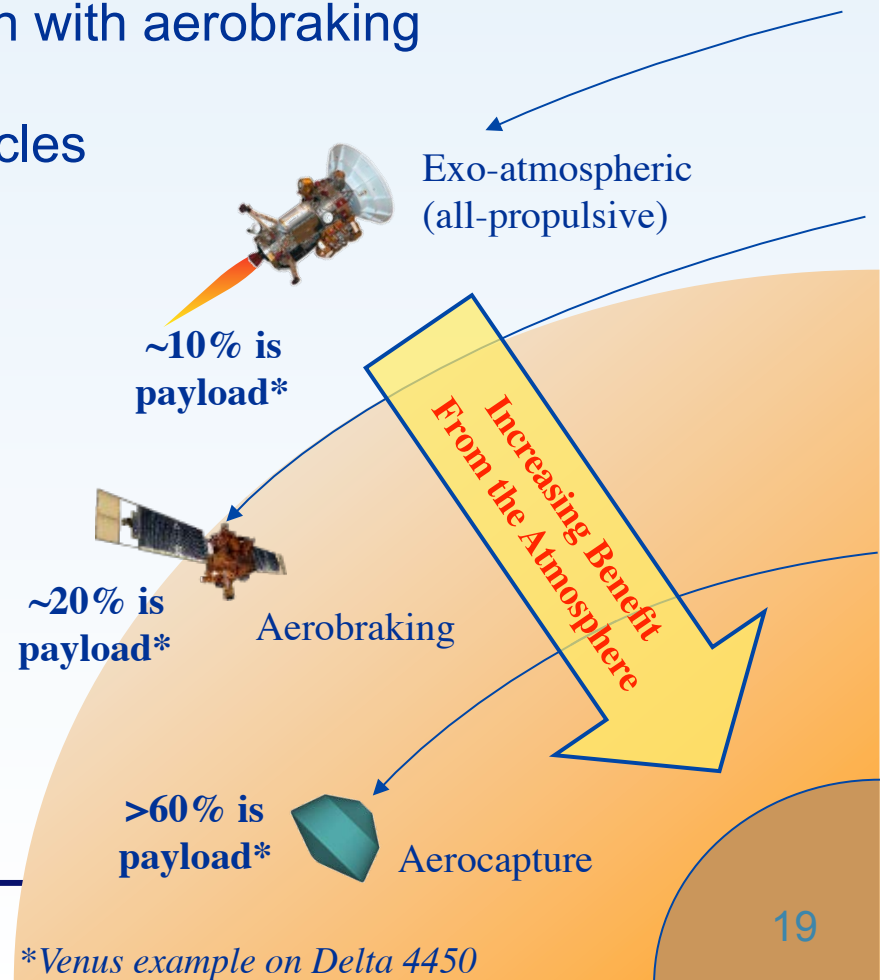
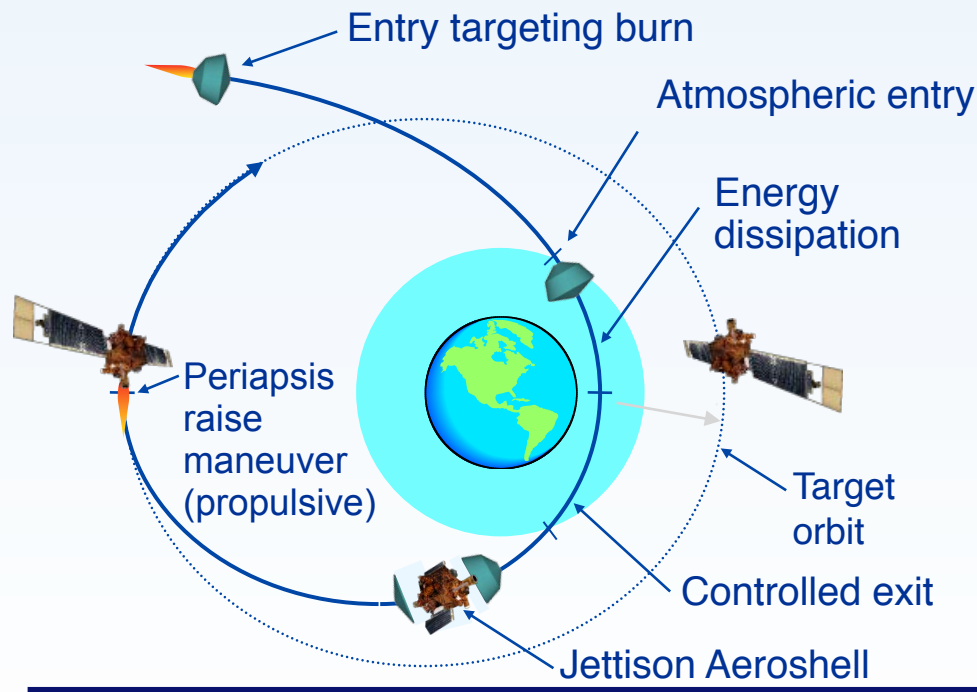
Projected Throughput: >800 kg  
**NEXT LDT Demonstrated (as of 4/30/2012): 715 kg**  
 Original NEXT Qualification Requirement: 450 kg



# Aerocapture Delivers More Science Than Traditional Orbit Insertion

- Aerocapture

- Provides much higher useful payload fraction than for chemical propulsion or aerobraking
- Allows shorter trip times to outer planets/moons
- Achieves required orbit faster than with aerobraking (hours vs weeks/months)
- Allows use of smaller launch vehicles



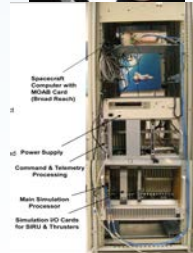
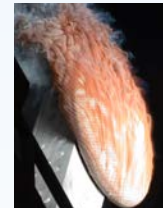
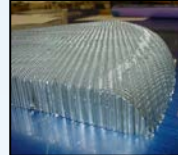
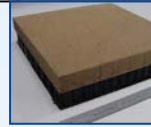
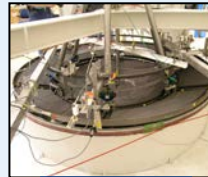
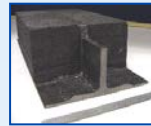
Glenn Research Center at Lewis Field

\*Venus example on Delta 4450

# Aerocapture Technology Development Products

Elements at TRL6 and Ready to Infuse

- **Rigid aeroshell and TPS products**
  - **Carbon-Carbon hot structure**
    - 2-meter rib-stiffened 70-deg aeroshell tested and finite element model validated, capable up to  $700 \text{ W/cm}^2$ , **30% lighter** than Genesis capsule equivalent
  - **High-temperature aeroshell structures** (composite and honeycomb sandwich):
    - Composite honeycomb and modified adhesives raise TPS bondline by  $65^\circ\text{C}$ , system stagnation tested to over  $300 \text{ W/cm}^2$ , **15% lighter than MER**
    - Titanium honeycomb and modified facesheet resins and fibers, coupon tested and manufactured at 2.65-meter scale, raises bondline by  $150^\circ\text{C}$ , **reducing system mass up to 30%** over traditional
  - **Ablative Thermal Protection System Materials**
    - “Family system” approach provides range of densities and robustness levels for wide range of applications:  $50$  to  $1,100 \text{ W/cm}^2$
    - Extensive arcjet testing, application at flat-panel, 1-meter, and 2.65-meter (pending) scales



- **Aerocapture Guidance and Control Hardware-in-the-Loop Testbed:**
  - 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**
  - Improved aerothermal prediction capabilities, particularly by validating codes through ground test of fundamental physics
  - Engineering-level atmospheric models developed and improved for nearly every destination in the Solar System; incorporated directly into high-fidelity flight dynamics simulations
- **Aerocapture Quick-Look Tool**
  - End-to-end engineering-level conceptual design and trade tool for assessing aerocapture concepts
  - Available through LaRC software request process

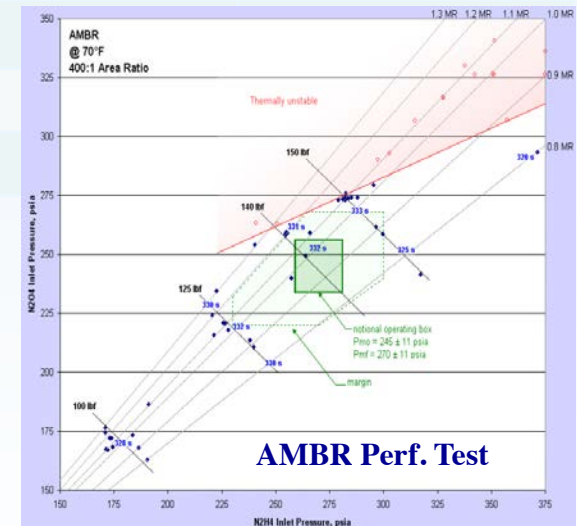
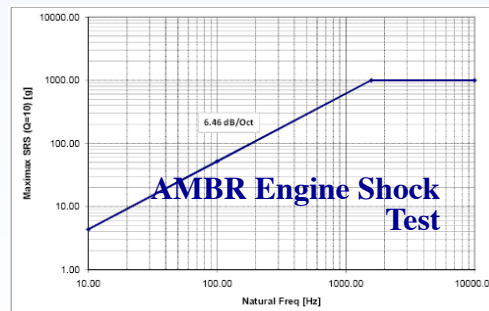
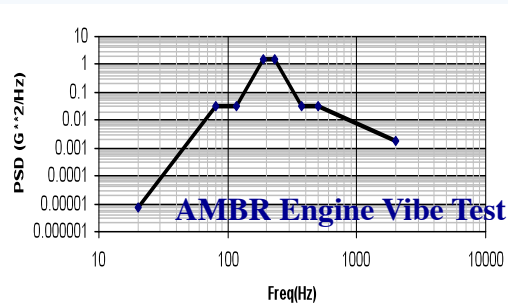
# Aerocapture 2010 and 2011 Highlights

- Significant progress on 2.65-m aeroshell manufacturing demonstration unit (completion March, 2012)
- Sandia Solar Tower test of advanced 1-m aeroshell
- Ball hardware-in-the-loop GN&C testbed complete
- Aerocapture and advanced aeroshell materials incentivized by SMD in latest Discovery AO
  - Decadal Survey endorsed this, saying, “**NASA should continue to provide incentives for these technologies until they are demonstrated in flight.**”
- MEDLI integrated into MSL aeroshell, and ready for entry August 2012 - *ISPT hardware infusion*
- Space Environmental Effects testing complete (radiation, cold soak, and micrometeoroid)
- Quick-Look Tool (SAPE, Systems Analysis for Planetary Entry) released



# AMBR: a Proven Design for Higher Performance

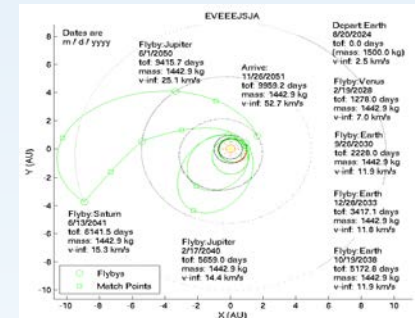
<u>Characteristics</u>	<u>HiPAT DM</u>	<u>AMBR Design</u>	<u>AMBR Test Results 10/1/08</u>	<u>AMBR Test Results 6/25/09</u>
Trust (lbf) (N2H4/NTO)	100		150	141
Specific Impulse (sec)	326/329		333.5	333
Inlet Pressure (psia)	250		275	250
Chamber Temperature (F)	3100	4000	≥3900	3900
Oxidizer/Fuel Ratio	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		



# Mission Design Tools / Systems Analysis

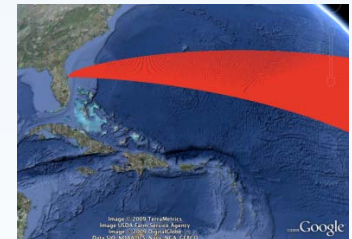
In order to infuse new technologies, users must be able to assess the payoff.

- Sponsored development of Mystic, MALTO, Copernicus, and OTIS
  - Initiated because results could not be independently validated
- Held MALTO training course in 2008
- Held Copernicus training course in 2009
- OTIS training as needed (most recent 2011)
- Aerocapture Quicklook Tool Released in 2010



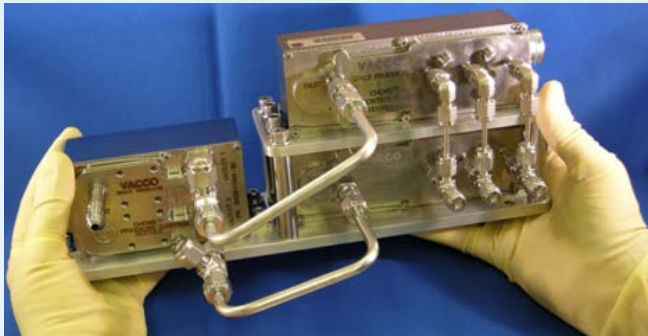
## Mission / system design studies define technology requirements

- Critical to quantify mission benefits before hardware investment
- Mission design for NEXT requirements
- Refocus Study led to NEXT throttle table extension
- Refocus Study led to HIVHAC power range, life requirement
- Decadal study support quantified science benefit for SEP, REP, and AMBR engine technology



**“If we want people to buy cars, they need to learn to drive.” - Oleson**

# Xenon Flow System Options for HIVHAC

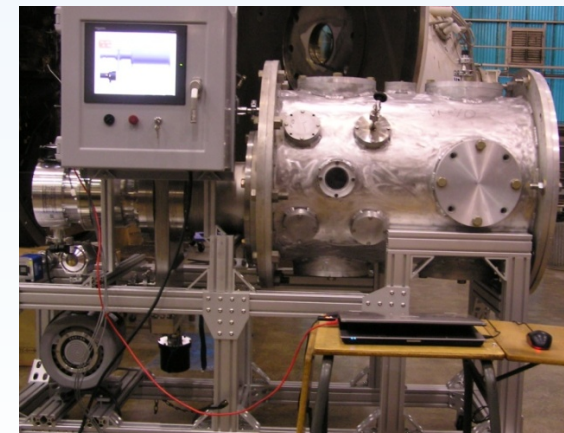
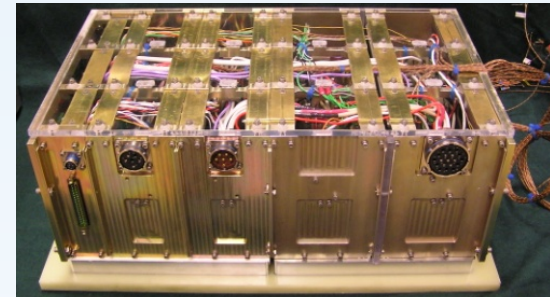
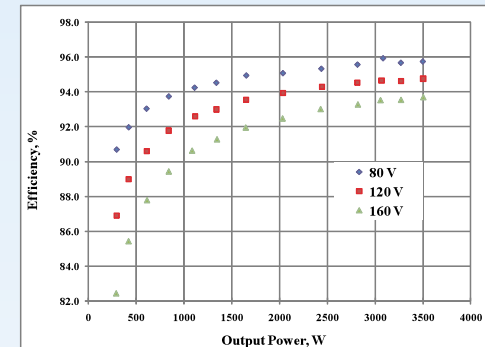


- **The HIVHAC project goal is to use a low-cost light-weight XFS**
- A number of XFSs are available for integration with the HIVHAC thruster including the Moog flight qualified BPT-4000 XFS (TRL 9), the Aerojet manufactured NEXT thruster XFS (TRL 6), and the VACCO advanced XFS (TRL 6) developed under a NRA selection.
- The VACCO XFS represents a dramatic improvement over the NSTAR flight feed system and also represents an additional 70% reduction in mass, 50% reduction in footprint, and 50% reduction in cost over the baseline NEXT XFS
- HIVHAC thruster hot-fire testing with the VACCO XFS was performed last year for three thruster-XFS configurations to verify the XFS integrated operation with a Hall thruster
- As a result of the successful testing of the HIVHAC thruster with the VACCO XFS, NASA GRC and the AFRL are acquiring a flight-like VACCO xenon control module (XCM) for integration with the HIVHAC thruster LDT, the goal is to use the LDT as an opportunity to qualify the VACCO flight XCM over extended operation



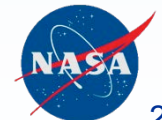
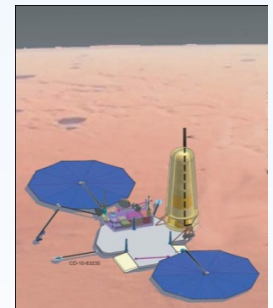
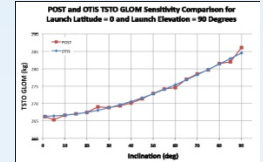
# Power Processing Unit (PPU) Options for HIVHAC

- The functional power requirements of a HIVHAC PPU are that it operates:
  - Power range 0.3 to 3.9 kW
  - Input voltage range 80 to 160 V
  - Output Voltage range 200 to 700 Vdc
  - Output current range 1.4 to 5 A
- NASA is looking at various options to perform some critical design and testing of PPU converter topologies dependent on funding availability.
  - The near term plan is to leverage converter/PPU development by other projects where possible and applicable
- One option for developing a HIVHAC PPU is modifying the design of the BPT-4000 PPU
- Another option is to develop a HIVHAC PPU that is a new custom design
- Within NASA's small business innovative research (SBIR) program, there are three projects that are developing wide range discharge modules for integration with Hall thrusters



# MAV Notional Development Plan

- **Phase 1: Early investment (~\$4M funded by ROSES NRA, 6 month studies)**
  - System definition and development studies (~6 months)
  - Propulsion subsystem development and tests for select MAV concepts (~3 years)
- **Phase 2: Component technology development to TRL 6 and system architecture selections (~3 years, ~\$40M, may include follow-on options)**
  - Develop component technologies to reach TRL6
  - Test components' performance in realistic temperatures, storage, EDL g-loads as appropriate
  - Culminates in the final downselect to a single concept, whose high-risk components have known performance and survivability characteristics
- **Phase 3: Integrate and develop a MAV. Perform integrated testing and qualification. (~5 years, ~\$210M, includes Phase 3 options)**
  - Perform three high-altitude flight tests to assure at least two successful tests and measure performance prior to MSR lander PDR.
  - At least one flight test must be performed on unit that has successfully completed environmental qualification/life testing
- **Flight Project responsibilities, after completion of technology program:**
  - Update design based on test results, fabricate flight unit hardware, spare, and interface test articles (mechanical, electrical/testbed), complete flight acceptance test, and deliver to ATLO



# MMEEV Design Trade Space

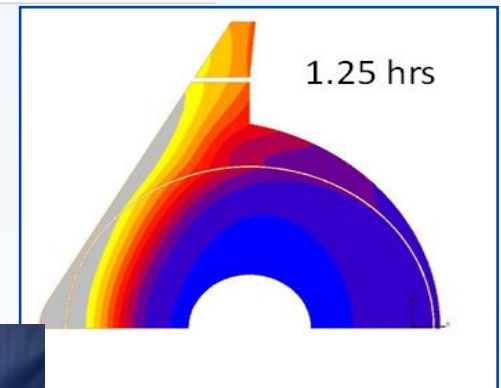
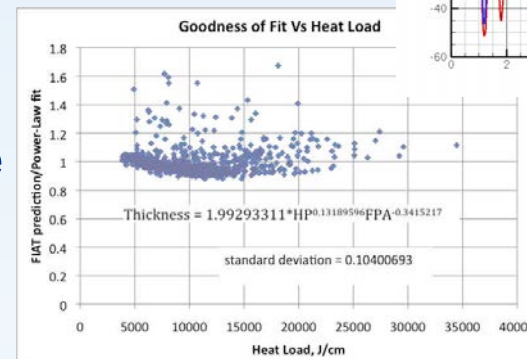
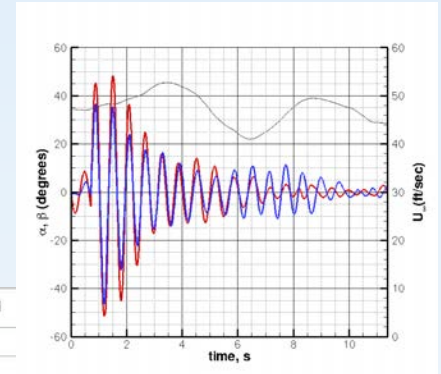


*Since each individual sample return mission may have a unique set of performance metrics of highest interest, the goal is to provide a qualitative performance comparison across the specified trade space. From this, each sample return mission can select the most desirable design point from which to begin a more optimized design.*

- Several MMEEV design requirements will vary greatly across sample return missions.
  - Payload accommodations :
    - consider payload masses between 5 and 30 kg
    - assume spherical volume with fixed density
    - vary vehicle diameter from 0.5 to 2.5 m
  - Entry conditions (inertial) :
    - entry velocities between 10 and 16 km/s
    - entry flight path angles between  $-5^\circ$  and  $-25^\circ$
- MMEEV performance is evaluated across the trade space in several areas of likely interest to sample return missions.
  - Total vehicle mass (at entry)
  - Configuration
  - Aeroheating
  - Impact dynamics

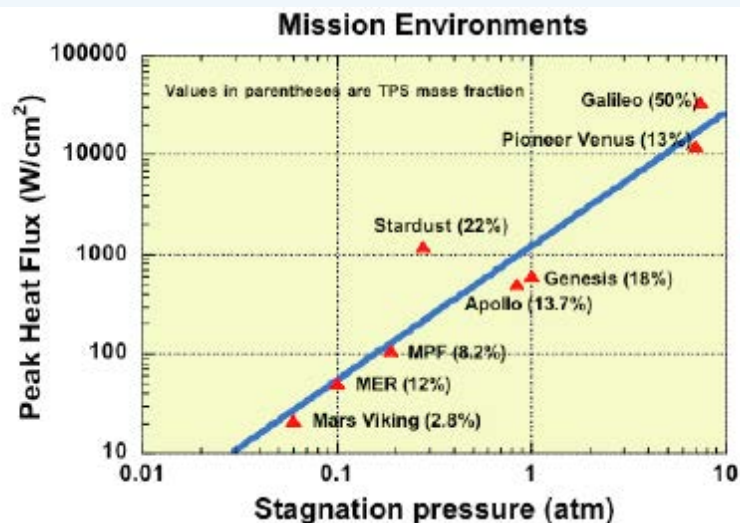
# MMEEV 2010 and 2011 Highlights

- Completed preliminary Vertical Spin Tunnel testing to characterize subsonic aerodynamics
- Developed forebody Mass Estimating Relationships (MER) for PICA and Carbon Phenolic
- Added greater fidelity to Trade Space design modules, primarily the Parametric Vehicle Model
- Completed initial integration of Trade Space design modules with System Analysis for Planetary Entry tool to create MMEEV-specific version of tool (was “EDL Quick-Look” now M-SAPE)
- Developed a preliminary Thermal Soak model for MMEEVs
- Completed preliminary foam impact testing



# MMEEV 2010 and 2011 Highlights

- Completed Hayabusa re-entry observation and analysis
- Completed MMOD impact assessment
- Completed carbonization of heritage Avtex rayon stock, plus alternate rayons: NARC, LYOCELL, ENKA, and C2B. In storage at ARC.
- Released RFQ to have vendors demonstrate capability to produce CMCP, and a Detailed Heatshield Implementation Plan (DHIP). ATK and AEE selected, only ATK will make coupon.
- Secured support and set timeframe for next Carbon Phenolic Workshop—February, 2012



**THE TPS GAP**

