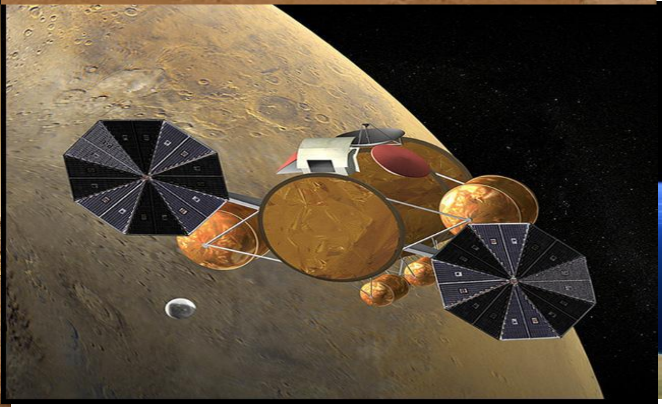
The Status of Spacecraft Bus and Platform Technology Development under the NASA ISPT Program



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

IEEE Aerospace Conference, Big Sky, MT

March 6, 2013

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

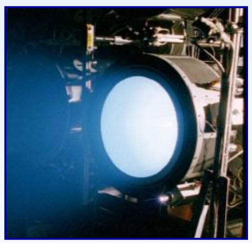
NASA's ISPT Program develops critical propulsion, entry vehicle, and other spacecraft and platform subsystem technologies to enable or significantly enhance future planetary science missions. The current ISPT focus is TRL 3-6+ product development.

•*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.*

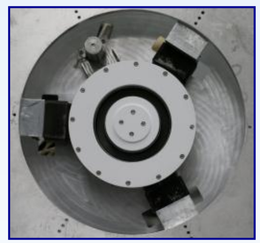
Propulsion System Technologies

AMBR High-Temp Rocket Engine

7 kW NEXT Ion Propulsion System

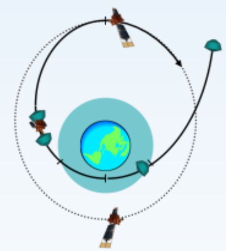


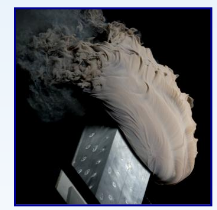
4 kW HIVHAC Thruster & Hall Propulsion System



Entry Vehicle Technologies

Aerocapture





Multi-Mission Earth Entry Vehicle

Spacecraft Bus & Sample Return Technologies

Mars Ascent Vehicle

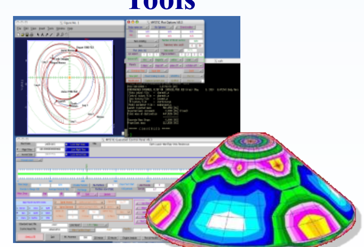
PV Array Systems for planetary missions

Spacecraft Bus Components

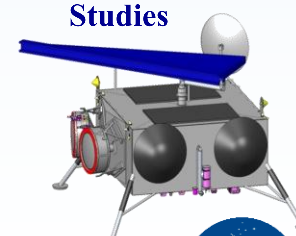
Extreme Environments

Systems & Mission Studies

Mission Analysis Tools

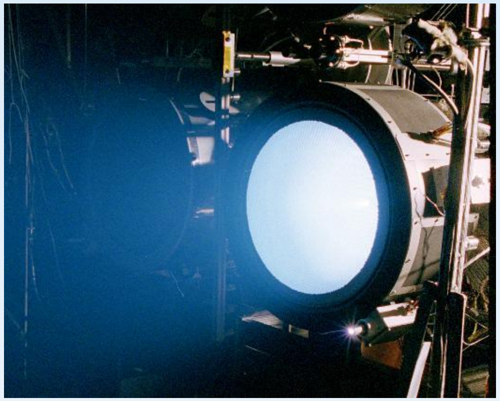


Mission and System Studies

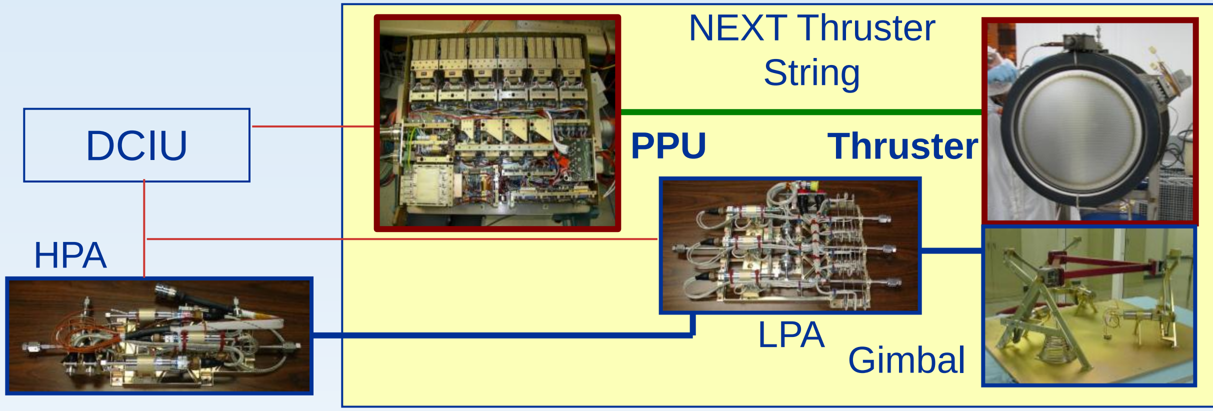


NEXT: Expanding SEP Applications For SMD Missions

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

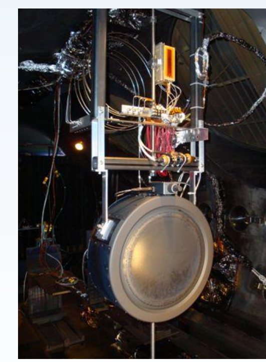


NEXT PM ion thruster operation at NASA GRC



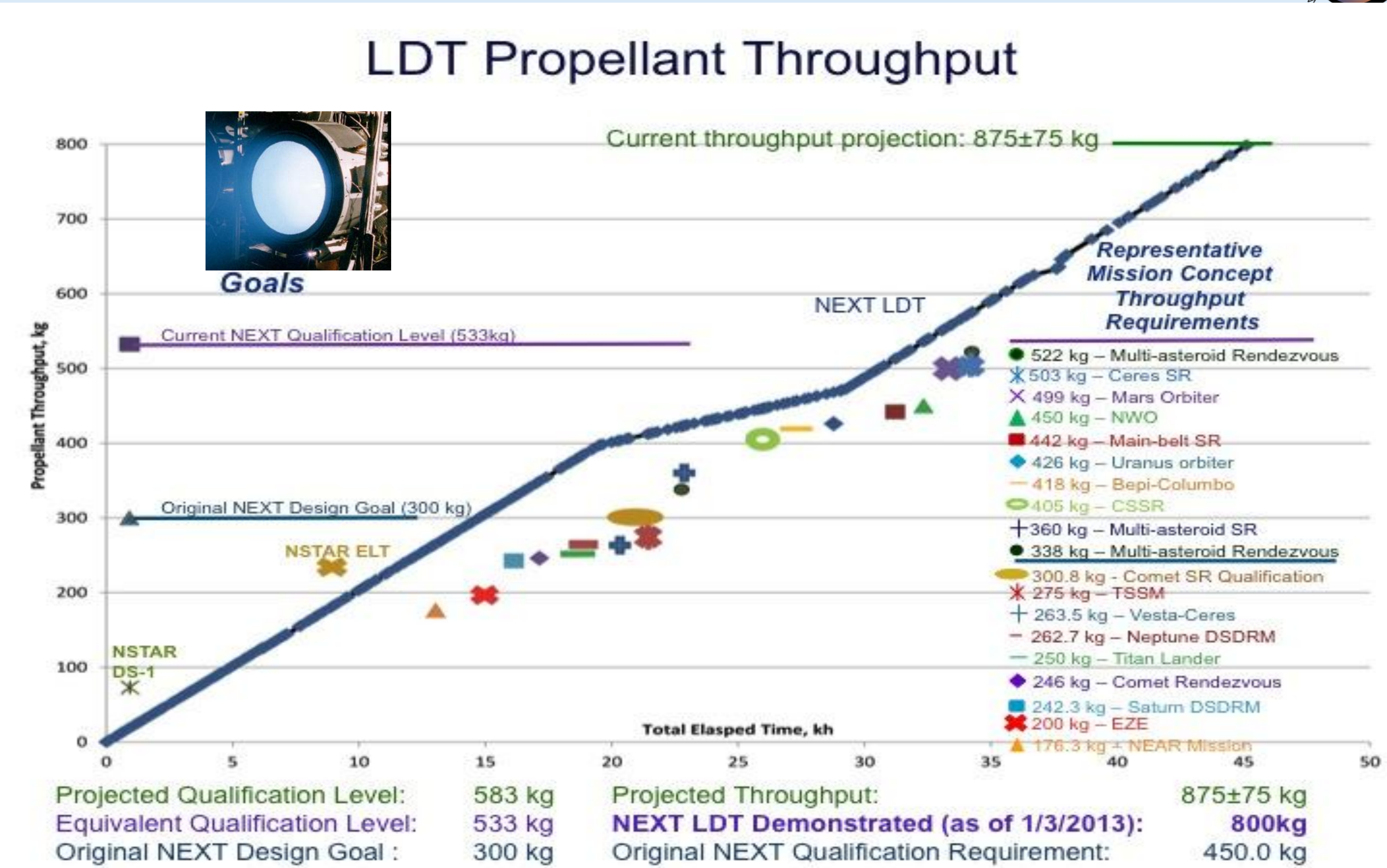
* Rated Capability Goal 300Kg → Design/Qualification Goal (1.5x Rated) 450Kg
Projected Life Limit >800Kg → Potential Rated Capability >530Kg

NEXT Thruster has exceeded all goals!

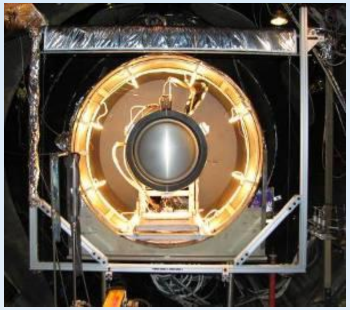


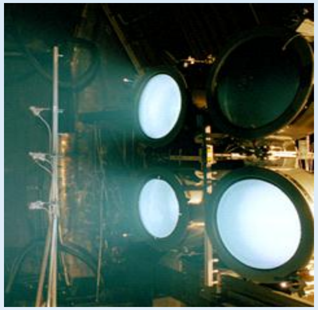
- Single-String System Integration Test: **Complete**
- Multi-String System Integration Test: **Complete**
- Thruster Life Test: 450Kg throughput goal **Complete**
- *As of January 31, 2013, the LDT has achieved >810 kg xenon throughput, >45,679 hours of operation and >31.2 Mn-sec of total impulse*
- Life Test will conclude in FY13 and transition to post-test inspections of thruster
- Unprecedented diagnostics used for NEXT thruster performance characterization and spacecraft interaction effects testing ongoing at TAC

NEXT Mission Benefits & Applicability



NEXT Mission Benefits & Applicability

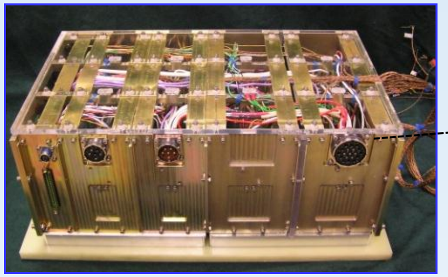




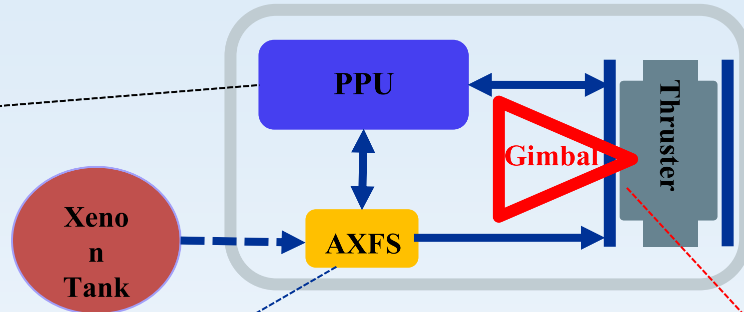
CHARACTERISTIC	NSTAR (SOA)	NEXT	Improve-ment	NEXT BENEFIT
Max. Thruster Power (kW)	2.3	6.9	3x	Enables high power missions with fewer thruster strings
Max. Thrust (mN)	91	236	2.6x	
Throttling Range (Max. / Min. Thrust)	4.9	13.8	3x	Allows use over broader range of distances from Sun
Max. Specific Impulse (sec)	3120	4190	32%	Reduces propellant mass, enabling more payload and/or lighter spacecraft
Total Impulse (10^6 N-sec)	4.6	>30	>6x	Enables low power, high ΔV Discovery-class missions with a single thruster
Propellant Throughput (kg)	150	>530	>3x	

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

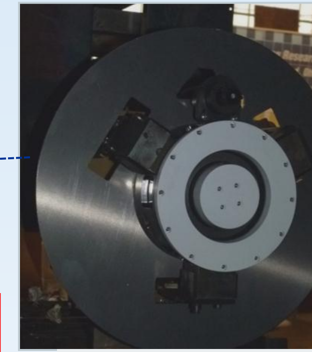
Objective: *Develop key components of a HIVHAC Hall propulsion system (thruster, PPU/DCIU, feed system) to TRL 6 to enable/enhance new SMD Discovery missions; expand operational capability to close near-earth mission applications*



CPE Brassboard PPU



Single String

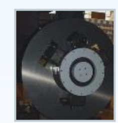


HIVHAC EDU2

Gimbal

VACCO XFCM

- **The HIVHAC EDU thruster offers improved performance and mission benefits over SOA**
- **The HIVHAC project has leveraged OCT SBIR funding to advance the HIVHAC thruster system readiness**
- **A flight-qualified VACCO XFCM was delivered to NASA GRC in March 2012 and will be integrated with the HIVHAC thruster**

• Critical tests have been completed, or are imminent, on high fidelity hardware	EDU2 	BB PPU/DCIU 	Feed System 
Functional , Performance, & Vacuum Testing	**Complete**	**Complete**	**Complete**
Qual-Level Vibration Test	**Complete**	**Planned FY13**	**Complete**
Qual-Level Thermal	**Planned FY13/Q2**	**Planned FY13**	**Complete**

Ultra Lightweight Tank Technology (ULTT) for future planetary missions

Objective:

- To design ultra-lightweight propellant and pressurant tanks sized for MSL/MSR Skycrane with an option to manufacture and qualify.
- Goal: Achieve highest mass saving with reliability

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"

Benefits

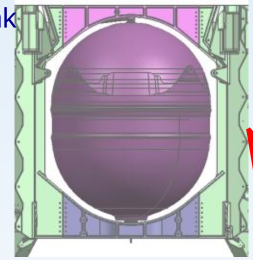
- **23** kg mass savings are achievable for 3 tanks sized for the Skycrane **(48% mass reduction)**
  - Mass savings can be passed on to the scientific payload or increase mass margin
- Broad impact to virtually ALL space missions as most use liquid propellants or pressurant
  - Europa Explorer tank mass can be reduced by 60 kg

Baseline Approach

- To complete CDR design package (June 2013)
- Option: Build and test three (3) Skycrane size tanks
- Option: Ready the tanks for flight demonstration in 2019 or beyond

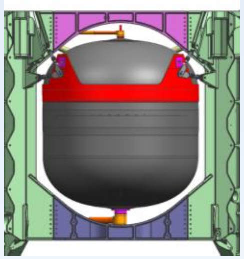
Descent Stage Propellant Tanks

Existing MSL Titanium Tank

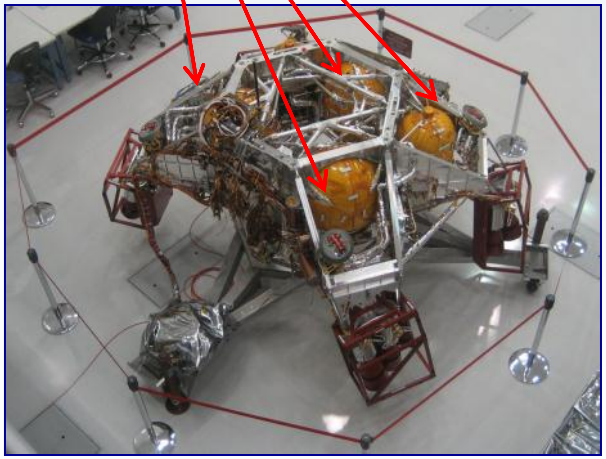


594mm Diameter, ~720mm Tall

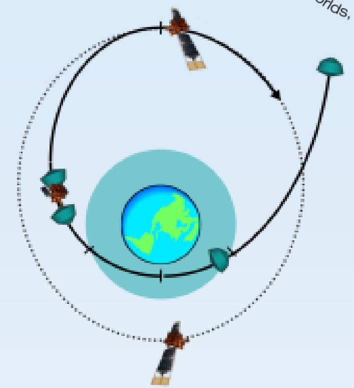
Drop in replacement ultralight tank



594mm Diameter, 684mm Tall



Entry Vehicle Technologies (EVT)



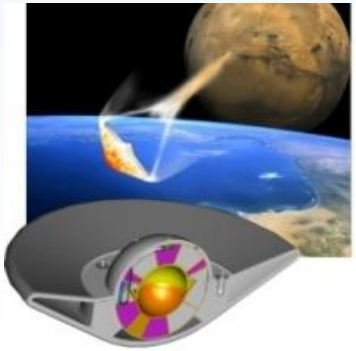
EVT Objectives

•Collaboratively develop high-payoff entry system technologies in support of NASA's science missions

•Fully develop the tradespace and advanced system engineering methods in support of the Multi-Mission Earth Entry Vehicle (MMEEV) design

•Define technology needs/benefits within the context of the Planetary Science Decadal Survey

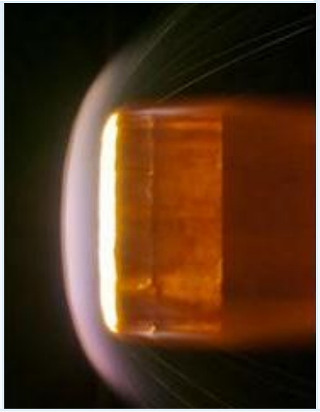
•Facilitate the infusion of ISPT's entry system products to robotic science missions (aerocapture, TPS, aeroshell structures, MMEEVs, modeling and tools)



FY-12 Accomplishments: SEE Arc-jet Testing

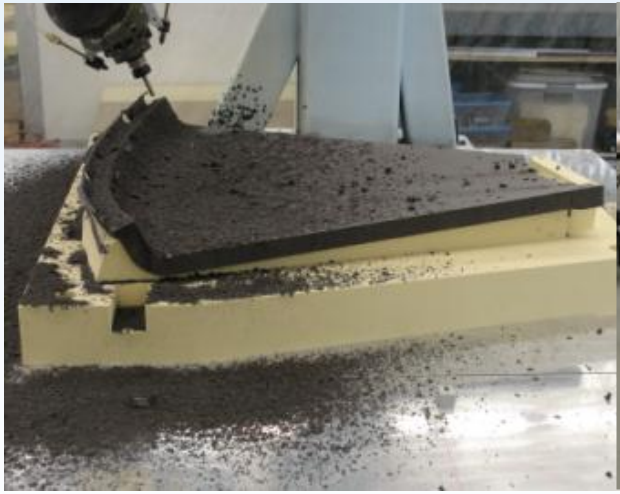
- ***Objective: Investigate the effects of severe space environment exposure on candidate TPS materials***
- Materials selected (those previously matured):
  - Ablative TPS: Phencarb, SRAM, SLA-561V
  - Non-ablative TPS: Carbon-Carbon
  - Forebody and backshell applications
- Effects tested
  - Cold soak
  - Ionizing radiation
  - Hypervelocity (MMOD) impact
  - Followed by simulated entry conditions in ARC's AHF and IHF

- Preliminary results indicate that ablators are robust to combinations of severe space environments



FY-12 Accomplishments: 2.65m MDU Aeroshell

- ***Objective: Validate modular honeycomb-reinforced ablator and high-temperature aeroshell structure design (400˚C bondline) manufacturing techniques in a Manufacturing Demonstration Unit (MDU)***
- Modular TPS approach required for aeroshells >5m
- Final surface machined, plans for CT scanning in FY-13
    - Scanning at Lawrence Livermore National Laboratories ~Feb
    - Will show bondline, other defects; any density anomalies



Machining flank module

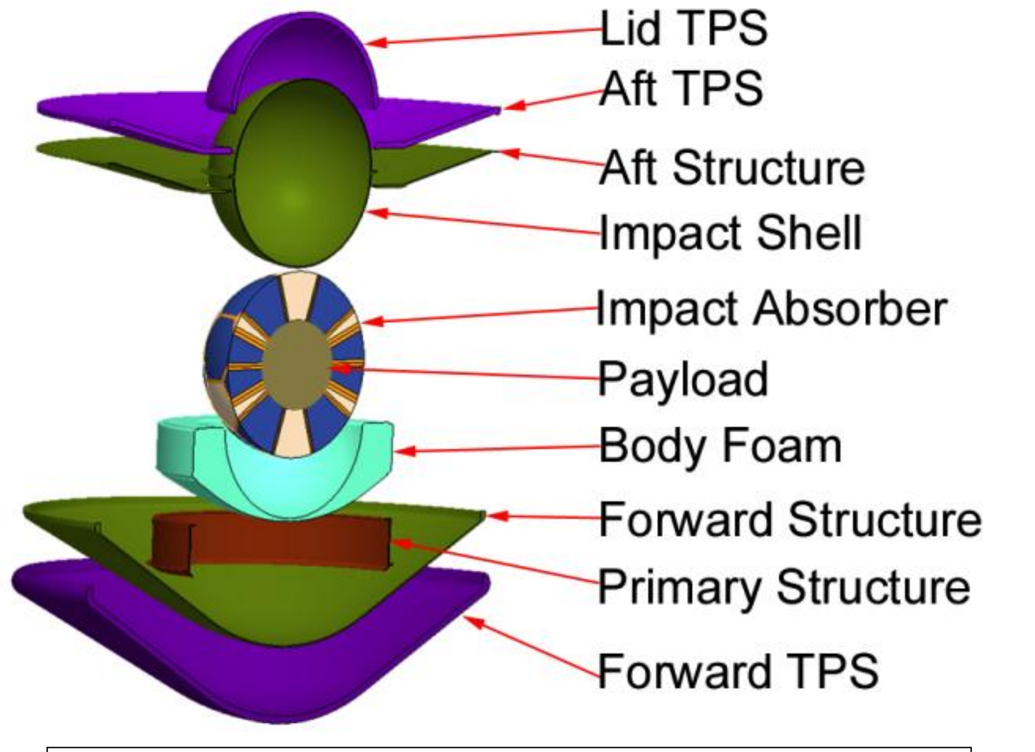
Packing module gaps

Final Aeroshell surface

TPS work performed by Applied Research Associates' Ablatives Laboratory

Multi-Mission Earth Entry Vehicle (MMEEV) Concept

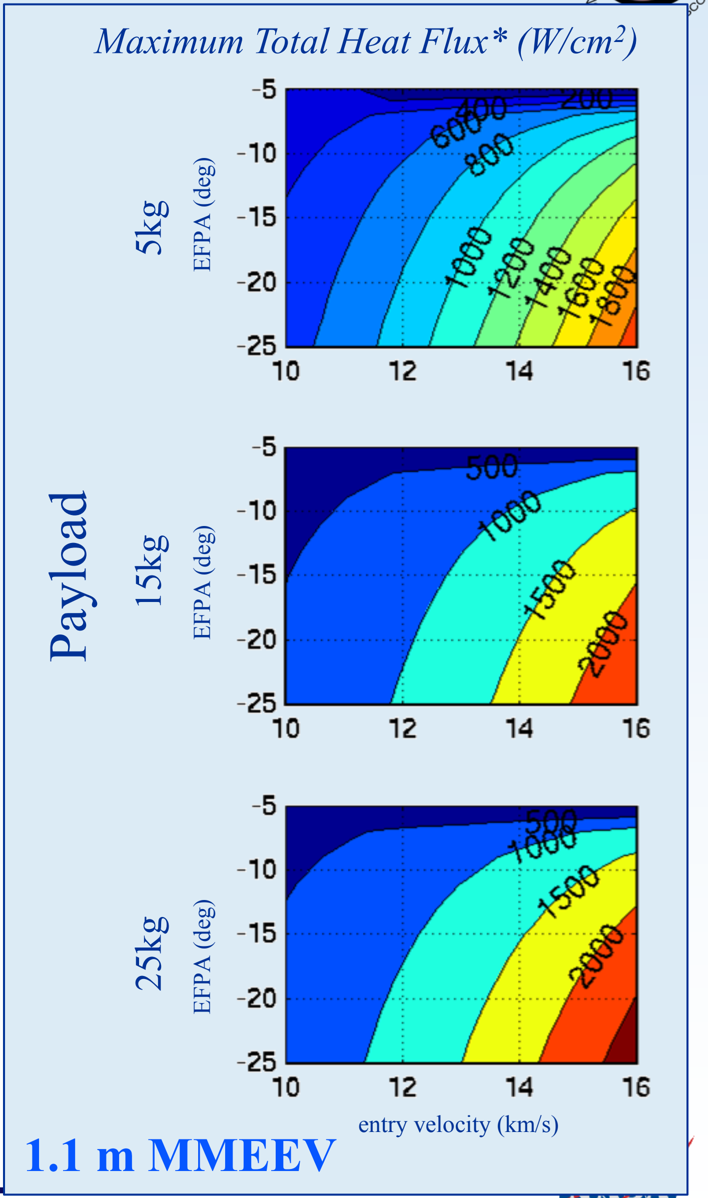
- Passive, Single-Stage EDL method to minimize cost and risk
- Eliminates limited-reliability systems
- Well-suited for Mars Sample Return (MSR) and other sample return missions
- Detailed model available in the M-SAPE tool (see next slide)



MMEEV Parametric Variable	Range
Payload	5 to 30 kg
Vehicle Diameter	0.5 to 2.5 m
Inertial Entry Velocity	10 to 16 km/s
Inertial Entry Flight Path Angle	-5° to -25°

FY-12 Accomplishments: M-SAPE Enhancements

- ***Objective: Develop models to significantly improve the analysis fidelity of the Multi-mission System Analysis for Planetary Entry (M-SAPE) tool***
  - M-SAPE integrates all EDL SE disciplines (aero, traj, struct, etc)
  - Provides visualization of design trade space and vehicle optimization
- Models developed:
  - Thermal soak
  - TPS Mass Estimation Relationships
  - Impact sphere finite element
- Models have been developed and incorporated into M-SAPE

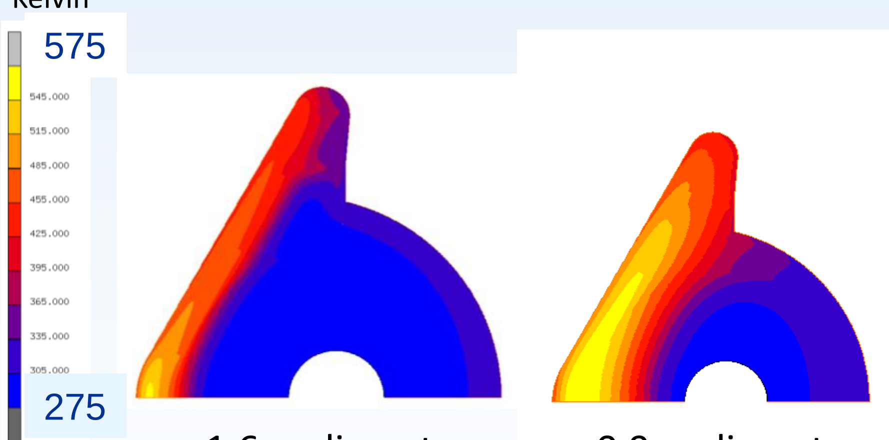


SAPE tool is already available for distribution through the LaRC software release process

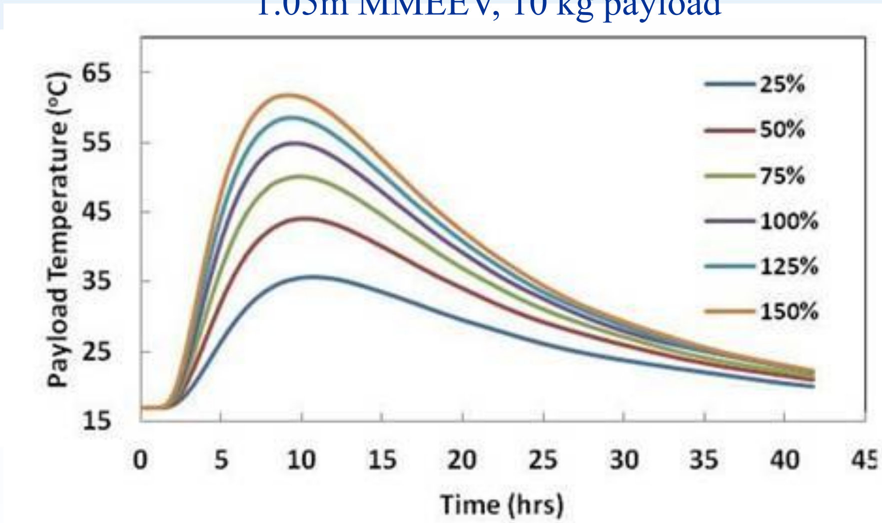
FY-12 Accomplishments: Thermal Soak Analysis

- Maintaining scientific samples at the desired temperature through Earth entry and recovery is a key science requirement
- Thermal soak may be a design driver, affecting mass
- Thermal soak model has been developed and is being parameterized for incorporation into the M-SAPE tool

CP TPS, High Heat Load Trajectory



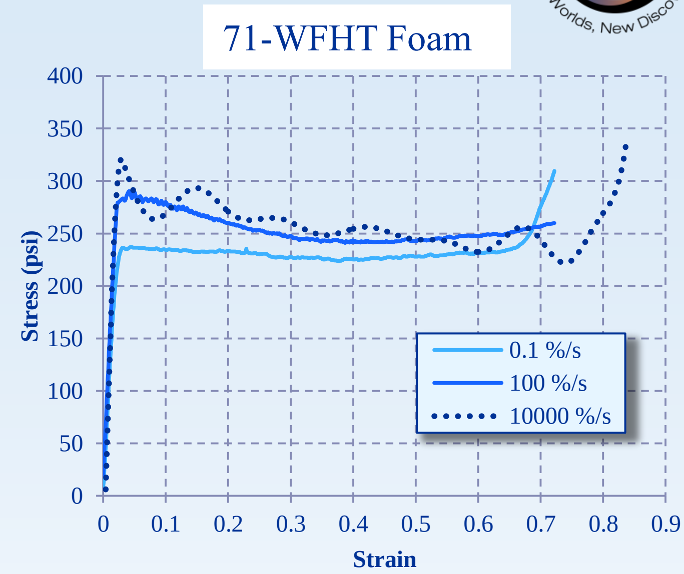
1.6 m diameter   0.9 m diameter

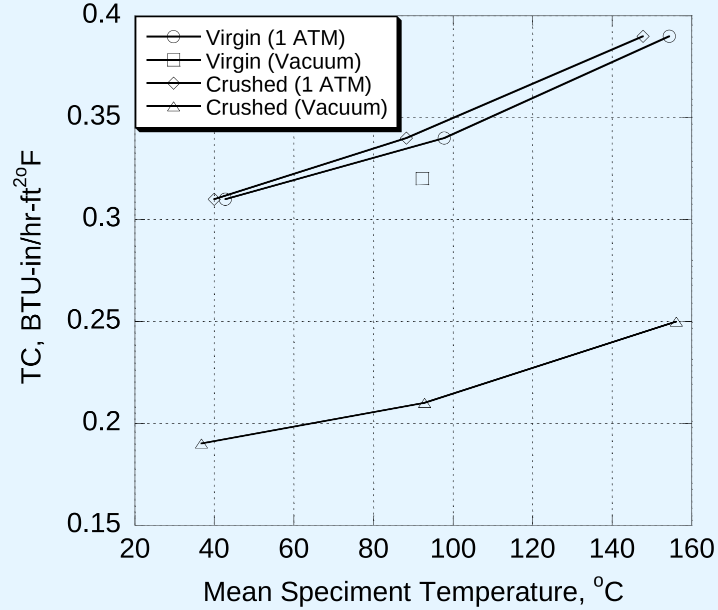


Ref.: Agrawal, et al. "Thermal Soak Analysis for Earth Entry Vehicles."
AIAA 43rd Thermophysics Conference, New Orleans, LA, June, 2012.

FY-12 Accomplishments: Impact Foam Testing

- Objective: Provide mechanical and thermal conductivity data to model Rohacell foams for MMEEV applications
- Range of Rohacell foams examined
  - Densities of 71, 110, and 200 kg/m^3
  - Included high-temp 110 XT foam
- Testing included
  - Large variation of strain rate
  - Thermal conductivity (crushed and virgin)
- Results indicate
  - Significant effect of strain rate and strain rate with density
  - Crushed foam thermal conductivity unchanged from virgin condition

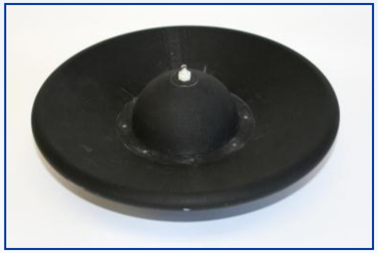




EVT FY-13 Plans

- Document and release M-SAPE
  - Publish an on-line database with access for approved users
  - ~10k cases with variations of payload mass, payload density, EFPA, TPS type, etc
  - Provide limited on-line access for additional cases
- CT scan 2.65 m Aeroshell
  - Provide validation for the modular assembly technique
- Analyze and document Space Environmental Effects Testing results (AIAA report)
- Complete Thermal Soak Analysis
- Archive and fully document prior Aerocapture work
- Complete MMEEV Vertical Spin Tunnel testing →
  - ***Objective: Provide significantly improved MMEEV trade space coverage for vehicle centerline length divided by diameter, CG, and inertias***
- Perform an entry vehicle Uranus Mission Study
- Support Woven TPS development plans

1.2m baseline



1.2m with back shell extender

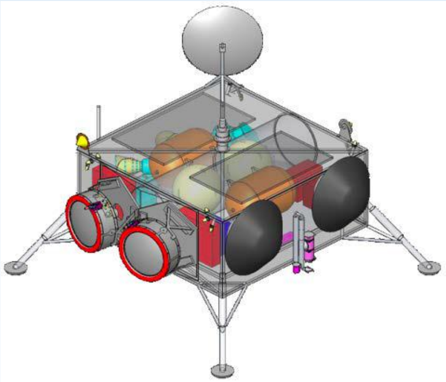
ISPT Systems Analysis

<u>Systems Analysis Objective #1:</u>

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.

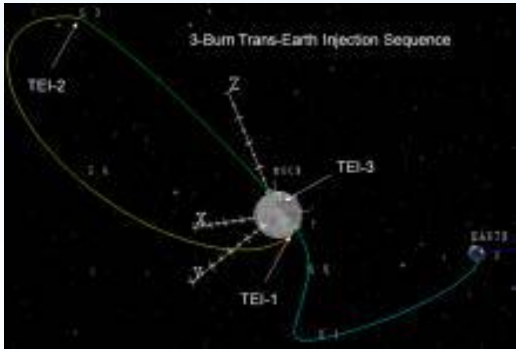
Mission / system design studies define technology requirements

- 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

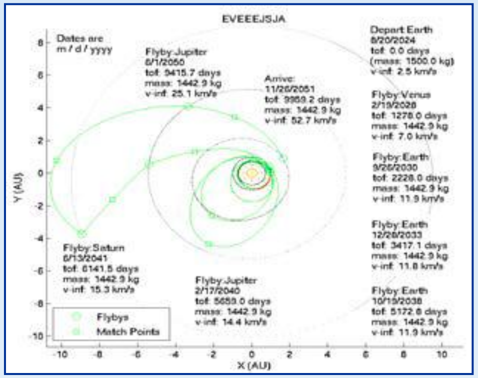


Recent Studies:

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



ISPT Mission Design Tools

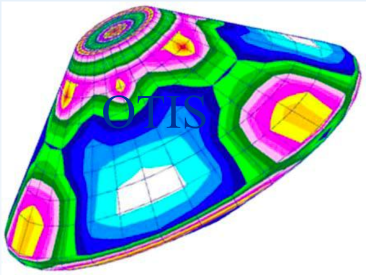


<u>Systems Analysis Objective #2:</u>

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

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 tools training courses: MALTO in 2008, Copernicus in 2009, training as needed (most recent 2011)
- Aerocapture Quicklook Tool Released in 2010



Tool Success:

- Agency point-of-contact for trajectory analyses (e.g. HILTOP Validation)
- 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
- Mystic used for Dawn mission operations, and tools used in Discovery proposals

FY-12 Accomplishments: Venus & Saturn Mission Study

- ***Objectives:***
  - Identify entry technologies that could be leveraged to enable these missions to be viable and enable more science
  - Is there an alternative TPS to HCP? What are the characteristics of these alternative TPS?
- Results indicate:
  - For a range of relative entry velocities and entry masses viable EFPA intervals have been established
  - Spallation threshold determines the steepest EFPA for the following ballistic coefficient ranges:
  - 250 to 300 kg/m^2 for Saturn entries
  - 230 to 260 kg/m^2 for Venus entries
  - Alternates to heritage CP must be able to tolerate high dynamic peak pressures (> 1 bar). Spallation thresholds >10 bar allow for the maximum flexibility in design space
  - Alternates to heritage CP should have a lower threshold heat flux for ablation (2,500 W/cm^2). Heat flux threshold determines the shallowest entry angle.

ISPT FY13-14 Budget and Content

The ISPT budget run-out: $5.6M in FY13, and $3.2M in FY14

1) Conclude Lt Wt COPV propellant tank NDI tech development at CDR in 2013.
2) Conclude NEXT LDT after ≥ 800Kg throughput and conduct post test analysis, and complete NEXT PPU post-repair performance and EMI testing in 2013.
3) Complete Aerocapture activities and documentation in 2013. Complete M-SAPE tool development, validation testing, and documentation in 2014.
4) Focus remaining technology budget resources in 2012 and 2014 on Hall System Technology Development for Discovery-class and MSR missions.

Budget distribution for ISPT		PY13 plus PY12 Carry-in	Tentative PY14
Entry Vehicle Technologies	Earth Entry Vehicles & Aerocapture	$0.97M	$0.65M
Propulsion Technologies	NEXT: Long Duration Test (LDT), and PPU Perf Validation & EMI Testing	$1.68M	
	Hall System Development	$1.91M	$1.3M
Spacecraft Technologies	Lt Wt COPV Propellant Tanks	$0.53M	
Systems/Mission Analysis		$0.50M	$0.10M
Project Management + Reserves		$1.28M	$1.10M
		$7.2M	$3.2M

ISPT Technology Infusion

- ISPT is maturing technologies to be proposal/flight-ready
  - Development:
    - Hall Propulsion System for low-cost Discovery missions
    - Ultra-light weight propellant tank design as a drop-in replacement for Skycrane on a future Mars mission.
  - Proposals:
    - Technology infusion incentives were offered under the recent Discovery and New Frontiers AO's for NEXT, AMBR, and Aerocapture
    - Supporting use of ISPT developed technologies on proposals to OCT BAA's (AMBR, Solar Sails, Balance Flow Meter, and ultra-light weight propellant tank)
  - Flight:
    - Mars Science Laboratory (MSL) using ISPT developed HEAT sensors as part of the MSL Entry, Descent, and Landing Instrumentation (MEDLI) package
    - Fabricating 2 flight qualified AXFS. Interest (commercial, too) has increased due to pursuing the flight qualification step!

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

Questions?

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ISPT Program Manager
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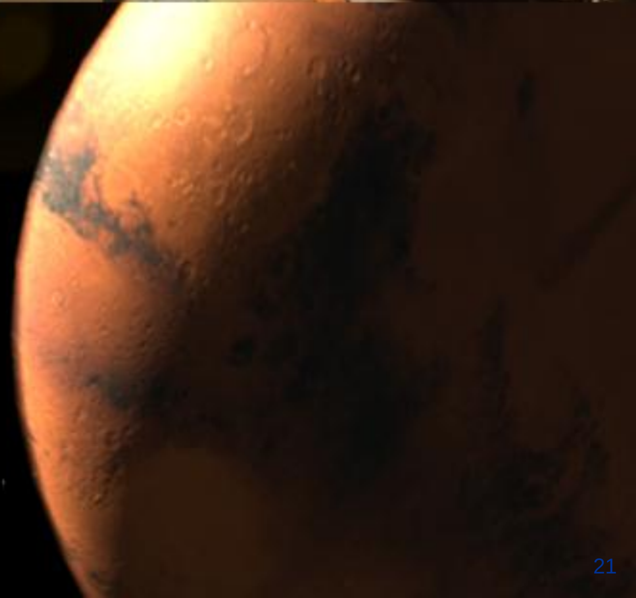
216-433-8709

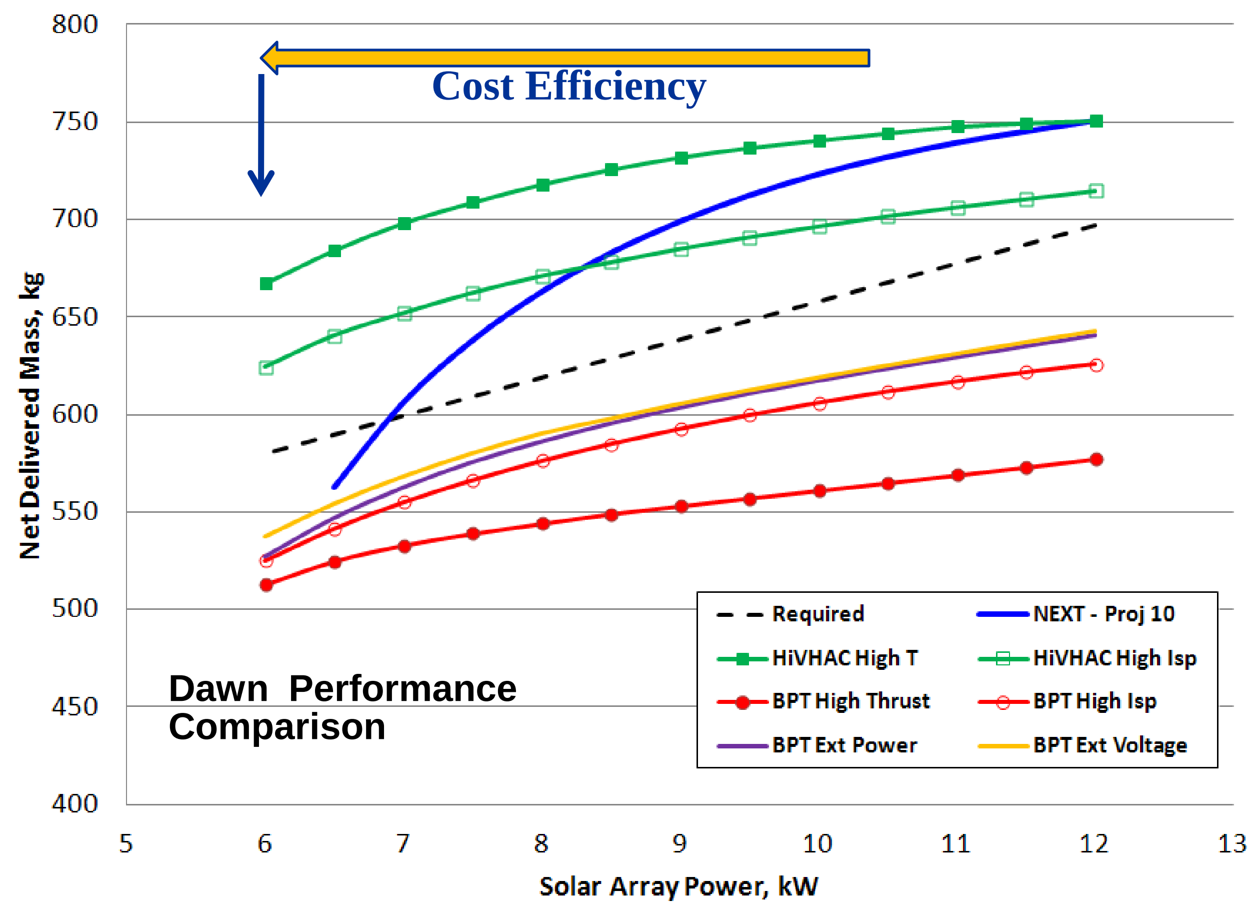


Hall System Mission Analysis

- **Compared HIVHAC, BPT-4000, SPT-140, and NEXT performance**

- **Comparison of Mission Performance**

1)Dawn – Discovery DRM
2)Kopff Comet Rendezvous – Discovery DRM
3)Nereus Sample Return – Discovery DRM
4)NEARER – Double NEA Sample Return
5)Wirtanen – CSSR – NF DRM
6)C-G - Decadal CSSR - NF DRM
7)Uranus – Decadal Flagship DRM



Hall System Mission Analysis (cont)

Thruster	Summary of Mission Performance Comparison
HIVHAC	• Performance is sufficient for all Discovery Class missions evaluated - High Thrust throttle table generally shows higher performance than high Isp • Is the highest "cost efficient" EP system (Requires the lowest system power and spacecraft mass)
BPT-4000	• Has sufficient performance for a subset of Discovery Class missions • Modifications to the BPT-4000 for higher voltage operation can increase BPT-4000 mission capture - Modifications to BPT-4000 do not match HIVHAC performance for low/modest power spacecraft (i.e. cost efficient)
NEXT	• Performance is sufficient for all Discovery Class missions evaluated • Is the highest overall performance, and is required for Flagship EP missions.

Advanced Xenon Feed System (AXFS)

OBJECTIVE

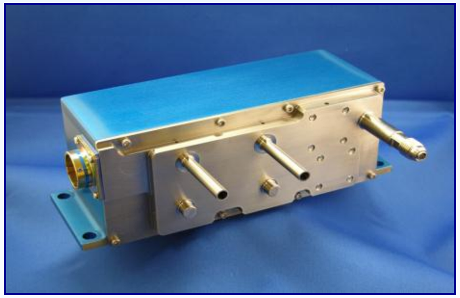
- ISPT award a contract with VACCO industries to develop a modular Advanced Xenon Flow System (AXFS) with significant reductions in mass, cost, and volume over SOA while increasing system reliability.
  - Flow control accuracy error < 3% EOL
  - TRL 6 testing
  - Award for two Flight CMs, 1 PCM, 1 controller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

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.**

Dawn Feed System



VACCO XFCM

	NSTAR	NEXT	AXFS	XFCM
Mass, kg	11.4	5.0	1.5	1.25
Estimate Footprint, cm^2	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 to leverage commercial investments and push the limits of technology without adding risk to EP projects.

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