Solar Electric Propulsion (SEP) Systems for SMD Mission Needs

In-Space Propulsion Technology (ISPT) Program

Program Executive: Len Dudzinski

Project Manager: David J. Anderson

January, 2014

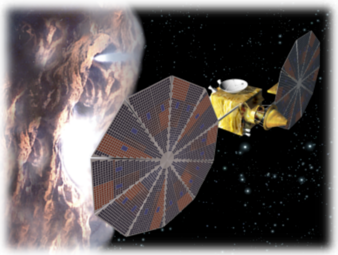
SEP Brings Significant Benefits to Planetary Science Missions

Multiple rendezvous for small bodies

Enables many asteroid and comet missions that are impractical without SEP

Control of arrival conditions

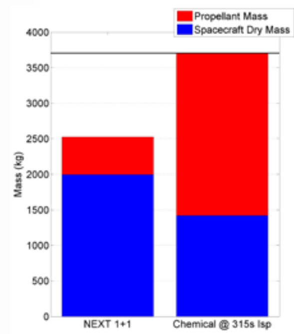
- Achieve lower speed arrival or control arrival time for Mars entry
- Change direction and velocity of approach to reach more landing sites



Reduced number of mission critical events (risks)

Large/critical maneuvers, aerocapture, aerobraking

- e.g., orbit insertion, earth avoidance, response to anomalies…



More mass delivered to destination

- SEP facilitates launch on a smaller (and cheaper) launch vehicle due to performance efficiencies
- Could enable more mass for instruments or mass margins
- Provides performance margin and resilience to mass growth

Shorter trip times

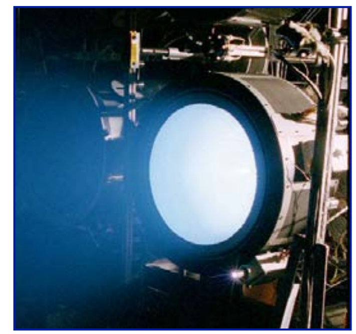
Might expand feasible mission set beyond the asteroid belt including return of samples to Earth

Launch window flexibility

- SEP facilitates longer and more frequent launch windows for deep space missions
  - e.g., Dawn delay was possible to accommodate Phoenix launch
- Decreased reliance on gravity assist availability

Why Solar Electric Propulsion (SEP)? Key Attributes!

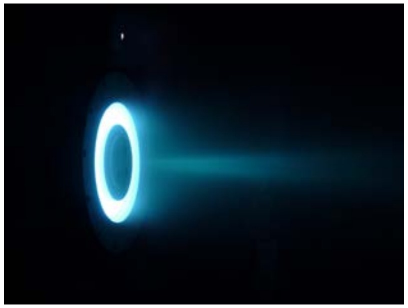
- Proven technology
  - Hall and ion thrusters have been used for years on many missions
- Enabling technology
  - SEP is the only feasible way to do most high ΔV missions (>4 km/s)
  - Operational agility
    - Planetary SEP is throttlable, can gimbal, and has the flexibility of multiple strings (redundancy)
  - Extended lifetime



- Mission synergy
  - Many missions (e.g., communications, deep space) already require large solar arrays that are under utilized for portions of the mission
  - Power for SEP can be leveraged for Communication

Upcoming Opportunities - New Frontiers and Discovery: SEP as an Enabler

- "1st Driver" Cost and low risk – cost caps for competed missions
  - COTS SEP has flown, better understanding of cost, operation, and risk
  - Find a way to do more with less – enabling technology



- "2nd Driver" Mass and power
- Mission design
  - Delta V (ΔV); Mission Duration (Time of Flight); Deep-space Environments
  - COTS SEP optimized for Earth-orbit applications, will not achieve all desired planetary missions, SEP with planetary requirements in mind is needed

Planetary Decadal Survey Identified Missions Using SEP

Discovery
- Dawn *
- Kopff Comet Rendezvous *
- Nereus Sample Return *

Other Candidate Discovery
- Flybys of multiple asteroids and comets
- Asteroid and comet orbital/rendezvous
- NEO sample return or geophysical mission
- Landed investigations of Phobos & Demos
- Jupiter-family comets Stardust-like mission
- Flyby of Oort cloud comets
- Mars atmosphere sample collection & return

New Frontiers
- Comet Surface Sample Return (CSSR)
  - Wirtanen *
  - Churyumov-Gerasimen *
- Trojan Tour and Rendezvous *

Other SMD
- *New Worlds Observer*
- *Extra Zodiacal Explorer (EZE)*

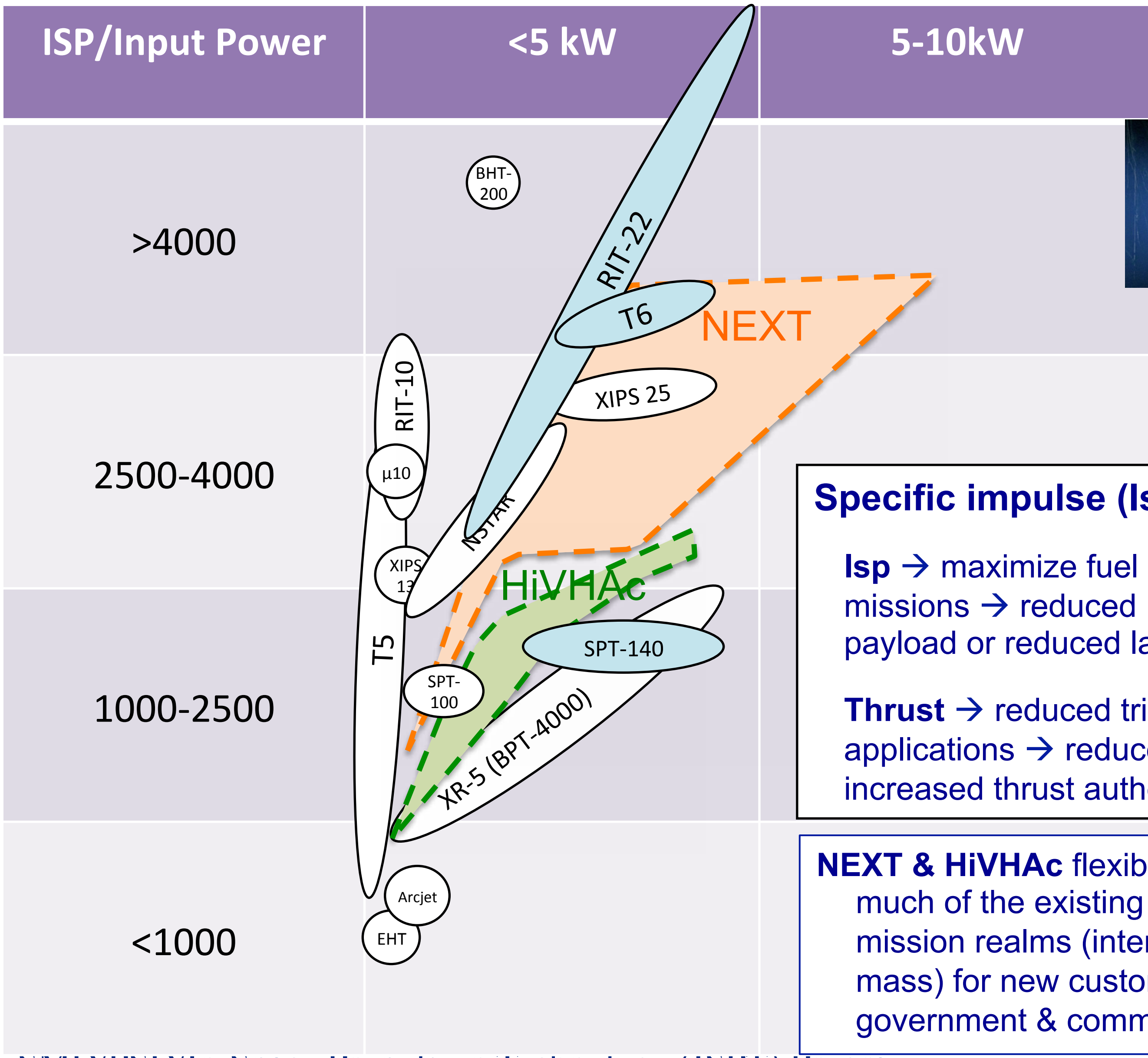
Flagship 2013-2022 & Priority Deferred
- Uranus Orbiter w/SEP & Probe *
- Mars Sample Return – Orbiter/Earth Return *
- Titan-Saturn System Mission (TSSM) *

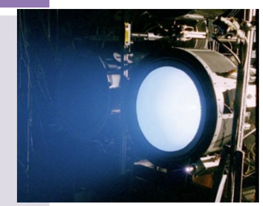
Other Decadal Missions Considered
- Mercury Lander *
- Venus
- Chiron Orbiter *
- Neptune-Triton-KBO Mission *
- Asteroid Interior Composition Mission
- Near-Earth Asteroids 2020-2040 *
- Comet Cryogenic Sample Return *
- Saturn Ring Observer *

- **New Frontiers: 4 of 7 expected missions are could be enabled by SEP**
- **Discovery: Most small body missions**
  - **Several smaller high priority science missions enabled if an affordable solution exists**

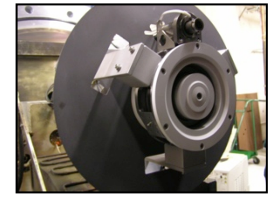
* NOTE: Decadal Design Reference Mission (DRM)

Solar Electric Propulsion Market Options

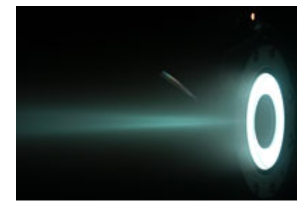




NEXT



HiVHAc



BPT-4000

Specific impulse (Isp) vs. thrust

Isp → maximize fuel efficiency → interplanetary missions → reduced launch mass → more science payload or reduced launch vehicle size/cost

Thrust → reduced trip time → near-Earth applications → reduced mission ops costs → increased thrust authority

NEXT & HiVHAc flexibility & performance envelopes much of the existing market while extending new mission realms (interplanetary, orbit transfer, high mass) for new customers (e.g., international, government & commercial)

Representation of SEP vs Mission Performance Comparison

Metrics: Solar Array Power (kW) / Net Delivered Mass (kg) for a closed mission

Mission Concept	NEXT	HiVHAc High T	HiVHAc High Isp	BPT-4000 High T	BPT-4000 High Isp
Dawn (D)	7-12 kW 600-750 kg	6-12 670-750	6-12 625-715	---	---
Kopff Comet Rendezvous (D)	7-12 680-745	6-12 720-740	6-12 650-720	---	6 555
Nereus Sample Return (D)	5-12 750-1100	5-12 920-1175	5-12 800-1020	5-12 1020-1350	5-12 1020-1340
NEARER (NF)	7.5-10.5 730-910	6-12 720-890	7.5-12 725-860	---	8-12 745-850
Wirtanen CSSR (NF)	12.5-15 750-880	11-15 740-860	---	---	---
C-G CSSR (NF)	14-20 1000-1600	13-19 1250-1310	---	---	---
Uranus Decadal (FL)	15-20 2750-3020	---	---	---	---
MSR ERV (FL)	1577	1740	---	1634	Closes mission

NOTE: SEP system, PV array, and Ops Costs were not assessed in this mission performance comparison

SEP meets performance for >40 SMD missions studied

Summary of SEP System vs Planetary Mission Comparison

NEXT has the highest overall performance

- NEXT is required for Flagship EP missions
- NEXT performance is sufficient for all Discovery Class missions evaluated
- Ion EP is operating in space like it does in ground demonstrations

BPT-4000 has sufficient performance for a subset of Discovery Class missions

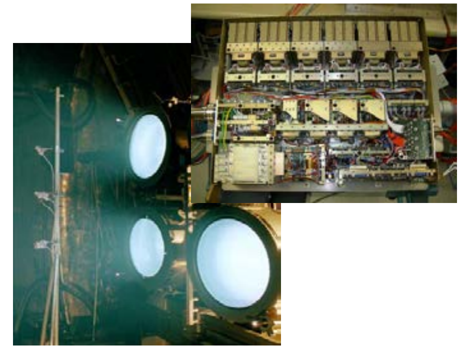
- COTS BPT-4000 is a good match for Mars Sample Return
- Modifications to the BPT-4000 for higher voltage operation can increase BPT-4000 mission capture
    - Modifications to BPT-4000 do not match HIVHAC performance for low/ modest power spacecraft (i.e. cost efficient)

HiVHAc performance is sufficient for all Discovery Class missions evaluated

- High Thrust throttle table generally shows higher performance than high Isp
- HIVHAC is the highest "cost efficient" EP system
- Requires the lowest system power and spacecraft mass

*Full study not concluded

Recommended SEP System Development Options

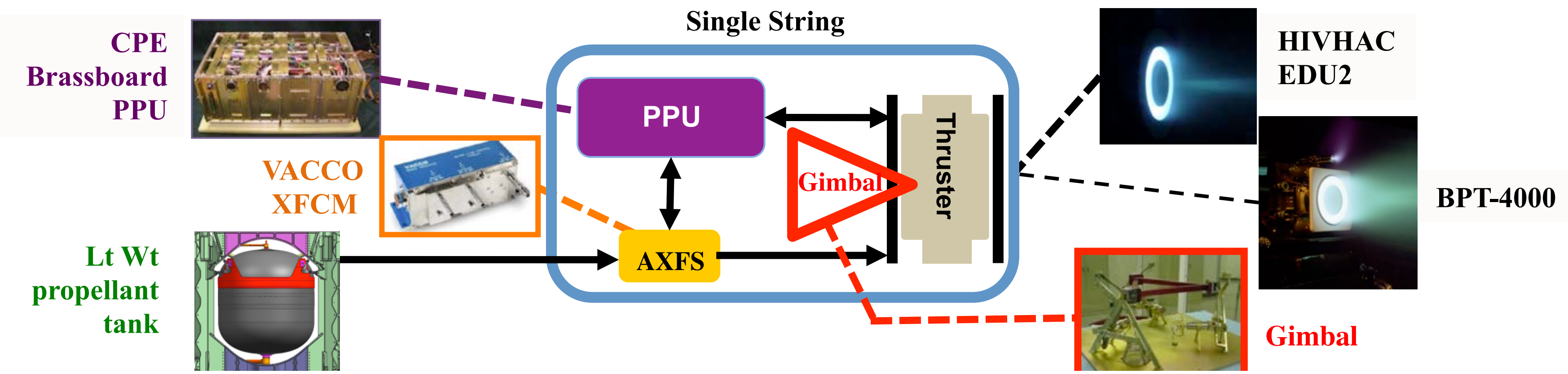


SMD: NEXT PPU and System Certification

- Satisfy potential NEXT system user needs with qualification of a NEXT PPU and certification of NEXT system.
- Prepare AO documentation and support specific users & missions.

SMD: Planetary Hall System Development

- Complete development of a low-cost Hall propulsion system with a focus on cost-capped Discovery missions and application to New Frontiers missions.
- The key components under development would be a thruster, power processing unit (with digital control interface), and feed system. Components would be designed, fabricated and tested individually, then assembled in an integration test and qualification life test.



STMD: SEP Development

- 12kW Hall Thruster development for ARRM and SEP TDM
- Lighter weight, lower cost 20kW PV Array Development (ATK Mega-Flex, DSS Mega-ROSA)

NASA Science as SEP Buyer

- Planetary Science Division has been supporting SEP technology development for >12 years
  - Needed to do compelling science
  - Buy spacecraft capabilities from industry when needed
- Solar Electric Propulsion, like NEXT or HiVHAc, enables Planetary Decadal Survey missions with compelling science
- Expected cadence for SEP Science missions ~1-2/decade (science competition)
  - Discovery, New Frontiers, Explorer
- In-Space Propulsion Technology program funding ends in FY14
  - If the science community/AG's wants SEP for the planetary missions it wants to fly, then let NASA know it's important to have this capability

Questions?

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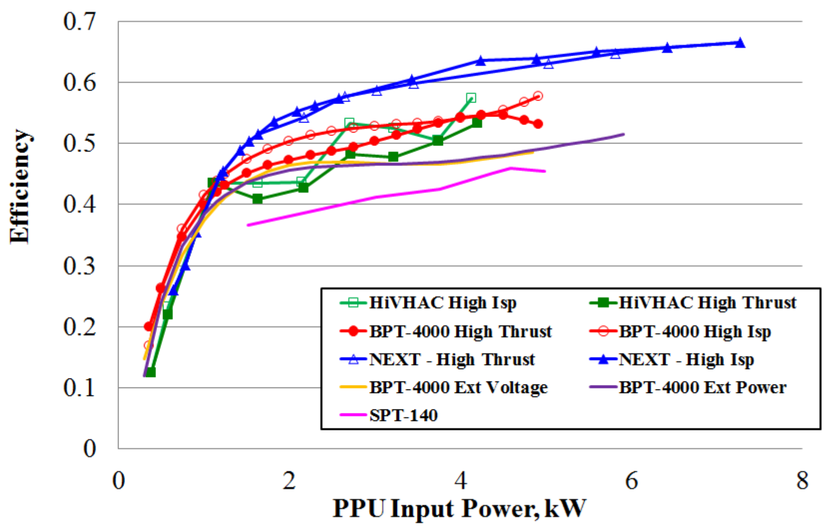
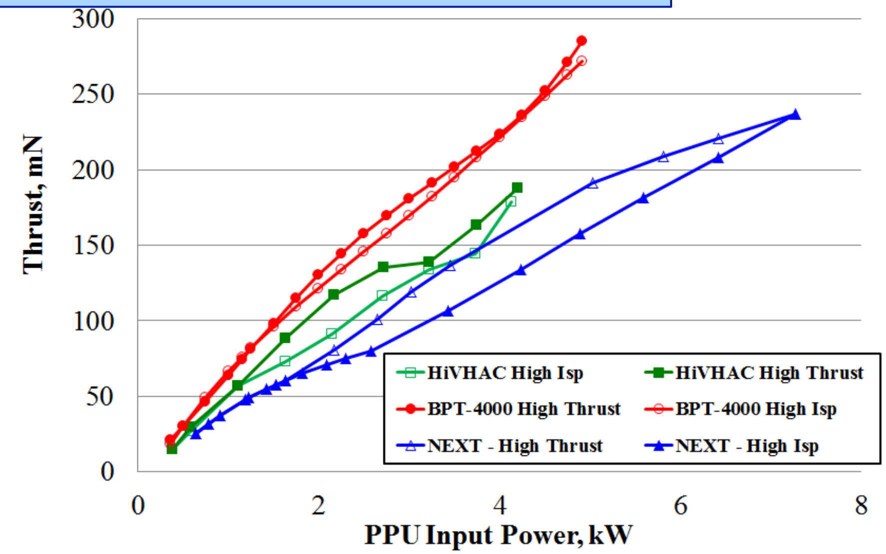
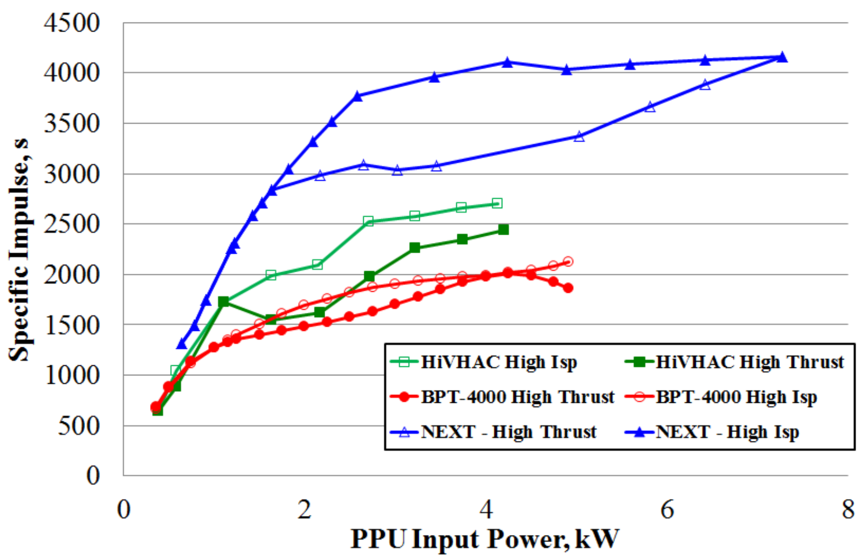
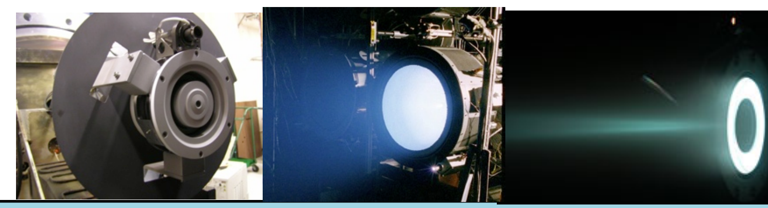
Direct Comparison of Thruster Performance

Key SMD propulsion drivers: Isp, power throttling, life







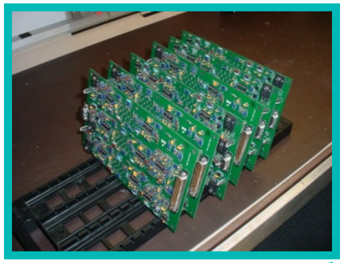


Specific impulse (Isp) vs. thrust

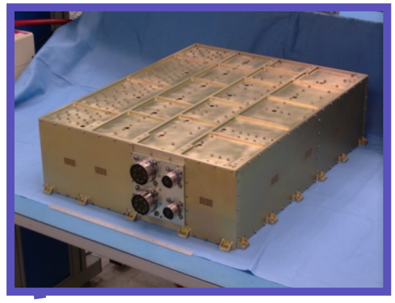
Isp → maximize fuel efficiency → interplanetary missions → reduced launch mass → more science payload or reduced launch vehicle size/cost

Thrust → reduced trip time → near-Earth applications → reduced mission ops costs → increased thrust authority

The What: NEXT Ion Propulsion System

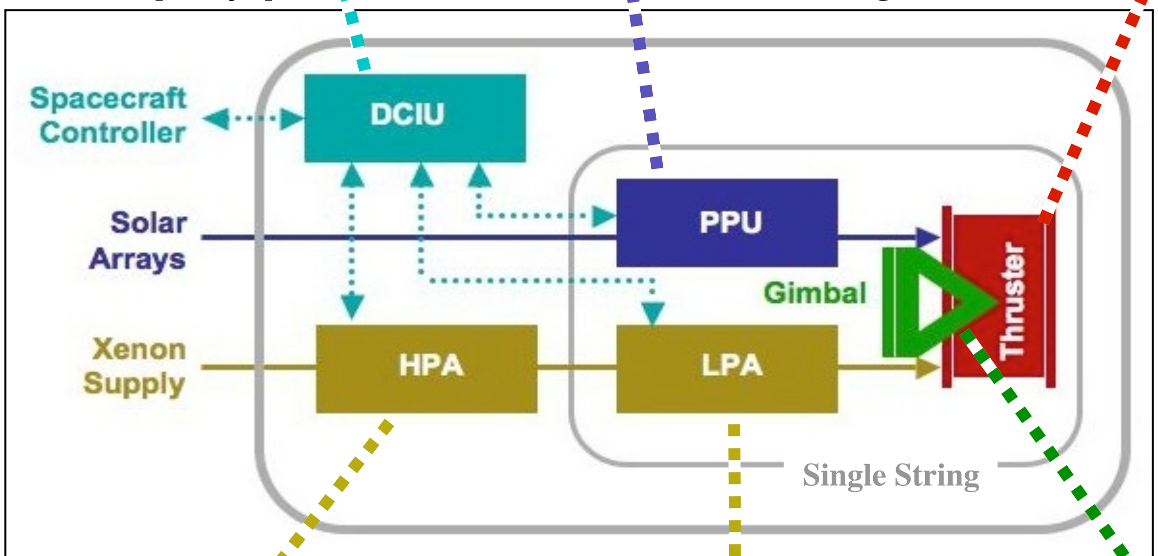


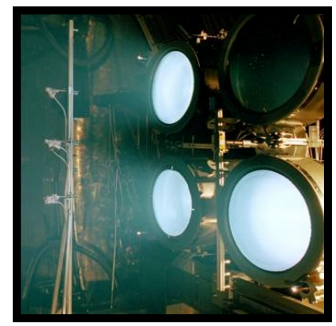
Digital Control Interface Unit (DCIU) Simulator [Aerojet]



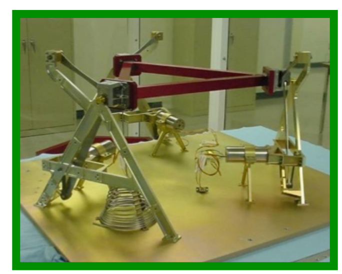
Power Processing Unit (PPU) [L-3 Com, Eng Model]

Thruster [Aerojet, Prototype Model]

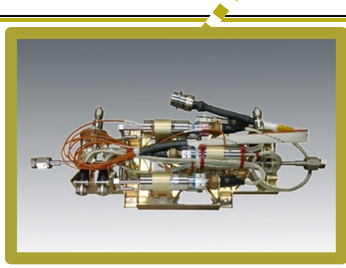




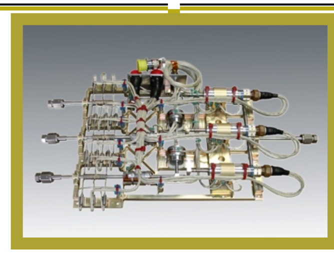
NEXT system testing at GRC



Gimbal [ATK, Breadboard]



High Pressure Assembly (HPA)



Low Pressure Assembly (LPA)

Propellant Mgmt System (PMS) [Aerojet, Eng Model]

NEXT System Development

- Requirements to meet <u>all</u> NASA planetary mission classes
- Development of high fidelity components and systems to TRL 5 with significant progress towards TRL 6 initiated October, 2003, $55M investment
  - Thruster long duration test successfully exceeded duration records covering all studied NASA missions
  - Feed system, DCIU algorithms, gimbal advanced to reasonable maturity (residual risks acceptable)
  - PPU had multiple component failures
  - Not shown – Photovoltaic Arrays – use other developments

- NASA developed in-house plan to bring to "proposal-ready"
  - PSD will not be able to fund remaining work

Hall EP System

Hall EP Technical Interchange Meeting held Dec. 2013

- NASA GRC, JPL, MSFC and USAF/AFRL

Top Priorities

- Develop common flight Hall 5kW-class modular PPU with capabilities for PSD mission needs for any Hall thruster (COTS or NASA developed)
    - Qualify unit and procure 3 flight PPU's as GFE
- Evaluate commercial Hall thrusters (BPT-4000 (XR-5), SPT-140)
    - Delta qualify (as necessary) for PSD environments/life
    - Facility effects assessment
    - Ground-test-to-flight-modeling protocols
- Complete HiVHAc system
    - Assess/incorporate magnetic shielding, and qualify thruster
- Leverage STMD Hall system to PSD mission needs

- Maintain Mission analysis capabilities and tool development for SEP

Hall vs. Ion Thruster

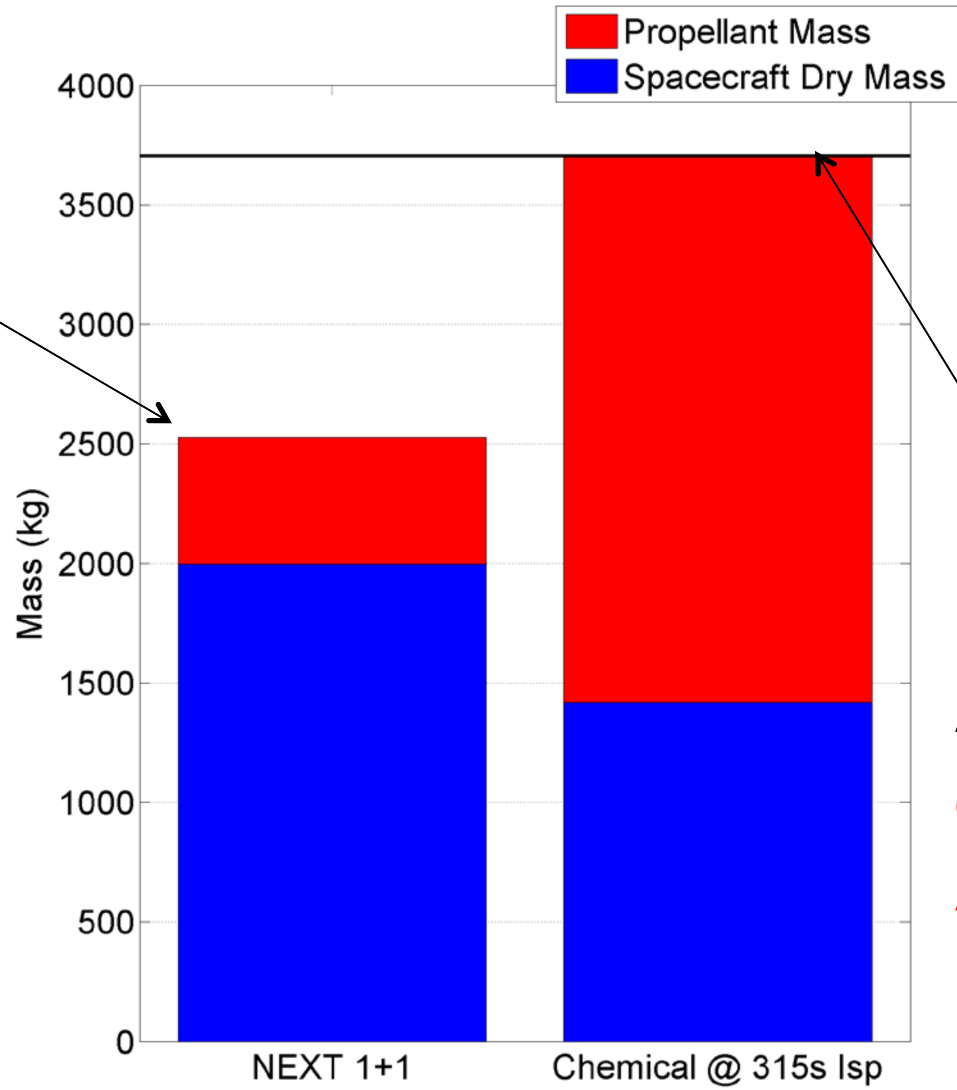
- Ion: NASA Evolutionary Xenon Thruster (NEXT)
  - High power, high *Isp,* moderate thrust
  - Over 50,000 hours and over 900 Kg of Xenon throughput in continuous ground testing
- Hall: HiVHAc, BPT-4000, and SPT-140 Thruster
  - Moderate power, moderate *Isp,* high thrust
  - BPT-4000 Flown successfully on the Advanced Extremely High Frequency Space Vehicle in Nov, 2010

Hall/Ion Thruster Trade:
Comet Sample Return Example - Agility

- Although the BPT4000 thruster can (i.e., a given target on a given year) result in better situational performance, the NEXT thruster is typically advantageous over a full target sweep.

Example of Chemical vs. Electric Propulsion: Comet Sample Return Example – Mass and Cost Savings

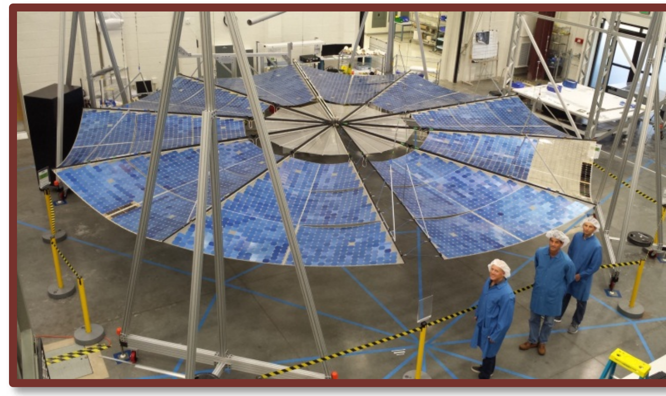
Atlas V-401 Capacity
@ C3 = 8.4 km^2/s^2
21% fuel, before margin
12 year TOF baseline
11 year TOF backup



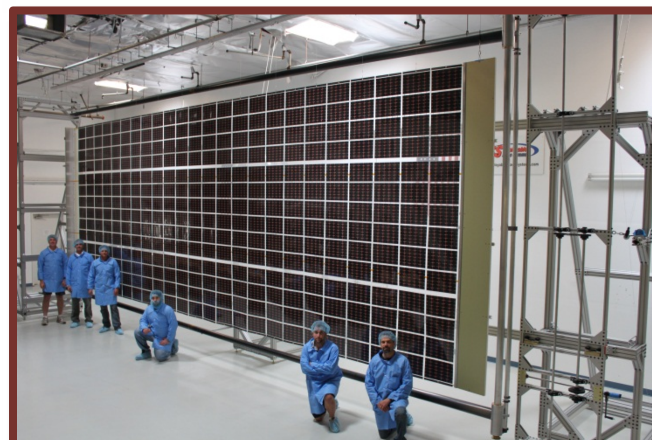
Atlas V-551 Capacity
@ C3 = 25.5 km^2/s^2
62% fuel, before margin
13 year TOF baseline
Alternate target req'd for backup

STMD SEP Project
Solar Power Element Overview

- **OBJECTIVE:** **Design and build 20-kW-class solar arrays to meet mass, volume, strength, stiffness, and environmental requirements anticipated for human exploration missions**
- **APPROACH:** **Two contracts: a fan-fold design from ATK and a roll-out design from DSS. Both use flexible blankets to dramatically reduce mass and stowed volume compared to rigid panel structures.**
- **FY13 MAJOR ACCOMPLISHMENTS:**
  - ✓ **Brought concepts from idea to hardware: Passed SRR, MDR, and MRR reviews**
  - ✓ **Conducted structural, thermal, and environmental tests on key subsystems**
  - ✓ **Characterized PV coupons in plasma environment and single event radiation effects on high power, high voltage electronic parts**
- **FY14 PLANS:**
  - – **Demonstrate TRL 5/6 with thermal vacuum deployment tests**
  - – **Demonstrate extensibility to 250kW-class systems analytically**



MegaFlex Engineering Development Unit employs an innovative spar hinge to reduce stowed volume.

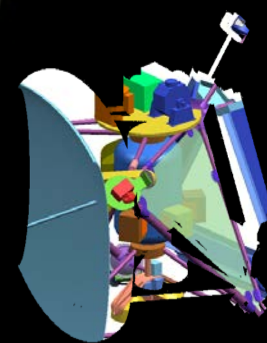


Mega-ROSA Engineering Development Unit employs an innovative stored strain energy deployment to reduce the number of mechanisms and parts.

Contact: Carolyn.R.Mercer@nasa.gov NASA GRC

National Aeronautics and Space Administration

Technology Infusion Study
- DRAFT Findings & Recommendations



SBAG Meeting, Washington, D.C.

January 2014

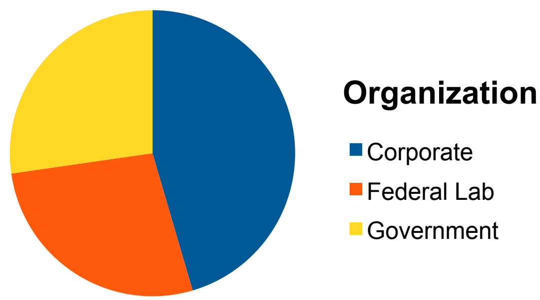
Team Members:

- David Anderson
- Linda Nero
- Carl Sandifer II
- Timothy Sarver-Verhey
- Daniel Vento
- June Zakrajsek

Tech Infusion Study Motivation and Implementation

- **Planetary Science Decadal and PSD Assessment Groups state that PSD technology investment recommended**
- **However, PSD Technology Infusion Poor. Why?**

- **Technology Infusion Study**
  - Objective: ***Provide PSD with recommendations on how to more effectively infuse new spacecraft systems technologies into future competed missions enabling increased scientific discoveries, lower mission cost, or both***
  - **"Infusion Technologies"** are defined as: ASRG, Aerocapture, AMBR, NEXT, and Hall effect thruster
  - RFI to solicit community input to enable recommendations on how to effectively use technology investments in future missions (March)
    - » 11 RFI Responses – Complete April
    - » Analysis Phase – Complete December
    - » Report/Recommendation Phase – Preliminary
    - » Discussion Phase – Starting



Seeking Respondent and Community Feedback on Draft Recommendations

Tech Infusion Executive Summary – DRAFT Findings

- End-User Community (Industry/proposers) wants to use NASA developed technologies to support PSD missions (Decadal finding & recommendation)
  - Technologies enable or are applicable to 36 of 47 mission identified in the Decadal
- Enabling technologies are not ready (reality & perception)
  - Need to resolve technology readiness issues
  - Need to complete developments, document better, and qualify
  - Proposers perceive SOMA to judge new technologies as high risk
- Current incentives for technologies are not sufficient to overcome real or perceived risks, and implementation/accommodation costs – limits ROI
- PSD is losing credibility when it comes to technology development and infusion.
  - Not selecting missions with incentivized technologies
  - Dropping investment (e.g. terminating ASRG, not finishing NEXT)
  - Uncertainty if, or how, PSD will incentivize technologies in future (Decadal to continue)

Tech Infusion Exec Summary – DRAFT Recommendations

I. Strategic

- Maintain tech programs to assist future infusion activities, & retain PSD capabilities
- Accept increased risk and cost regarding use of infusion techs in future AO's

II. Process/Structure

- Complete development and qualification of the current infusion technologies
- Implement a defined, transparent, and independent process for validating and documenting infusion techs have achieved $\geq$TRL 6, $\geq$9-months prior to AO release
- Expand use of mission capability enhancement studies to improve the understanding of mission requirements and constraints with implementing tech's
- Determine accommodation costs/burdens associated with new technologies
- Incentives approach must address accommodation costs/impacts, and the completion of system-level development work (TRL 6 to flight infusion)
- Present infusion technology incentive approach 9-12 months prior to AO release
- AOs should establish/designate missions that mandate the use of infusion techs

Tech Infusion Exec Summary – DRAFT Recommendations

III. Resources

- Provide tech development resources for PSD unique/critical mission needs
- Provide sufficient resources over shorter development timescales to mature infusion technologies which improves tech infusion in future AO's

IV. Culture/Communication

- Establish a customer advisory board to advise PSD on technology needs, performance requirements, and evaluation approaches (strategic)
- Establish partnerships to broaden interest, appeal, and create sustaining support for new technologies
- Ensure robust communication opportunities between tech developer, mission manager, proposing, and evaluation communities to encourage better understanding of technologies
  - Ensure a representative POC or SME is available

Next Steps

- Follow up discussions to clarify observations, identify/quantify shortfalls, and understand technology needs at associated readiness levels
  - Socialize findings & provide opportunities to elaborate on responses with RFI/Science/Industry Community
    - » Open Dialogue Ask proposers: “How do you want to be incentivized?”
  - Discuss related RFI responses with SOMA
  - Socialize findings and recs. with SBAG, OPAG, etc…, and PSD PE’s

- Share and receive feedback on recommendations
  - ***Seek Respondent and Community Feedback and endorsement of Draft Recommendations***
  - ***REQUEST: Complete DRAFT Recommendation Ranking Template (H/M/L) and return***

NAME: ____________________ Telephone: ____________________

Institution ____________________ Email: ____________________

PSD Tech Infusion
Study Recommendations
Community Feedback

___ Science Community ___ Mission Community ___ Spacecraft/Sub-system Manufacturer ___ Academia ___ Other

Instructions: Fill out requested info above, and then Rank the 14 Draft Recommendations as either "High", "Medium", or "Low"

	ID #	Recommendation Wording	How Details	High	Med	Low
Process/Structure - AO Strategies for Tech Infusion						
	R2	PSD through the AOs should establish/designate missions that mandate the use of infusion technologies	* Determine the science missions that would benefit significantly from infusion technologies			
	R1	Incentives approach for infusion technologies must address the completion of system-level development work (from TRL 6 to flight infusion) and address accomodation costs/impacts	* Any technology being considered for incentivization must have an assessment of readiness and associated risk. * Qualify a new technology to DRM requirements, then re-qualify as necessary to Mission specific requirements when known * Evaluate accommodation of infusion technologies to mitigate barriers in the AO incentive approach (cost, risk, knowledge, etc...). - See (R7) for accommodation cost determination step.			
	T5	PSD should present the incentive approach for the use of infusion technologies 9-12 months prior to AO release to establish common understanding for SOMA, industry & mission implementers, and technology developers	* Documentation validating TRL 6 of infusion technologies should be released 6-9 months prior to AO release * Incentive approaches should address maturation of the technology from TRL 6 to flight implementation			
	T3	To achieve more Decadal Survey science goals, PSD should increase the risk and cost that it is willing to accept regarding the use of infusion technologies in future mission AO's.	* PSD should determine it's threshold regarding GFE versus cost sharing incentive limits for each infusion technology (including accomodation costs/impacts) * The user community wants PSD to provide technologies as GFE and cover accomodation costs/impacts thru ATLO and Ops			
Process/Structure - Technology Development and Implementation						
Technology Development and Systems Engineering						
	R7	Determine accommodation costs/burdens associated with new technology adoption factor into a mission needs	Account for accomodation costs/burdens in R2			
	T4	Establish approach to sustain technology capability so that future PSD mission needs can be met	* Develop PSD unique requirements to meet mission needs, and identify if technology needs are PSD unique * Evaluate use or modification of commercial products to meet PSD unique mission requirements * Develop PSD unique technologies with industry (transfering the technology out of PSD) to open the possibility of commercial flight opportunities * Commercialization/"Multiple-use" should be considered at the beginning of technology development for risk reduction and establishing flight heritage			
	T2	The use of mission capability enhancement studies should be expanded to improve both the understanding of mission requirements and the constraints associated with implementing new technologies				

- Prepare final report on Technology Infusion program (FY14, Q2)
  - Synthesis of RFI response, follow-on communications, and internal stakeholder communications
  - Share final outcome with community post PSD agreement

Questions?

Contact Info:

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Findings/Recommendations Development Process

Process for Capturing and Consolidating Findings

1. Extracted **545** relevant responses from **190** pages
2. Grouped similar extracted responses and developed **71** short finding statements
3. Consolidated statements into the **4** common themes from the Planetary Science Technology Panel's (PSTRP) Issues & Recommendations
    - Strategic, Process/Structure, Resource, and Culture/Communication
4. Determined level of respondent agreement within the finding statement

Process for Capturing and Consolidating Recommendations

1. Consolidated **113** explicit/implicit RFI recommendations into **11** respondent-based recommendations, and developed **12** team-based recommendations
2. Consolidated into **14** Recommendations, and grouped under the **4** Themes
3. Developed Scoring (aimed for comparable # of H, M, L) and Ranking methodology (Ave.)
4. Team scored and ranked recommendations to test process
5. ***Next steps to solicited scoring of combined recommendations from the RFI responders and science community via the AGs -> Develop Final Ranked Set***

DRAFT Recommendations to Improve Tech Infusion

I. Strategic: Technology Investment Portfolio

- Establish a dedicated PSD spacecraft component tech program to:
  - Assist future infusion activities
  - Sustain PSD unique technical expertise/facilities/capabilities so future PSD mission needs can be met
- To achieve more Decadal Survey science goals, PSD should increase the risk and cost that it is willing to accept regarding use of infusion techs in future AO's

II. Process/Structure: AO Strategies for Technology Infusion

- AOs should establish/designate missions that mandate the use of infusion techs
- Present incentive approach for the use of infusion technologies 9-12 months prior to AO release to establish common understanding
- Incentives approach for infusion technologies must address accommodation costs/impacts, and the completion of system-level development work (TRL 6 to flight infusion)

DRAFT Recommendations to Improve Tech Infusion

II. Process/Structure: Technology Development and Implementation

- Imperative that PSD complete development and qualification of the current infusion technologies (ASRG, NEXT, etc…) to alleviate risks and meet the needs of future PSD missions

- Implement a defined, transparent, and independent process for validating and documenting that infusion technologies have achieved $\geq$TRL 6, 9-months (or more) prior to AO release
- Determine accommodation costs/burdens associated with new technology adoption

- Expand use of mission capability enhancement studies to improve the understanding of mission requirements and the constraints associated with implementing new tech’s

DRAFT Recommendations to Improve Tech Infusion

III. Resources

- Provide resources to enable successful technology infusion and being a "smart buyer" for PSD unique/critical mission needs
- Provide sufficient & sustained resources to mature new/infusion techs to TRL 6 by AO release
- Shorter development timescales will improve infusion with mission opportunities

IV. Culture/Communication

- Establish a customer advisory board to advise PSD on technology needs, performance requirements, and evaluation approaches
- Partnerships to broaden interest, appeal, and create sustaining support for techs
- Ensure robust communication opportunities between tech developer, mission manager, and proposing communities to encourage better understanding of techs
  - Ensure a representative POC or SME is available to ensure infusion technologies are used properly to maximal benefit