National Aeronautics and Space Administration

Solar Electric Propulsion

Technology Development

Chemical Propulsion

- **Chemical propellant provides the high thrust to weight required to escape earth's gravity well**

- **Chemical propellants convert the stored energy into kinetic energy**

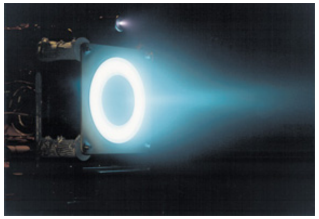
- ***<u>However,…the inherent energy in the propellant is a limiting factor</u>***

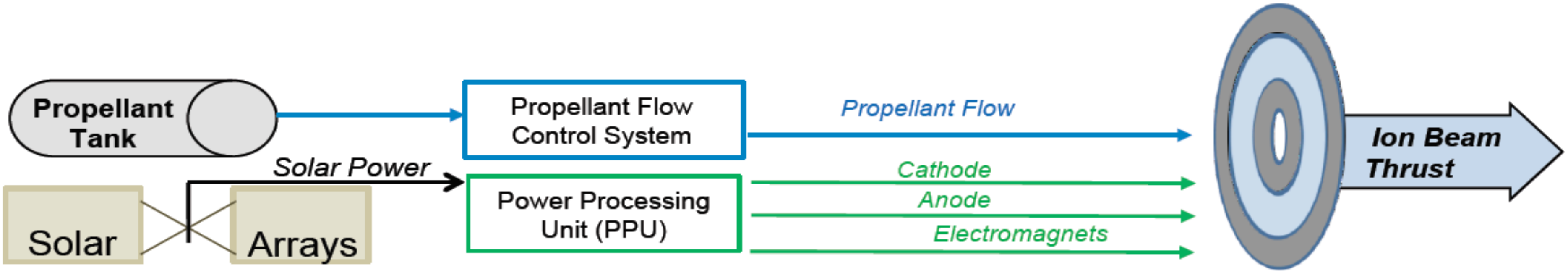
  - ***As the propellant energy defines exhaust velocity and hence ISP***

  - ***While the path to reducing propellant mass is typically to increase specific impulse/exhaust velocity***

Solar Electric Propulsion

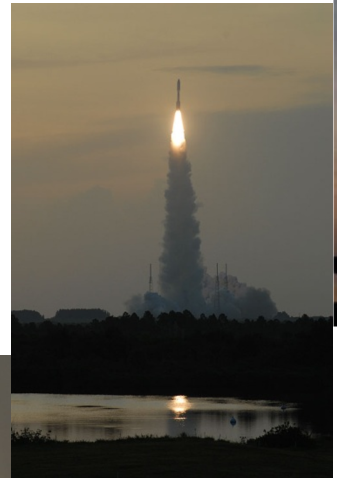
- **Solar Electric Propulsion (SEP) uses solar energy from solar arrays converted into electricity.**
- **Electricity is then used to ionize and accelerate propellant to produce thrust.**
- **SEP Fuel efficiency and Thrust**
  - SEP has higher specific impulse,….1.5 to 10X more efficient than chemical
  - Specific impulses range from sub-1000 to over 7,000 sec. depending on type of thruster
  - Thrust is weaker, but can provide thrust over a longer duration
  - SEP thrust level is directly tied to the available power on the spacecraft
  - If mission is not time sensitive (wks/months vs days to orbit transfer), SEP uses less fuel to same destination
  - Less fuel can reduce weight (20-50%), which can reduce launch costs
- **Mission life**
  - SEP's high fuel efficiency enables longer mission life
  - Ideal for deep space, long-life missions, station keeping

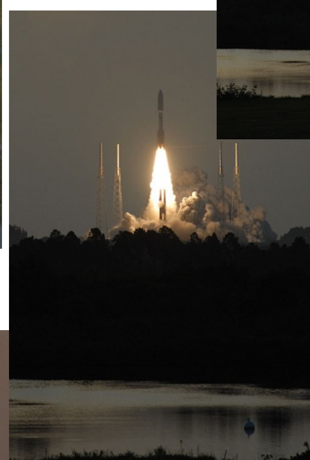


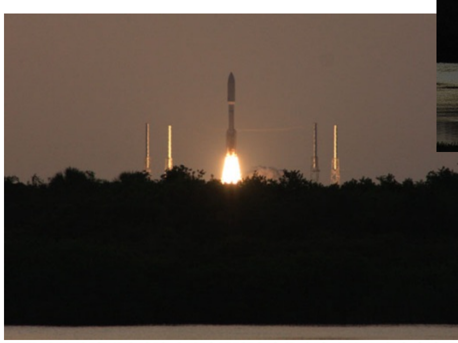


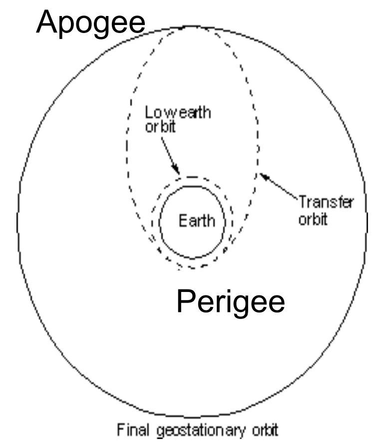
EP Coming of Age,….or the Advanced EHF Story

August 14, 2010: Launched on a ULA Atlas 531 with 3 Aerojet solid boosters and a Centaur upper stage









Typical launch drops in a Geosynchronous Transfer Orbit (GTO)

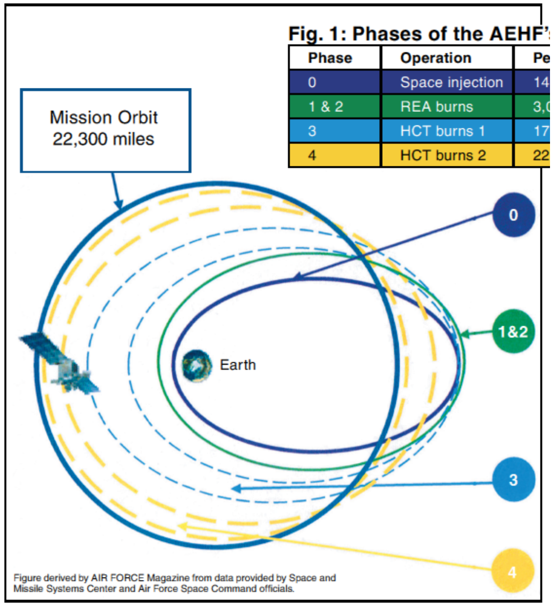
- **185 km (115 mi.) x 36,000 km (22,200 mi.) x 27 deg inclination**
- **Burn Liquid Apogee Engines (LAE) to circularize at GEO**
- **Typically half the launch mass is propellant for this burn**

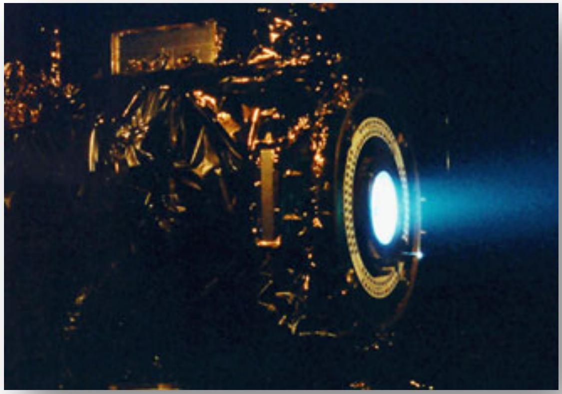
AEHF so large, planned to use Electric Propulsion Hall thrusters to do partial orbit transfer

- **Initial GTO is 225 km x 50,000 km**
- **LAE burns raise perigee to 19,000 km**
- **Hall thrusters do the rest**
- **AEHF uses 2500 kg propellant to get to orbit, but saves nearly 1000 kg over full chemical**

Los Angeles, We Have a Problem

- <u>August 15, 2010</u>: Attempted to ignite apogee engine, shut down after a few seconds as spacecraft detected a problem. Not yet highly concerned
- <u>August 17, 2010</u>: Attempted to ignite a second time, also shut down. Signs of overheating.
- Tiger team rapidly determined that there was a propellant line blockage and further attempts at firing could cause an explosion.
- Spacecraft is losing 5 km altitude a day and accelerating.
- <u>August 22, 2010</u>: Plan formulated to save the spacecraft:
  - Use 22 N (5 lb.) hydrazine engines to raise perigee to avoid decay
  - Use .25 N (0.06 lb.) Hall thrusters to perform most of the transfer
- <u>September 22, 2010</u>: Perigee is raised by the hydrazine engines to 4900 km – safe from orbital decay from aerodynamic drag.
- <u>October 24, 2011:</u> Hall thrusters complete transition from GTO to GEO
  - What was going to take 3 months took a little over a year
  - The spacecraft had a launch mass of over 6 metric tons and was lugging almost 500 kg of useless oxidizer
  - If the original plan was to use Hall thrusters for the entire orbit raising operation, it would have saved several additional tons of propellant





The Hero

NASA Study Findings on Future SEP Applications

- **There have been multiple architecture studies where SEP has "traded well"**
  - "Electric Propulsion is key for achieving affordable missions to an asteroid or similar long-range destination." -- *Human Space Exploration Framework Summary 2011*
  - "Electric Propulsion is enabling for this mission. It cannot be done with other propulsion types." -- *ARRM MCR 2013*
  - Human Exploration of Mars DRA 5.0
    - Combined SEP-Chem for Piloted Mars Mission (GRC/JSC COMPASS Study)
    - SEP-Chem with Iodine Propellant for Piloted Mars Mission (GRC/MSFC COMPASS Study)

- **SEP reduces the cost of missions ranging from commercial applications in LEO to Manned Missions to Mars**

- **SEP's major benefit over other in-space propulsion alternatives is more efficient use of propellant**
  - Reduced wet mass reduces Initial Mass to LEO (IMLEO)
  - Reductions in IMLEO in turn reduce the number or size of launch vehicles

SEP Can Revolutionize Space Exploration in the 21st Century

Left to Right Planning
or
"What Are We Doing To Get There?"

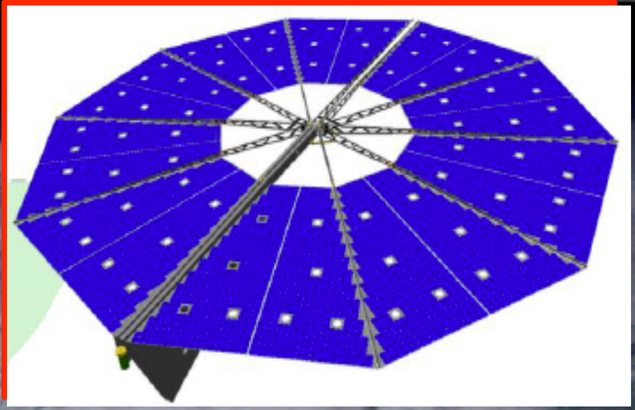
Technology Investment

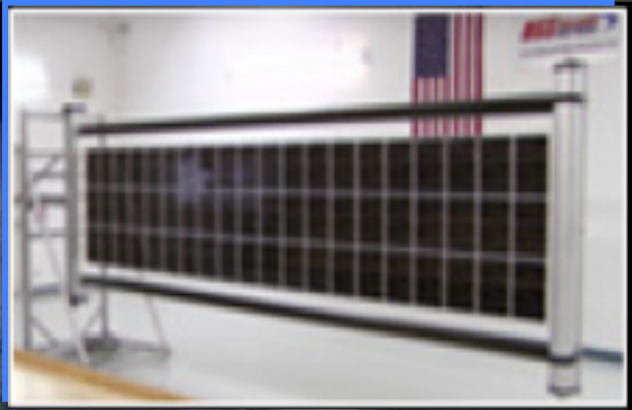
- Current NASA STMD investments include advanced next-gen solar arrays and higher power electric propulsion technologies to enable 30-50kW-class SEP
- Two teams selected through competitive NRA for development of Solar Array Systems (SAS):
    - Alliant Techsystems Inc. (ATK) & Deployable Space Systems (DSS)
- NASA in-house EP development of 12-15kW class HET system using either direct-drive and/or high voltage power processing unit

ATK MegaFlex:
Partners – AMA, Ball, Emcore, JPL, SpectroLab
Start Date: October 2012
Anticipated Duration: 18 months

DSS Roll Out Solar Array (ROSA):
Partners - Emcore and JPL
Start Date: October 2012
Anticipated Duration: 18 months

In-house EP System Development:
Partners - GRC and JPL
Start Date: January 2012
Anticipated Duration: 36 months

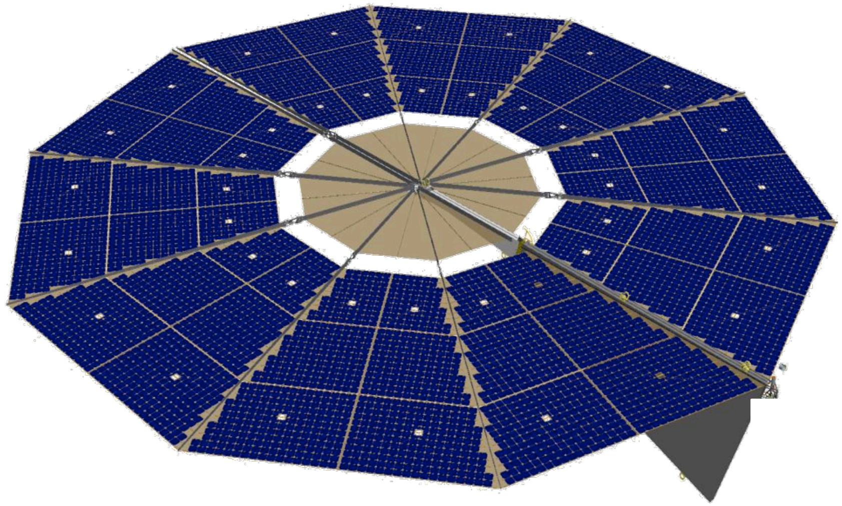




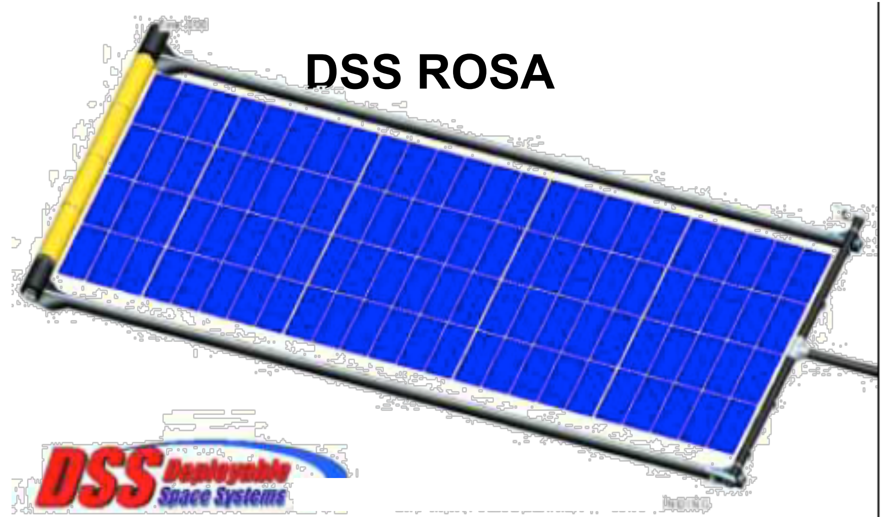
STMD Solar Array System (SAS) Project

- **Solar Array Systems Project**
  - ATK MegaFlex
    - 12m diameter
    - 20kW EDU
  - DSS Roll Out Solar Array (ROSA)
    - 5.5m x 15-20m
    - 20kw-25kw
- **Common Elements**
  - High Power Density (150w/kg)
  - High stowed power density (>50 kW/ m^3)
  - 300V buss operation
  - Designs extensible to 300kW objective system

ATK MegaFlex



DSS ROSA



STMD Solar Array Cost Project

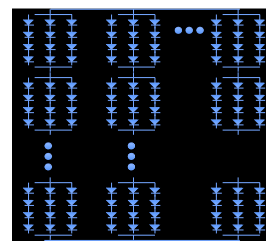
Fundamentally change design and manufacturing paradigm

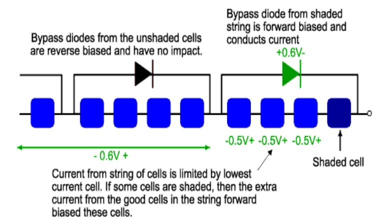
- Space Solar Cell R&D is completely absorbed in making incremental improvements to III-V & IMM
- Larger cell size and ELO techniques to reuse substrate dominate government and industry investment strategies
- <u>Underlying thought processes remain fixated on mass and efficiency</u>
  - *May make sense when 25kW mission costs > $1B*
  - *May not make sense when 300kW mission costs < $1B*

Over 50% of costs are in array layup, and they are dominated by <u>Touch Labor</u>

New design concepts must be considered:

- Use semi-conductor industry processes
- Modularize panels
- Create backplanes via "PCB" construct
- <u>Accept less efficiency for lower cost and mass parity</u>
- Miniaturization of cells lends itself to multiple benefits
  - Less waste in manufacturing
  - Better thermal properties
  - Better concentrators
- Remove lattice and current matching constraints with mechanical stacking





"Smart Array" Technology

- Cells connected in parallel then in series
- Cells chosen and reconfigured on the fly
- Reduces amount of materials used
- Eliminates the need for Bypass Diodes = Mass Savings

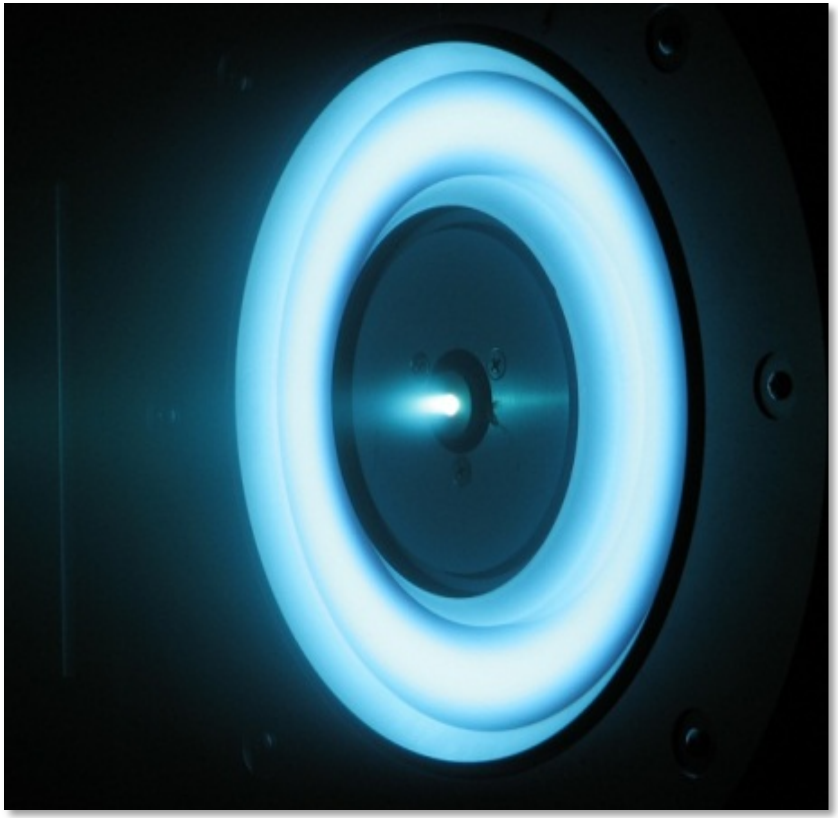
STMD Advanced In Space Propulsion (AISP) Project

Thrusters

- Present TRL 9 “Industry Benchmark” is the Aerojet BPT-4000
  - 4.5-kW, 2000-s Hall thruster
- AISP Thruster Focused on future HEOMD Applications
  - Magnetically Shielded Hall Effect Thruster
  - 12-15kW
  - 2000s-3000s ISP
- Miniature Electrospray Propulsion (MEP) Thruster
  - Small Satellite mN thrust applications
  - Potential to grow to larger missions

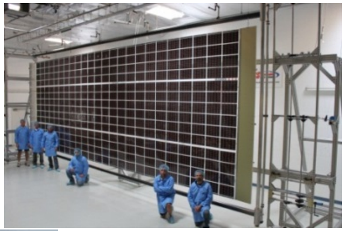
Power Processing Unit (PPU)

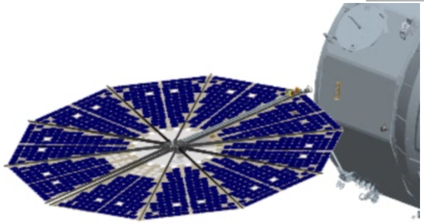
- High voltage input
- Direct Drive Unit (DDU) research
- High Operating Temperature



NASA’s 3000-s Isp, Magnetically-shielded Hall Thruster

Future Technology Development

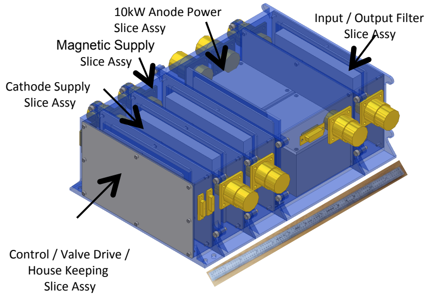




Large autonomously deployable solar arrays:

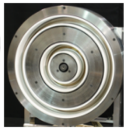
- 300kW class array systems (150kW per wing)
- Increased packing density and lower mass arrays
- Reductions to cost of arrays
- Increased operational voltage

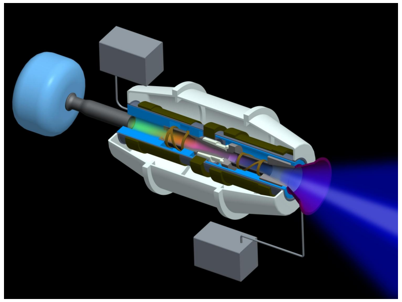
High Power PPU

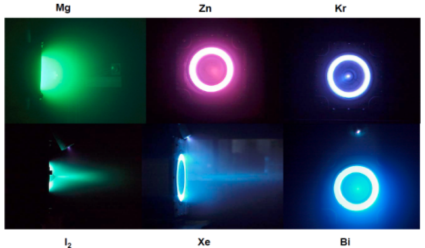


- High efficiency operation (> 96%)
- High temperature operation (~100^{0}C)
- Space qualified parts for 300V operation

High Power Thruster







- 100 kW Class Thruster
- 20,000hr - 40,000hr Life
- Variable ISP
- Alternate Propellants

STMD's SEP Tech Demo Mission (TDM) Objectives

Technology

Demonstrate enabling SEP technologies in all relevant space environments (from LEO to beyond GEO)

- Next gen electric propulsion
- Solar arrays
- High voltage
- Tech infusion

Integrated System

Solve the system technology and operational issues related to implementation of a high performance SEP vehicle

- Power system dynamic behavior
- Thermal control
- Attitude control

Extensibility

Provide an evolutionary step to the high power SEP systems needed for future human exploration

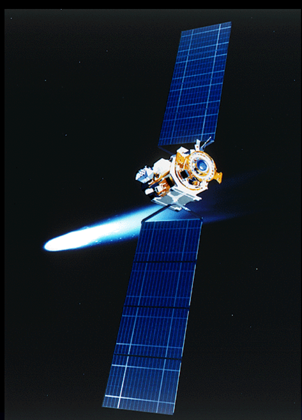
- Prove low thrust systems can deliver heavy payloads
- Build upon the recent success of AEHF
- Inform future exploration architecture studies
- Retire risks associated with Van Allen radiation belts

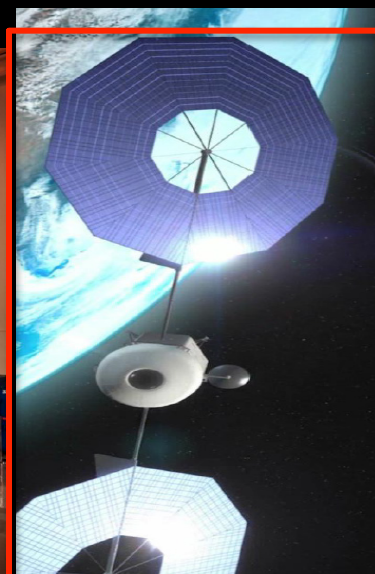
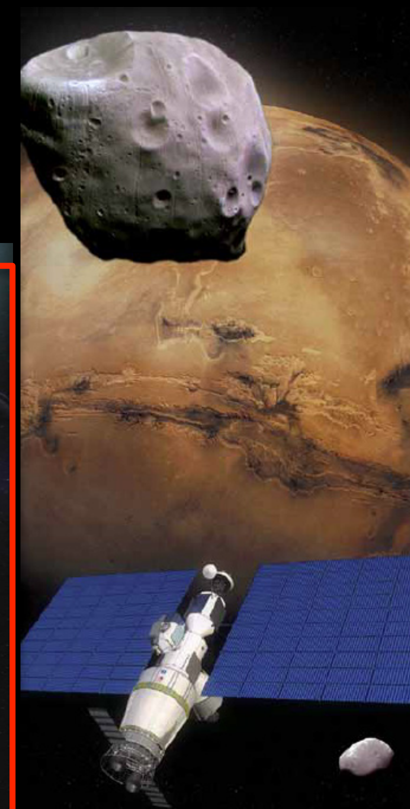
Capability

Provide a valuable beyond-LEO payload delivery capability

- Wide range of potential missions (HEOMD, SMD, DoD, Commercial Space)
- Enables cost savings via launch vehicle step down
- Operational capability enables partnership opportunities

SEP Mission Continuum



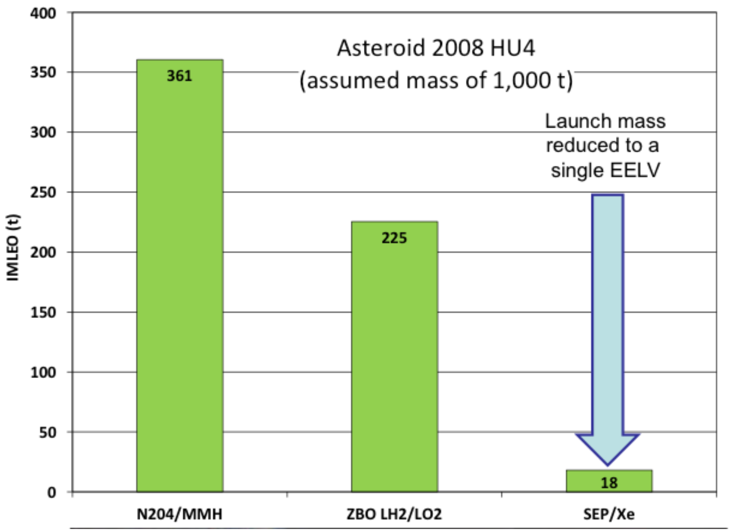




Deep Space 1 1998	**Dawn 2007**	**AEHF Rescue 2010**	**Asteroid Redirect Mission**	**Far-term Exploration Missions circa 2030's**
Technology Demonstrator	Deep-Space Science Mission	MILSATCOM Satellite saved with Hall Thrusters	Robotic Mission to Redirect Asteroid to Trans-Lunar Orbit	Crewed mission beyond Earth space
490kg	1220kg	6000 kg	13,000 kg	70,000 kg
2.5 kW power system 2kW EP system	10 kW power system 2.5kW EP system	~15kW-class power ~4.5kW-class EP	50kW-class power system 10 kW-class EP	350kW-class power system 300kW-class EP
ΔV = 2.7km/s	ΔV = 10km/s	ΔV > 10km/s	ΔV ≈ 10 km/s	ΔV ≈ 8 km/s

ARRM -- STMD SEP TDM Synergy

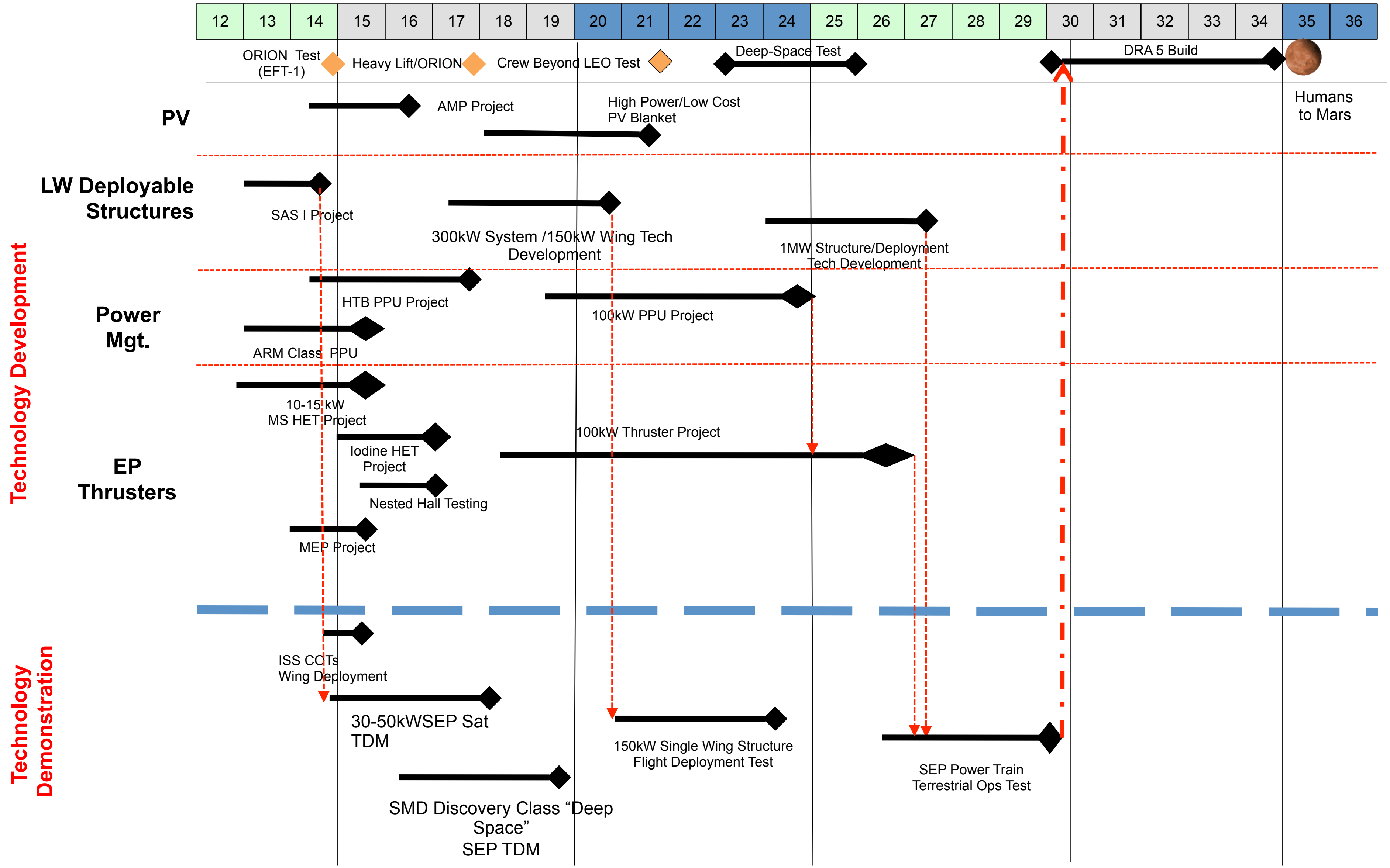
- STMD is seeking an affordable demonstration of high-power, 30- to 50-kW, light-weight solar arrays and high-power electric propulsion
- The electric propulsion technology under development by STMD is enabling for an Asteroid Retrieval Mission
- Combining the SEP Technology Demonstration Mission (TDM) with the Asteroid Retrieval Mission would validate:
  - ✓ High-power, light-weight solar arrays
  - ✓ High-power SEP
  - ✓ Asteroid retrieval

High-Power SEP is enabling for Asteroid Retrieval



30-kW SEP Technology Demonstration Concept (GRC)

Notional SEP Strategic Roadmap



Summary

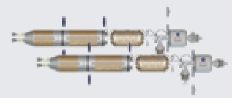
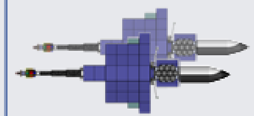
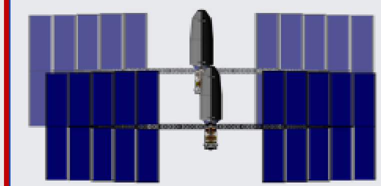
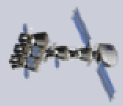
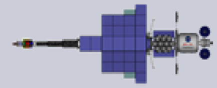
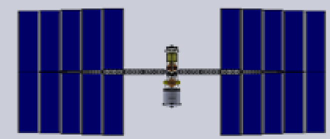
- SEP chosen for ARRM because it reduces launch mass, which is a proxy for total mission cost
- SEP is a credible alternative for multiple future Human Exploration Mission Concepts
- STMD is leading the way developing the technologies required to execute these missions concepts

SEP is a Viable, Low Cost Solution for NASA's Future Missions

Back-Up

DRA 5.0 Propulsion Alternatives Explored

"SEP-Chem can deliver crew to an orbit similar to chemical or NTP systems, and can substantially reduce the number of launches... with reasonable transport and stay times." *-- AIAA Space 2013 Paper #1648964*

Cargo Missions				
Crew Mission				
2037 Conjunction Class "long stay" mission	**Chemical Propulsion**	**Nuclear Thermal**	**Nuclear Electric**	**Solar/Chem**
Electric Propulsion Power level	n/a	n/a	2.5MW crew/ 1MW cargo	800kW Solar
Total Mass (t)	~1,250	~890	~770	~780
# Heavy Lift (SLS) Launches	~12	9 (7)	~7	~7
SLS Delivery to LEO (t)	105 & 130	105 (130)	105 & 130	105 & 130
SLS Shroud Dia./Barrel Length	10 / 22	10 / 25	10 / 25	10 / 15
Trip Duration (days to Mars, On Mars, back home)	180 / 500 / 200 880 days total trip	174 / 539 / 201 914 days total trip	309 / 400 / 224 980 days total trip	439 / 300 / 326 1065 days total trip
Comments	Requires propellant depot	Number of launches reduced to 7 with 130mt SLS		1-2 ATV launches required to provide consumables to L2

ARRM Reference SEP System

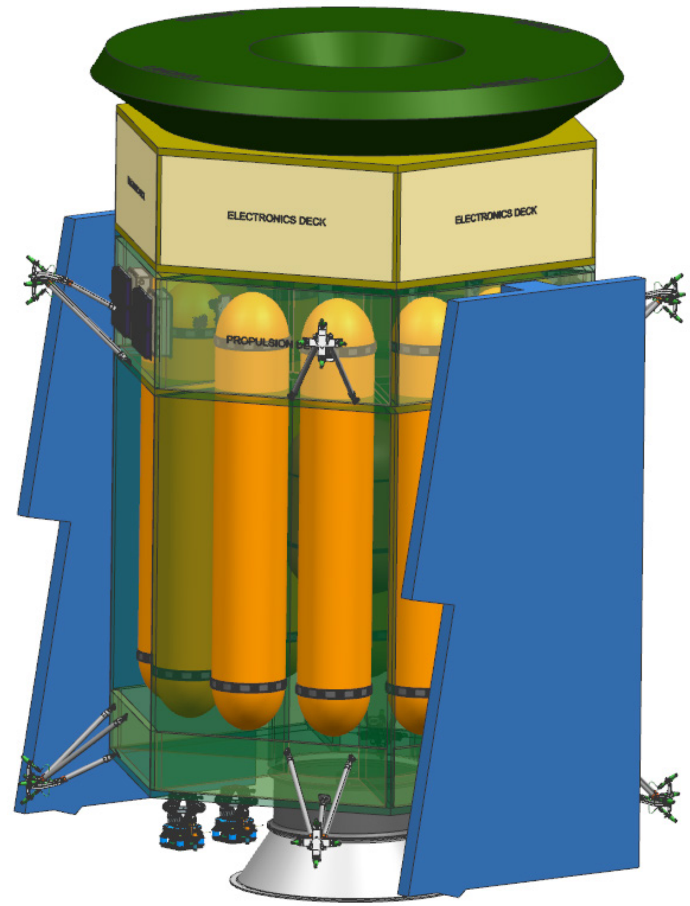
Provide the right balance between performance, extensibility, cost, and schedule

Electric Power System (EPS)

- Solar Array:
  - 50 kW BOL at 1 AU
- Power System Architecture
  - 300 V at max. power point

Ion Propulsion System (IPS)

- Electric Thrusters: Hall 10-kW, 3000-s *Isp,*
- Power Processor Unit (PPU): Conventional
- Xe Tanks: 50-cm dia. seamless Al-lined Composite Overwrapped Pressure Vessels (COPVs)



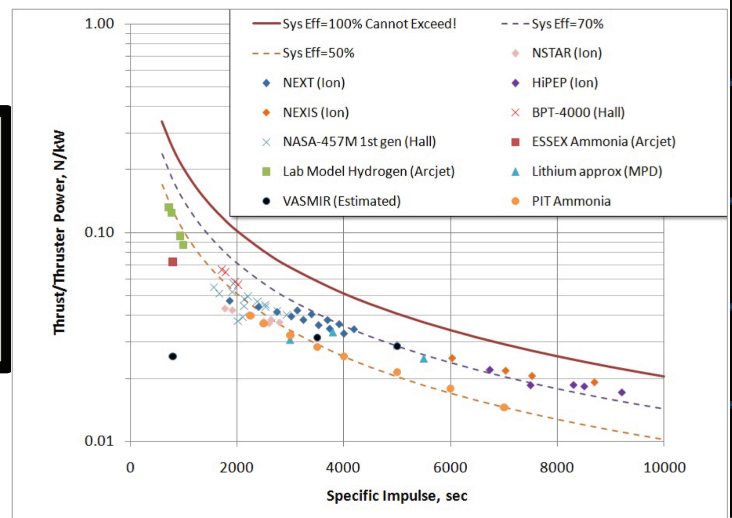
Example shown with stowed MegaFlex solar array and 12,000-kg Xe storage

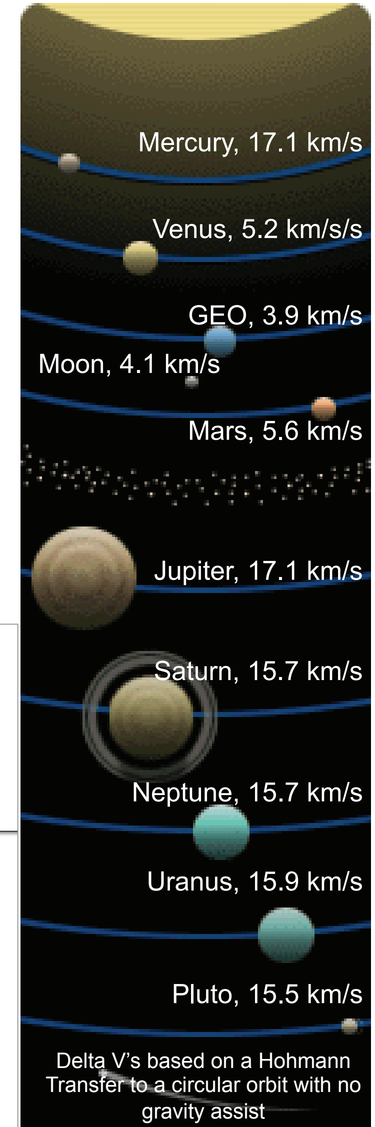
Delta V, SEP Power, and Specific Impulse

- **Sample Comparison -- Earth-to-Mars transit with 2000 kg spacecraft dry mass with varied power and specific impulse**

Specific Impulse	**4000 seconds**	**2000 seconds**
Propellant Mass	307 kg	661 kg
Power	**Trip Time**	
1.35 kW	9.3 years	2.3 years
5 kW	2.5 years	229 days
10 kW	457 days	114 days
50 kW	91 days	23 days

Doubling the specific impulse from 2000 to 4000 seconds more than halves propellant required but at the expense of transit time





FY14 Activities & Deliverables

Solar Power Element

- Test ROSA and MegaFlex solar arrays to achieve TRL 5/6: thermal vacuum deployment, vibro-acoustic tests, and vacuum deployed structural dynamics
- Ambient deployment of Mega-ROSA backbone
- Demonstrate Mega-ROSA and MegaFlex extensibility by analysis
- Complete photovoltaic coupon testing (plasma and thermal balance)

Electric Propulsion Element

- Design and fabrication of a 12.5kW magnetically shielded Hall Thruster
    - Baseline performance and wear testing (500+ hrs)
- In-house design, fab, and test of 300V/300V Input/Output (I/O) Power processing unit
- In-house design, fab, and test of a 120V/800V I/O PPU
- In-house design and fabrication of a 300V/300V Input/Output (I/O) Direct Drive Unit (DDU) – Fabrication and testing on hold until completion of PPUs.

FY14 Activities & Deliverables

Mission Concept Element

- Provide update ARRM SEPM reference configuration based on RCIT direction
- Develop derivative 300kW-class SEP concepst to support ARRM extensibility
- Revised risk assessment for EP, Solar Power, and recommended SEP TDM concepts (including ARRM)
- Completed procurement plan for SA, EP, and Xe COPV flight hardware
  - Draft RFPs w/implementation schedule & supporting materials, tank is JPL task per ARM
- Complete development of 30kW-class partner based SEP TDM concept approach
  - Cost share mission concepts with cost estimate, proposed implementation approach including cost share mechanism, and technical value assessment wrt SEP TDM objectives
- Complete development of μSEPSAT mission concept
  - Concept definition including estimated cost and technical value assessment wrt SEP TDM objectives
- Complete development of solar array wing mission concepts
  - Concepts for flying solar array wing on operational mission including estimated cost and technical value assessment wrt SEP TDM objectives