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Solar Electric Propulsion (SEP) Tug Power System Considerations

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This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

This report contains preliminary findings, subject to revision as analysis proceeds.

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Abstract

Solar electric propulsion (SEP) technology is truly at the "intersection of commercial and military space" as well as the intersection of NASA robotic and human space missions. Building on the use of SEP for geosynchronous spacecraft station keeping, there are numerous potential commercial and military mission applications for SEP stages operating in Earth orbit. At NASA, there is a resurgence of interest in robotic SEP missions for Earth orbit raising applications, 1-AU class heliocentric missions to near Earth objects (NEOs) and SEP spacecraft technology demonstrations. Beyond these nearer term robotic missions, potential future human space flight missions to NEOs with high-power SEP stages are being considered. To enhance or enable this broad class of commercial, military and NASA missions, advancements in the power level and performance of SEP technologies are needed. This presentation will focus on design considerations for the solar photovoltaic array (PVA) and electric power system (EPS) vital to the design and operation of an SEP stage. The engineering and programmatic pros and cons of various PVA and EPS technologies and architectures will be discussed in the context of operating voltage and power levels. The impacts of PVA and EPS design options on the remaining SEP stage subsystem designs, as well as spacecraft operations, will also be discussed.

[1]Michigan State University, USRP, summer intern.

Solar Electric Propulsion (SEP) Tug Power System Considerations

2011 Space Power Workshop
Power Systems Architecture
April 20, 2011
Presentation by: Tom Kerslake

NASA GRC Co-authors

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- Kristen M. Bury
- Jeffrey S. Hojnicki
- Adam M. Sajdak
- Robert J. Scheidegger

- Also thanks to many unnamed, but highly appreciated contributors

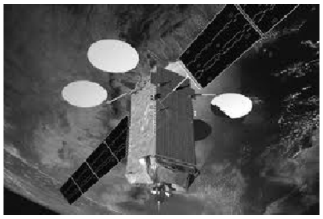
Outline

- What is SEP and why use it?
- SEP missions/spacecraft
- SEP tug subsystem impacts on power system design
- Solar array design considerations
- PMAD design considerations
- Cost challenge
- Closing Comments

What is SEP and Why Use It?

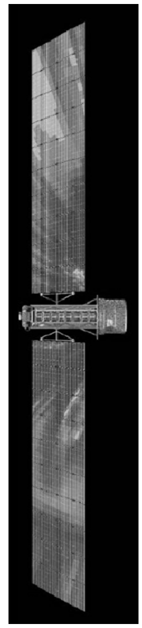
- SEP spacecraft have a solar electric power system (EPS) that provides power to electric thrusters
- Save mission mass and/or costs
  - Achieved via high Isp electric propulsion (~10X higher Isp than chemical)
- Enhance/enable mission capabilities
  - Delta-V
  - Operating life

SEP Missions, Spacecraft, and Tugs



1's kW
station keeping
orbit topping

Space Science



10's kW

SEP Tech Demo (SFD)

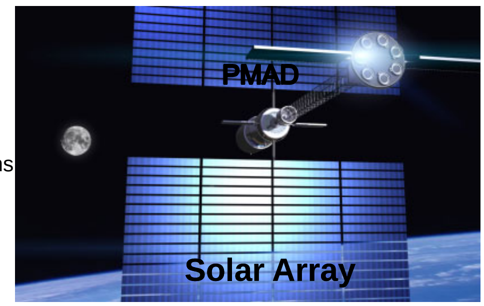
Earth and Space Science

Earth Orbit Transfers, GEO Servicing

High delta-V Maneuvering

100's kW

Lunar/Mars Human Missions (HEFT)



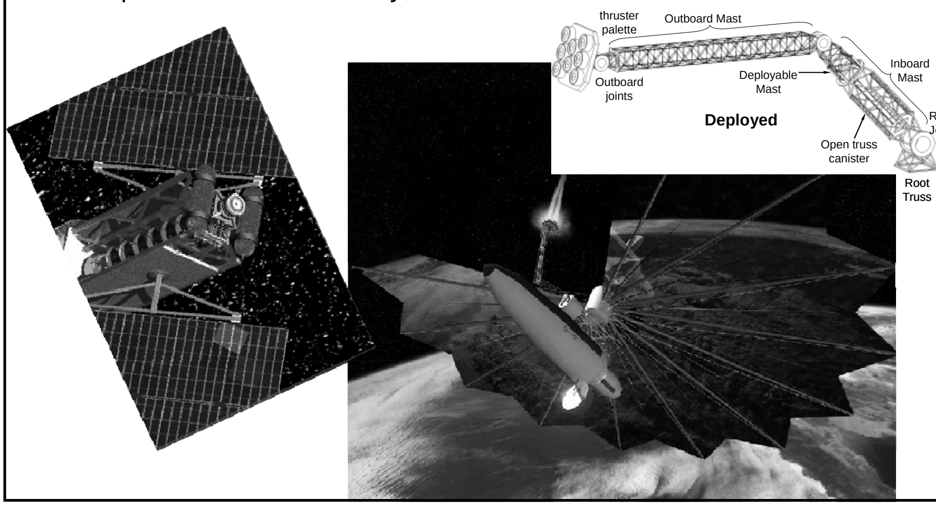
EPS and SEP Tug Subsystem Designs Are Highly Interdependent

Impact of / On	TCS	EPS	EP	Struc-Mech	ACS GNC	Comm	Stowed Config	Flt Ops	Crew
TCS		H							
EPS	M	H	H	H	H	L	H	H	M
EP		H							
Struct-Mech		H							
ACS-GNC		H							
Comm		M							
Stowed Config		H							
Flight Ops		H							
Crew		n/a							

H- High, M-Medium, L-Low

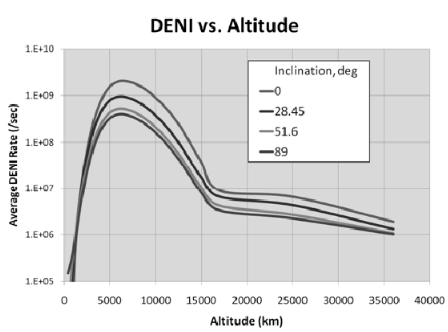
SEP Flightmode and Pointing – EPS Impacts

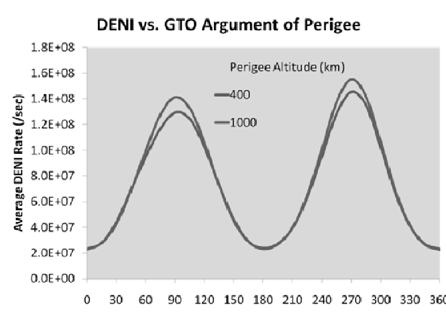
- From LEO to HEO, must point solar arrays and EP thrusters
  - With presence of large disturbance torques
- 1-, 2-DOF gimbal options, roll steering or solar inertial flight mode
  - Implications for solar array, ACS and EP thruster articulation



Orbital Mechanics – EPS Impacts

- SEP mission solar array / avionics radiation dose dominated (~98%) by trapped protons
  - Spiraling orbit inclination reduces dose by ~4x (0° to 51.6°)
  - GTO->GEO mission starting arg. of perigee can reduce rad dose by ~6.5X
    - Place perigee near nodes
  - Rad dose nearly independent of solar activity
  - EP steering Modes (minimize proton belt transit time)



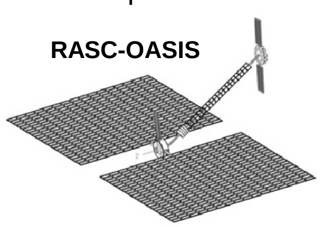


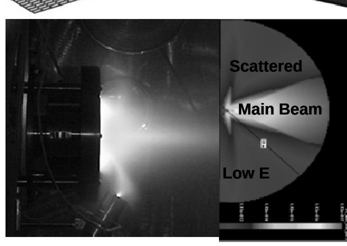
Space Operations – EPS Impacts

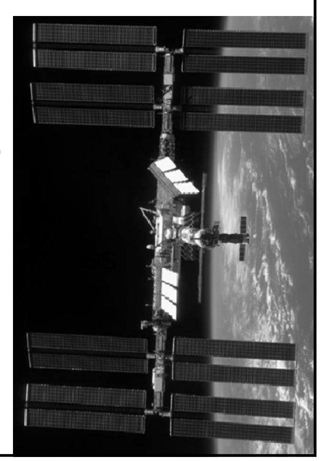
- Solar array and PMAD current/voltage sizing will be driven by EP subsystem design and ops
  - Conventional PPU-based EP subsystem
  - Direct drive DDU-based EP subsystem
    - Constant voltage (Isp) ops
    - Constant current (flow rate) ops
    - Variable voltage/current (such as Pmax, Max. Thrust, other)
- SEP tug operations will drive solar array/gimbal design
  - Fast, uniform, robust, reliable solar array deployment
  - Tolerance of large docking/plume loads during RPOD
  - High deployed strength and stiffness
    - > ~0.1-g thrust-to-weight for chemical stage burns
    - Avoid SEP tug and chemical stage controls-structures interactions
    - Limit solar array deflections

Solar Array Design Considerations

- Configuration: number of wings and articulation
  - Qual and recurring costs (modularity, optics), ground/flight testability
  - Wing stowage, deployment, gimballing complexity, performance
  - EP plume avoidance (manage sputtering erosion)

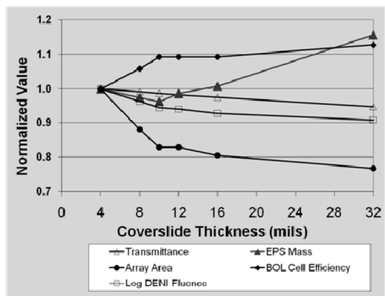






Solar Array Design Considerations

- Ambient and EP induced plasma interactions
  - Parasitic electron collection (Dominated by EP plasma)
  - Plasma/Vacuum/Sustained Arcing Avoidance/Management
- Radiation degradation optimization
  - Goal: Minimum SEP tug cost (or mass) by choice of:
    - Subsystem designs affecting EPS/EP performance, mission design and solar array design/sizing

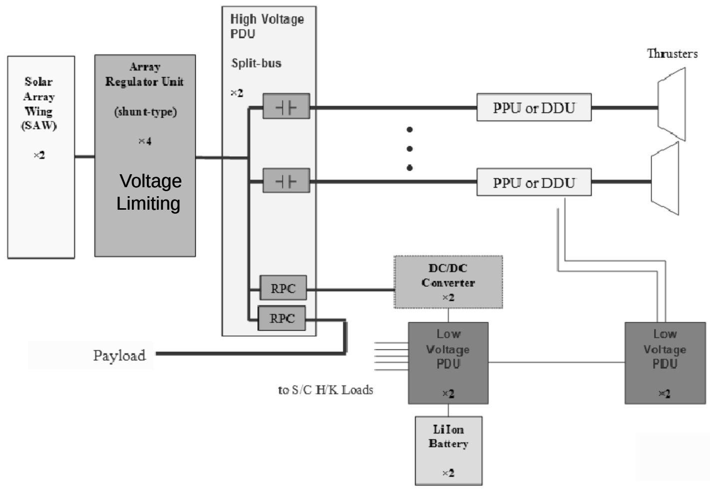


Solar Array Design Considerations

- Voltage selection
  - Large SEP tug missions optimize w/Hall Thruster Isp ~2000 sec (300-V)
  - 300-V class solar array designs consistent with de-rated performance of SOA EEE parts, insulators and gimbal roll-rings/slip rings
  - 300-V EPS saves 30-40% mass over 100-V to 160-V EPS SOA
  - Above considerations make 300-V class direct-drive option attractive
  - 300-V solar array technical challenges include higher electron collection current and availability of PMAD electronic parts
- Large solar array ground deployment testing
  - Key for risk mitigation/qualification without costly flight test
  - Designed for 1-g off-loaded, phased, thermal vacuum deployment
  - Designed to minimize qualification costs

SEP Tug Primary PMAD

- Distribution Architecture Options (Centralized or Channelized)
  - **Centralized/Channelized Hybrid Option Is Attractive -** Good cabling mass/efficiency, modularity, good fault tolerance with cross ties



PMAD Design Considerations

- Voltage level has large impact on PMAD design

- Compared to SOA PMAD, 300+ V PMAD
  - Higher efficiency system
  - Significantly less thermal load (direct-drive)
  - Significant cable mass savings (>60%) due to relatively lower currents
  - Down conversion needed to feed housekeeping loads
  - Limited electronic parts selection, especially for high radiation mission: may require wide bandgap electronics

PMAD Design Considerations (con't)

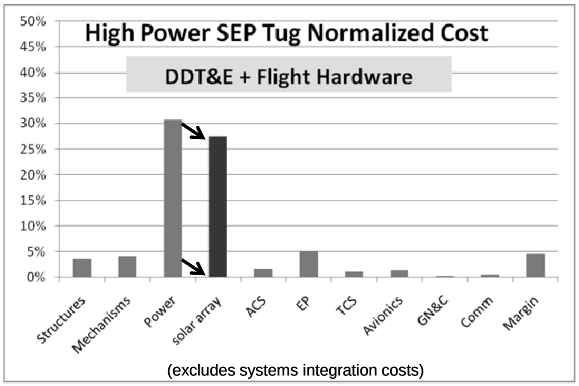
- EP operating mode has large impact on PMAD design
- Non-direct drive
  - Bus power to thruster PPU power conditioning and boost converter
  - Galvanic isolation decouples source (solar array) and thruster
  - Good bus power quality and prevents multi-thruster interactions on the bus
  - PMAD must deliver predetermined I/V range to PPU
- Direct drive offers
  - Bus power directly to thrusters via DDUs
  - Good: W/kg, power efficiency, reliability, recurring cost
  - Bus voltage control primarily tied to EP thruster operation
  - More work desired in the areas of:
    - Stability/ops during EP start-up/shut-down transitions
    - Cathode current sharing for multi-thruster ops
    - Effective grounding schemes

PMAD Design Considerations (con't)

- Solar array regulator/limiter (Protects from bus high voltage excursions)
- Fault tolerance a significant driver for human missions
  - Design for thruster-out capability (# failures tolerated?)
  - Cold-spare thrusters or nominally de-rated thrusters
- Grounding (negative solar array grounding desired)
  - Positive solar array ground unacceptable due to arcing/sputtering introduced
- 600-V rated EEE parts w/derating just sufficient for 300-V class bus
  - Limited parts may lead to undesirable board and PMAD box designs
  - May need to increase to 1200-V rated parts (more limited selection)
- EEE parts radiation tolerance (high flux, high energy protons)
  - Leads to high TID and enhanced SEE (MOSFET latch-up, gate rupture)
- SEP mission unique combination, high voltage/power/rad dose further limits choice of available parts
  - May need custom parts development/screening (including SiC parts) and more rad testing (TID and SEE) – all increasing costs
  - May require more box-level radiation shielding adding significant mass

SEP Cost Challenge

- Cost estimates show high power SEP stage affordability challenge – need major cost reductions (~2X)



- Major component cost challenge is the solar array
  - Recurring costs (particularly cell costs), qualification costs
  - Large-scale cell production availability

Closing Comments

- High power SEP tug missions offer attractive benefits
- Many {solvable} technical challenges remain and must be met
- Yet programmatically, to progress beyond just SEP mission studies, major cost reductions are needed

Thank You

- Questions?

Appendix Charts

More detailed, back-up information that is not part of the main presentation

Solar Electric Propulsion (SEP) Tug Power System Considerations;

*** Back-up Material ***

2011 Space Power Workshop
Power Systems Architecture
April 20, 2011

Tom Kerslake, Kristen Bury, Jeff Hojnicki,
Adam Sajdak, Bob Scheidegger

List of Abbreviations

a	constant
Arg	argument
BOL	beginning of life
Comm	communications
Conc	concentration (optical)
DDT&E	design, development, test & engineering
DDU	direct drive unit
Delta-V	change in velocity (of spacecraft)
DENI	damage equivalent normally incident
DOF	degree of freedom
DRM	design reference mission
EEE	electrical, electronic, and electromechanical
E-M L1	earth moon Lagrange point 1
EOL	end of life
EP	electric propulsion
EPS	electrical power system
g	acceleration due to gravity
GEO	geosynchronous earth orbit
GNC	guidance, navigation and control
GTO	geosynchronous transfer orbit
HEFT	human exploration framework team
HEO	high earth orbit
Imp	maximum power current
Isp	specific impulse (of EP thruster)
ISS	International Space Station
I/V	current / voltage
LEO	low earth orbit
LVLH	local vertical, local horizontal (flight mode)
Mech	mechanisms
MOSFET	metal oxide field effect transistor
OASIS	orbital aggregation & space infrastructure systems
OPS	operations
PDU	power distribution unit
PMAD	power management and distribution
Pmax	maximum power
PPU	power processing unit
rad	radiation
RASC	revolutionary aerospace systems concepts
Rev	(orbital) revolution
RPC	remote power controller
RPOD	rendezvous proximity operations and docking
SEE	single event effects
SEP	solar electric propulsion
SFD	SEP Flight Demonstration
SLA	Stretch lens array (Entech Technology)
SOA	state of the art
Struct	structures
TCS	thermal control system
TID	total integrated dose
V	voltage or volts
Vmp	maximum power voltage

What is SEP and Why Use It?

- SEP spacecraft have a solar electric power system (EPS) that provides power to electric thrusters
- Save mass and/or costs
  - Achieved via high Isp electric propulsion (~10X more than chemical)
- Enhance/enable mission capabilities
  - Delta-V
  - Operating life

SEP Missions, Spacecraft, and Tugs

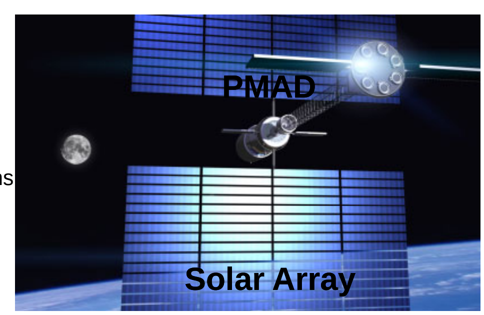
- Commercial, Defense, NASA

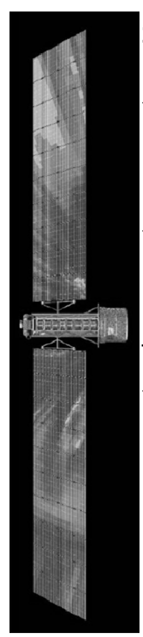
1's kW
station keeping
orbit topping

Space Science

100's kW

Lunar/Mars
Human Missions
(HEFT)





10's kW

SEP Tech Demo (SFD)

Earth and Space Science

Earth Orbit Transfers, GEO Servicing

High delta-V Maneuvering

SEP Spacecraft vs. a Stage or "Tug"

- SEP Spacecraft
  - EP system is just one of the spacecraft loads
  - Spacecraft instruments/payloads are mission focus
  - Missions tend to start in higher energy orbits
  - Lower or moderate EP power levels
  - Evolutionary power system design challenges
- SEP Stage or Tug (high Isp for multi-ton earth orbit transfers)
  - Spacecraft bus dedicated to SEP propulsion function
  - No focus on instruments or small attached payloads
  - Prime purpose is to move mass (spacecraft) from point A to B in space
  - Missions tend to start in lower energy orbits
  - Moderate to very high EP power levels
  - Many new power system design challenges
- This presentation to cover high power SEP tug with focus on:
  - low-Earth orbit to high-Earth orbit spiraling missions
  - Solar array and PMAD elements of the EPS (no issues with energy storage)

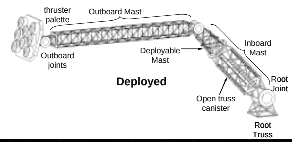
EPS and SEP Tug Subsystem Designs Are Highly Interdependent

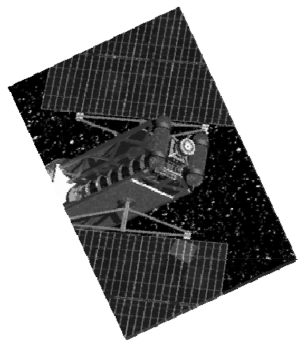
Impact of / On	TCS	EPS	EP	Struc-Mech	ACS GNC	Comm	Stowed Config	Flt Ops	Crew
TCS		H							
EPS	M	H	H	H	H	L	H	H	M
EP		H							
Struct-Mech		H							
ACS-GNC		H							
Comm		M							
Stowed Config		H							
Flight Ops		H							
Crew		n/a							

H- High, M-Medium, L-Low

SEP Flightmode and Pointing – EPS Impacts

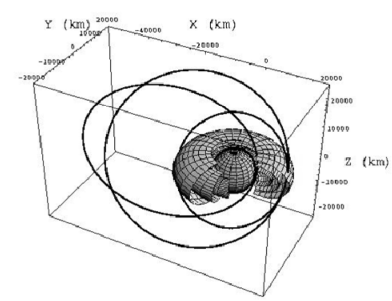
- From LEO to HEO, must fly tug to point solar arrays at the Sun and achieve desired EP thrust vector
  - Maintain attitude dead-band in presence of large disturbance torques
- Options
  - LVLH w/1-DOF solar array gimbal (large solar array off-pointing)
  - LVLH w/2-DOF solar array gimbal (potential solar array shadowing)
  - LVLH w/roll steering (ACS impacts, moderate solar array off-pointing)
  - Solar inertial (must move EP thrusters)

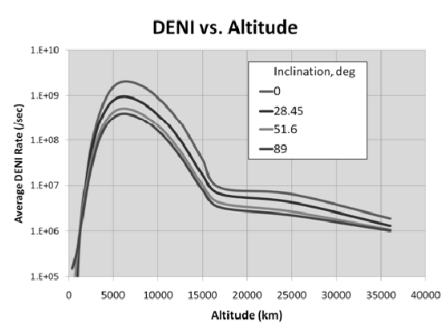




Orbital Mechanics – EPS Impacts

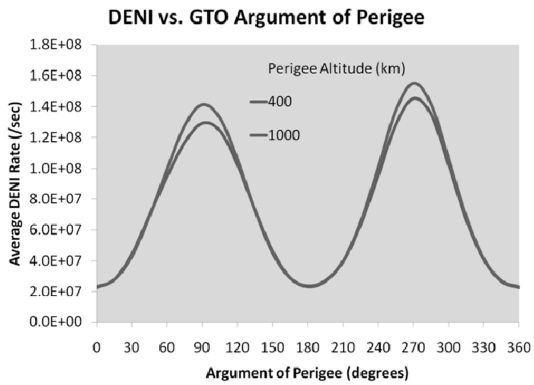
- Mission design to reduce solar array/avionics radiation dose
  - 1-year spiral LEO to E-M L1 Radiation Contributions:
    - Trapped electrons (~1%), Trapped protons (~98%), Solar flare protons (<1%)
  - Effective:
    - Increase inclination-reduce dose by factor of ~3.8x moving from 0° to 51.6° inclination
    - EP steering Modes (minimize proton belt transit time)
  - Ineffective: Launch date tied to min/max solar activity





Orbital Mechanics – EPS Impacts (con't)

- Mission design to reduce solar array/avionics radiation dose
  - GTO to GEO Radiation Contributions:
    - Trapped electrons (~1%), Trapped protons (~98%), Solar flare protons (<1%)
  - Effective: selected Argument of Perigee
    - Can reduce dose by ~6.5X by placing perigee near nodes
  - Ineffective: starting perigee altitude, launch date tied to solar activity



EP Operating Mode – EPS Impacts

<u>Conventional EP operating mode</u>

- EP PPU Buck/Boost Converter and solar array design EOL Vmp done in tandem (trade-off of costs, masses and efficiencies)
- Individual EP thruster operation is isolated from the EPS

<u>Direct-drive EP operating mode</u>

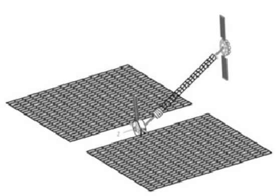
- Individual EP thrusters not isolated from the EPS
  - Ops of each EP thruster affects ops of others and EPS I/V levels
- Constant voltage (Isp)
  - Drives solar array string EOL voltage
  - Drives solar array/EPS channel current rating and shunt regulator size
- Constant current (flow rate)
  - Drives number of parallel solar strings to provide EOL current
  - May drive EPS channel voltage rating
- Variable voltage/current (such as Pmax, Max. Thrust, other)
  - Drives solar array EOL Vmp and Imp, EPS I/V design ratings

OPS/RPOD – EPS Impacts

- Initial orbit post-insertion OPS drives solar array deployment
  - Rapid deployment and power gen (nominally <1 rev, avoid energy storage over sizing)
  - Uniform deployment (minimize attitude disturbance torques)
  - Robust/reliable deployment (avoid failures altogether, or allow for contingency mission ops)
- Human SEP mission architectures include RPOD (in-space chemical stages)
  - Drives solar array deployed strength (plume and docking loads)
  - Drives solar array configuration and gimballing (docking vehicle ingress corridors, minimizing docking/plume loading, gimbal locking)
- In space operations (high-g chemical stage burns, >0.1-g)
  - Drives solar array deployed strength (burn cut-off base g-loads)
  - Drives solar array deployed stiffness (displacements and frequencies for stack ACS during the burn)
  - Drives solar array configuration and gimballing (minimize bending moment, attain preferred orientation, gimbal locking)

Solar Array Design Considerations

- Configuration: dual large wings versus multiple small wings
  - Ability to stow wings, deployment ops, deployment reliability/robustness, gimballing complexity, EP thruster location/plume avoidance, ground and/or flight testability, qualification and recurring costs (modularity), performance (sun-pointing accuracy provided and self shadowing)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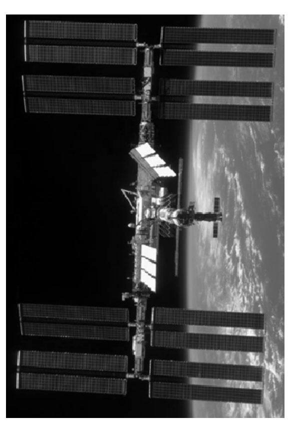
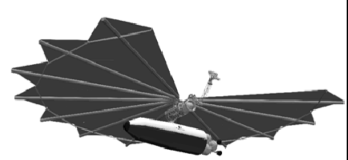
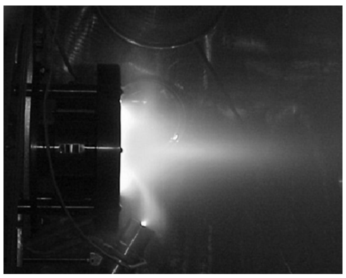


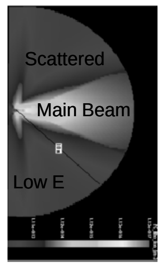
* Cost and performance will factor into conc. optics configuration: planar, 2X CellSaver or 8X SLA

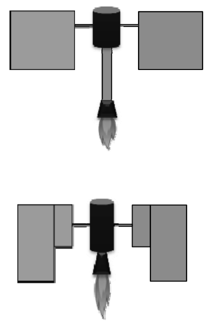
Human Mars DRM3.0


Solar Array Design Considerations

- Hall EP plume interactions (sputtering avoidance)
  - Optical/electrical coatings loss, structural material loss, contamination
  - Trade off complexity/mass of EP boom v notched/displaced solar array
- Design configuration must avoid high energy main beam ions
  - 45° cone rule-of-thumb from EP beam centerline
  - Low energy charge exchange ions are non-sputtering
  - Moderately high energy, scattered ions demand special design attention
  - Plume ion uncertainties for high power, multi-thruster, far field, in situ





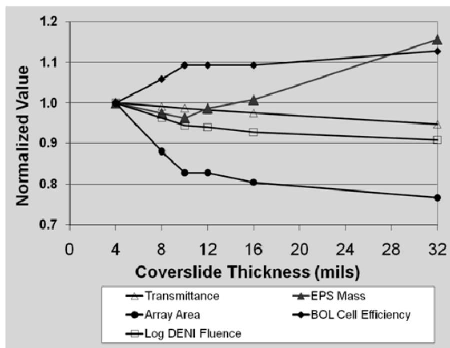


Solar Array Design Considerations

- Ambient and EP induced plasma interactions
  - Parasitic electron collection
    - Dominated by EP-induced plasma with high densities/energies
    - Solar array current loss mechanism, must oversize neutralizers/propellant
    - Design solar array strings with minimal exposed conductors
    - Plasma chamber coupon test data needed to verify collection levels
  - Arcing
    - Plasma/vacuum primary arcs not a concern during EP/neutralizer ops (ties spacecraft ground to plasma potential, minimizes voltage gradients)
    - Without EP ops, high orbit vacuum arcing must be managed conventionally (electrically bonded surfaces)
    - Sustained arcing avoided by proper design of solar array panel
    - Plasma chamber coupon test data needed to verify arc behavior

Solar Array Design Considerations

- Radiation degradation optimization
  - Goal: Minimum cost (or mass) of the SEP tug
  - Parameters affecting radiation dose
    - Avionics and tug subsystem designs, EP operation, mission design and solar array design/sizing
  - Solar cell type (BOL performance, rad. tolerance, conc. ratio)
  - Solar cell shielding (coverglass, substrate thicknesses/densities)



Solar Array Design Considerations

- Voltage selection
  - Using lower, state-of-the-art design voltages (100-V, 160-V) imposes a mass penalty on a high power SEP tug
    - 30-40% for EPS subsystem alone (harnessing and power electronics)
  - Large SEP tug missions tend to optimize with EP Isp ~2000 sec (300-V, Hall Thruster)
  - Above items lead to 300-V class direct-drive design option
  - To save mass, solar array Vmp is typically matched to the desired operating voltage at demanding point of the mission
  - 300-V class solar array designs consistent with de-rated performance of state-of-the-art cabling/connectors, diodes, insulators and gimbal roll-rings/slip rings
  - Higher string design operating voltages will increase parasitic electron collection current ~ (1+aV)^0.7
  - 300-V class solar array will drive PMAD parts selection

Solar Array Design Considerations

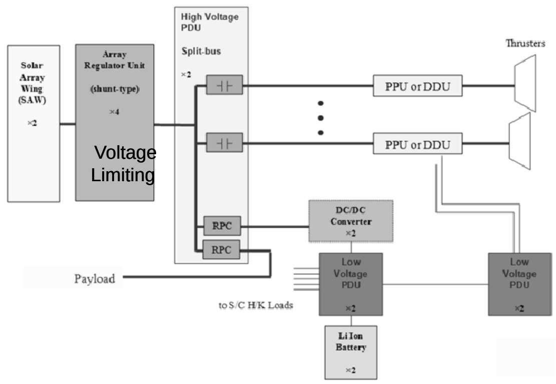
- Structural design (deployed strength/stiffness)
  - Very high deployed strength required (>0.1-g's)
    - High thrust, chemical stage burns, RPOD plume impingement
    - Above events are planned, allowing for solar array preferred orientations
  - Very high deployed first fundamental frequency required
    - Consistent with SEP tug controller frequency and allowable dead-band
    - Consistent with chemical stage/stack ACS control frequency
    - Minimize controls-structures interactions driven solar array loading
    - Achieve wing stiffness high enough to limit solar array deflections to acceptable levels

Solar Array Design Considerations

- Ground deployment testing of large solar array
  - Key for risk mitigation/qualification without flight test
    - Flight testing will be an affordability challenge and offers limited range of qualification
  - Solar array must be designed for g off-loaded, thermal vacuum deployment
    - Structures off-loading, optics off-loading (as needed), in situ post-deployment thermal-electrical performance (as needed)
  - Solar array must be designed for an acceptable risk level of phased deployment of full size or limited size hardware
    - Deployment phases: tie-down release, yoke/phasing structure, solar array panels/wings
    - World's largest vacuum facility (100-ft diameter and 122-ft height at NASA Plum Brook Space Power Facility) is not sufficient to test large SEP tug solar array designs envisioned
  - Solar array must be designed to minimize qualification costs

SEP Tug Primary PMAD

- Distribution Architecture Options
  - Centralized (All array power routed thru central distribution node, superior PMAD component mass/efficiency)
  - **Combined Centralized/Channelized Option is Desired** (Dual solar array wings feed dual centralized ARU inputs/outputs that feed channelized PDU segments for individual thrusters, reconfigurable with cross ties, superior cabling mass/efficiency, more modular, superior fault tolerance with degraded performance and/or over-sized solar array and power channels to route power between EP thrusters)



PMAD Design Considerations

- Voltage level has large impact on PMAD design
- SOA voltage system (120 - 160 Vdc)
  - PPU required to raise voltage in order to get desired ISP from thruster – less efficient, higher thermal load
  - Large cable mass required to handle high currents (mass inverse with square of voltage)
  - Conventional parts available; still may need radiation screening
  - Housekeeping loads can be fed from bus power without conversion
- High Voltage (300+ Vdc)
  - Direct drive option available – higher efficiency system and significantly less thermal load
  - Significant cable mass savings (>60%) due to relatively lower currents
  - Down conversion needed to feed housekeeping loads at conventional voltages
  - Very limited solid state parts selection, especially for high radiation spiral – may require wide bandgap electronics

PMAD Design Considerations (con't)

- Non-direct drive:
  - Delivers predetermined range of I/V to EP thruster PPUs
  - PPU power conditioning to the thruster
  - Decoupling, galvanic isolation between the source (array) and thruster
    - Simplifies ground testing of individual components (solar array, EPS, EP subsystem)
    - May simplifies design of solar array electrical simulator
  - Prevents interactions from multi-thrusters through the power bus
  - Improves overall power quality for the high voltage bus
- Direct drive offers:
  - Highest kw/kg performance and superior power efficiency
  - Increased reliability, lower recurring cost
  - Requires <u>no</u> new high voltage/power electronics tech development
  - Bus voltage control is primarily tied to EP thruster operation
  - Past direct drive system ground tests show stable operation, but more work is needed
    - Stability/ops during EP start-up/shut-down transitions
    - Cathode current sharing for multi-thruster ops
    - Effective grounding schemes

PMAD Design Considerations (con't)

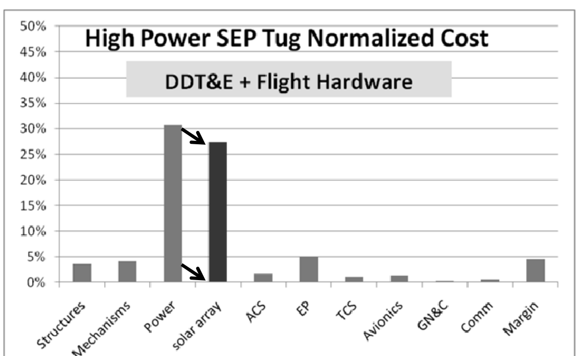
- Solar array regulator/limiter
  - Protects from short-lived, high bus voltage post-eclipse with low load
  - Additional mass/efficiency hit, and adds to thermal load
- Fault tolerance a significant driver for human missions
  - Reduced-power may be challenging at significant distance from Earth
  - Design for ability to tolerate loss of thrusters and/or power feeds
- Thruster out capability – How many failures tolerated?
  - Carry cold-spare thrusters, or
  - De-rate thrusters nominally and power up after failure(s)
- Grounding
  - Negative solar array grounding to the tug chassis desired
  - Positive solar array ground is unacceptable
    - Introduces solar array plasma arcing
    - Introduces untenable solar array sputtering from EP plume ions

PMAD Design Considerations (con't)

- EEE parts voltage level
  - 600-V rated parts with derating, just sufficient for 300-V class bus
    - Beyond this, may need to jump to 1200-V rated parts (more limited selection)
  - Use of limited existing acceptable parts may lead to heavier, more voluminous, and less reliable / less efficient circuit board and PMAD box designs
- EEE parts radiation tolerance (high flux, high energy protons)
  - Leads to high TID and enhanced SEE (MOSFET latch-up, gate rupture)
    - Dearth of manufacturer's SEE data will necessitate dedicated testing
    - SiC parts could be a solution
- SEP mission unique combination of high voltage/power and high radiation further limits choice of available parts
  - May need parts development, custom part builds, increased radiation testing, more stringent part screening, etc. which add costs
  - May require more box-level radiation shielding adding significant mass

SEP Cost Challenge

- Cost estimates show high power SEP stage affordability challenge – need major cost reductions (~2X)



(excludes systems integration costs)

- Major component cost challenge is the solar array
  - Recurring costs (particularly cell costs), qualification costs
  - Large-scale cell production availability

Closing Comments

- High power SEP tug missions offer attractive benefits
- Many {solvable} technical challenges remain and must eventually be met
- Yet programmatically, to progress beyond just SEP mission studies, major cost reductions are needed

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13. SUPPLEMENTARY NOTES
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14. ABSTRACT
Solar electric propulsion (SEP) technology is truly at the “intersection of commercial and military space” as well as the intersection of NASA robotic and human space missions. Building on the use of SEP for geosynchronous spacecraft station keeping, there are numerous potential commercial and military mission applications for SEP stages operating in Earth orbit. At NASA, there is a resurgence of interest in robotic SEP missions for Earth orbit raising applications, 1-AU class heliocentric missions to near Earth objects (NEOs) and SEP spacecraft technology demonstrations. Beyond these nearer term robotic missions, potential future human space flight missions to NEOs with high-power SEP stages are being considered. To enhance or enable this broad class of commercial, military and NASA missions, advancements in the power level and performance of SEP technologies are needed. This presentation will focus on design considerations for the solar photovoltaic array (PVA) and electric power system (EPS) vital to the design and operation of an SEP stage. The engineering and programmatic pros and cons of various PVA and EPS technologies and architectures will be discussed in the context of operating voltage and power levels. The impacts of PVA and EPS design options on the remaining SEP stage subsystem designs, as well as spacecraft operations, will also be discussed.

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