Earth Observation Telescope at L2

Draft Final Report

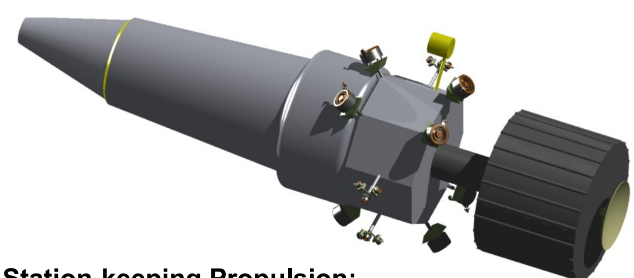
Station-Keeping Propulsion

Primary Contact: Tim Sarver-Verhey
<Timothy.R.Verhey@nasa.gov>
NASA Glenn Research Center

Station-keeping Propulsion Overview

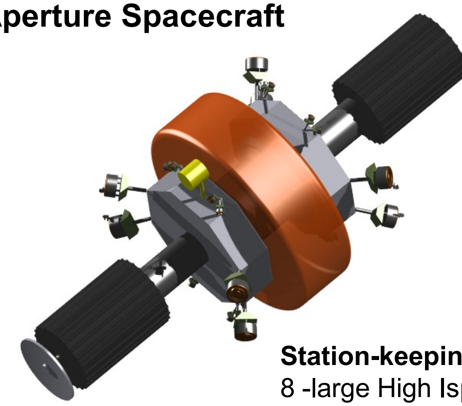
- Configuration:
  - Multiple thrusters on each spacecraft
    - Large electric thrusters for coarse control
    - Small electric thrusters for fine control
- Design Considerations:
  - Each spacecraft has different thruster configurations to prevent destructive interactions with other surfaces on spacecraft
  - Redundancy possible with operations impact
  - Available power limits operation to no more than two large thrusters operating at any one time
    - Thrusters required to operate in pairs to ensure balanced thrusting

Science Spacecraft



Station-keeping Propulsion:
8 -large High Isp Electric Thrusters
12 - small High Isp Electric thrusters

Aperture Spacecraft



Station-keeping Propulsion:
8 -large High Isp Electric Thrusters
16 - small High Isp Electric thrusters

Station-keeping Propulsion Design Drivers

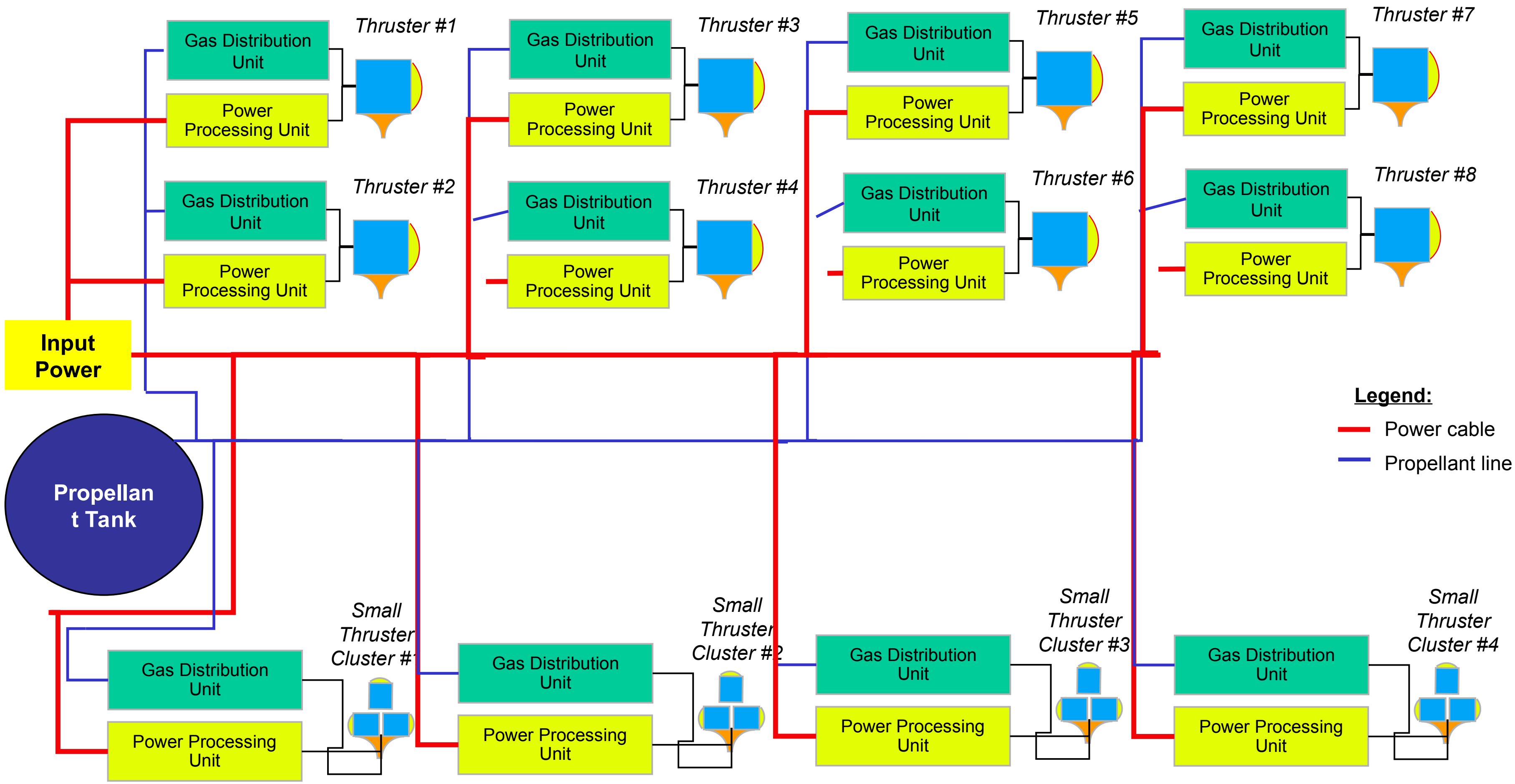
- Minimize power consumption
- Minimize size and mass
- Minimize propellant consumption
  - Thrusters to be operated at a high specific impulse & high efficiency
  - Limits operation
- Operation profile for thrusters required to accurately determine propellant load
  - Currently profile is TBD

Station-keeping Propulsion

- Capabilities:
  - Large thrusters for primary station-keeping thrust to keep spacecraft in position (radially) for observation
  - Small thrusters for fine control per telescope requirements
  - Thruster type: primarily Gridded Ion engines
    - Best choice for high specific impulse (propellant-limited) missions
    - However, in Current Best Estimate case, Hall thrusters probably best choice for aperture spacecraft primary thrusters because of relatively low specific impulse
  - Thrusters mounted on gimbals to enable some local pointing control
    - Reduces demands on spacecraft orientation required to maintain proper thrusting
  - Redundancy enabled by:
    - Shifting thruster use to other devices in event of failure
      - Vehicle operations will have to be changed to maintain thrusting capability
      - Dedicated power processing and propellant management systems on each large thruster required

- Issues:
  - Different masses of aperture & science spacecraft require different thrusters (sizes) to meet performance targets
    - Hence, different technology development programs
  - Significant technology development programs need to be initiated to develop engines that match the targets of the Current & Far-Term Best Estimates
    - Far-Term Best Estimate performance targets are extremely aggressive; driven by target vehicle mass & power limitations

Science Spacecraft Propulsion Configuration



Schematic of Station-keeping Propulsion System

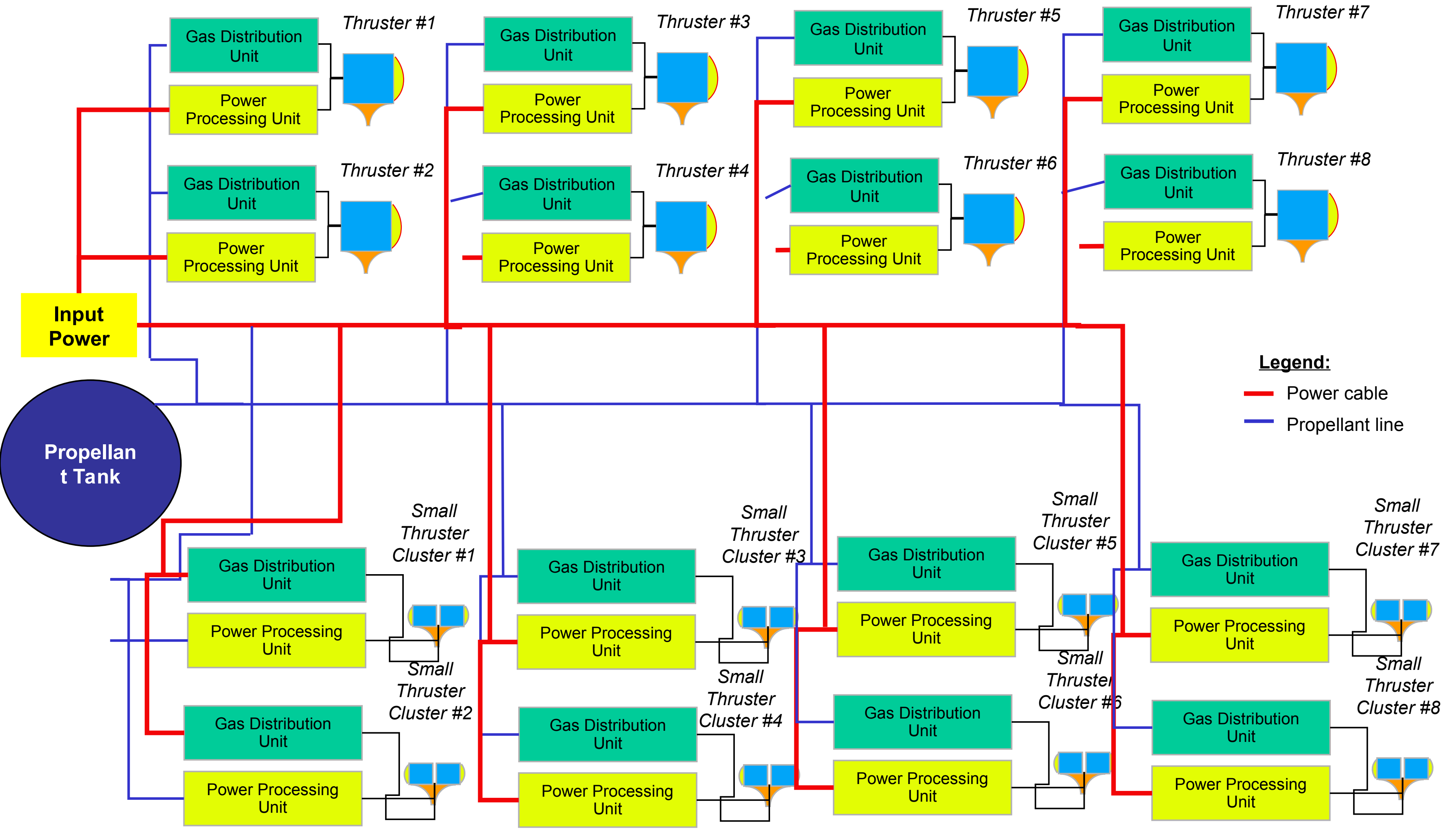
Science S/C Propulsion System

SCIENCE Spacecraft								
	Current Best Estimate				Future Best Estimate			
Item	Basis	Capability	Power (W)	Mass (kg)	Basis	Capability	Power (W), per thruster	Mass (kg)
Large Gridded Ion Engine		8 electric thrusters on s/c (notes 1,2,3)			Technology Projections guided by spacecraft mass limitations	8 electric thrusters on s/c (notes 1,2,3)		
	NSTAR, NEXT engines	2205 seconds specific impulse	1175	15.2	NSTAR, NEXT engines; HiPEP NRA engines	9325 seconds specific impulse	1225	6.7
		64% thruster efficiency				90% thruster efficiency		
Power Processing Unit		94% efficiency	75	13.0		98% efficiency	25	8.3
		Power into Thruster (W)	1250			Power into Thruster (W)	1250	
		Total Large Thruster System Mass (kg)		225.6		Total Large Thruster System Mass (kg)		119.6
		Specific Mass (kg/kWe)	22.6			Specific Mass (kg/kWe)	12.0	
Small Gridded Ion Engine		12 electric thrusters on s/c				16 small electric thrusters on s/c		
	NSTAR, NEXT engines	3970 seconds specific impulse	235	5.8	NSTAR, NEXT engines; HiPEP NRA engines	8400 seconds specific impulse	122.5	2.6
		64% thruster efficiency				90% thruster efficiency		
Power Processing Unit		94% efficiency	15	4.2		98% efficiency	2.5	1.8
		Power into Thruster (W)	250			Power into Thruster (W)	125	
		Total Small Thruster System Mass (kg)		120.0		Total Small Thruster System Mass (kg)		52.4
		Specific Mass (kg/kWe)	40.0			Specific Mass (kg/kWe)	34.9	
		Total Station-keeping Propulsion Dry Mass		345.6		Total Station-keeping Propulsion Dry Mass		172.0
Propellant Tank	5% tankage fraction (note 4)	Propellant Tank Mass		64.6	2.5% tankage fraction	Propellant Tank Mass		4.7
Propellant Load	Proprellant estimated for 6 years of operation (note 5)	Propellant Mass		1291.5	Propellant load estimated for 10 years of operation	Propellant Mass		186.7

Note 1. Propellant distribution unit included in thruster mass
Note 2. Gimbal & support structure mass included in thruster mass
Note 3. Operational assumptions: No more than two large engines running at any time; small engines to be operated without large engines on;
Note 4. Xenon assumed to be stored supercritically in all cases
Note 5. Propellant loads are simple estimates based on ideal mass flow through an electric thruster assuming that two large and two small thrusters are operating continously during the mission duration

- Substantial hardware & propellant mass reduction required to meet performance targets

Aperture Spacecraft



Schematic of Station-keeping Propulsion System

Aperture S/C Propulsion System

APERTURE Spacecraft								
	Current Best Estimate				Future Best Estimate			
Item	Basis	Capability	Power (W), per thruster	Mass (kg)	Basis	Capability	Power (W), per thruster	Mass (kg)
		8 electric thrusters on s/c (notes 1,2)			Technology Projections guided by spacecraft mass limitations	8 electric thrusters on s/c (notes 1,2,3)		
Large Gridded Ion Engine	NSTAR, NEXT engines	1715 seconds specific impulse	1175	15.2	NSTAR, NEXT engines; HiPEP NRA engines	9325 seconds specific impulse	1225	6.7
		64% thruster efficiency				90% thruster efficiency		
Power Processing Unit		94% PPU efficiency	75	13.0		98% PPU efficiency	25	8.3
		Power into Thruster (W)	1250			Power into Thruster (W)	1250	
		Total Large Thruster System Mass (kg)		225.6		Total Large Thruster System Mass (kg)		119.6
		Specific Mass (kg/kWe)	22.6			Specific Mass (kg/kWe)	12.0	
		12 electric thrusters on s/c				16 electric thrusters on s/c		
Small Gridded Ion Engine	NSTAR, NEXT engines	3090 seconds specific impulse	235	7.0	NSTAR, NEXT engines; HiPEP NRA engines	8400 seconds specific impulse	122.5	2.6
		64% thruster efficiency				90% thruster efficiency		
Power Processing Unit		94% PPU efficiency	15	5.5		98% PPU efficiency	2.5	2.3
		Power into Thruster (W)	250			Power into Thruster (W)	125	
		Total Small Thruster System Mass (kg)		200.0		Total Small Thruster System Mass (kg)		78.4
		Specific Mass (kg/kWe)	50.0			Specific Mass (kg/kWe)	39.2	
		Total Station-keeping Propulsion Dry Mass		425.6		Total Station-keeping Propulsion Dry Mass		198.0
Propellant Tank	5% tankage fraction (note 4)	Propellant Tank Mass		35.6	2.5% tankage fraction	Propellant Tank Mass		4.7
Propellant Load	Proprellant estimated for 2 years of operation (note 5)	Propellant Mass		711.6	Propellant load estimated for 10 years of operation	Propellant Mass		186.7

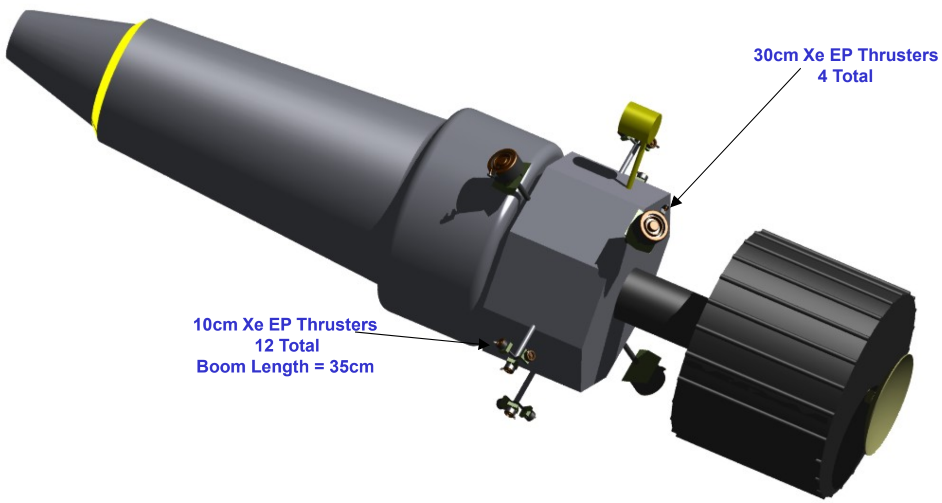
Note 1. Propellant distribution unit included in thruster mass
Note 2. Gimbal & support structure mass included in thruster mass
Note 3. Operational assumptions: No more than two large engines running at any time; small engines to be operated without large engines on;
Note 4. Xenon assumed to be stored supercritically in all cases
Note 5. Propellant loads are simple estimates based on ideal mass flow through an electric thruster assuming that two large and two small thrusters are operating continously during the mission duration

- Substantial propulsion hardware & propellant mass reduction required to meet performance targets
- Propulsion system on Aperture S/C is a concern because proximity to reflector system could lead to reflector degradation

System Trades

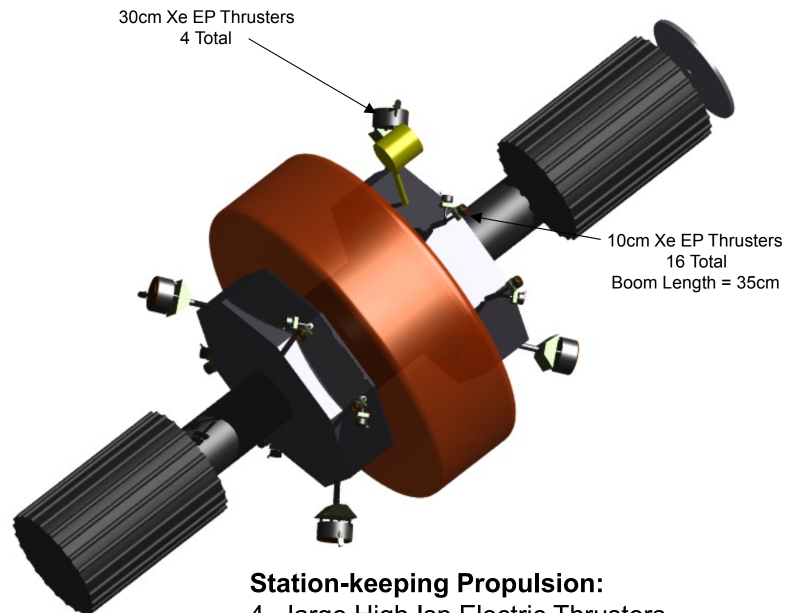
- Trade objective: Quantify benefits to spacecraft mass by reducing number of large thrusters on each spacecraft
  - From 8 to 4 thrusters
  - Mechanism to enable proper pointing of reduced number of thrusters is assumed to be part of spacecraft
    - Handled by some other subsystem
    - Mass & power requirements for device accounted for by other subsystem

Science S/C



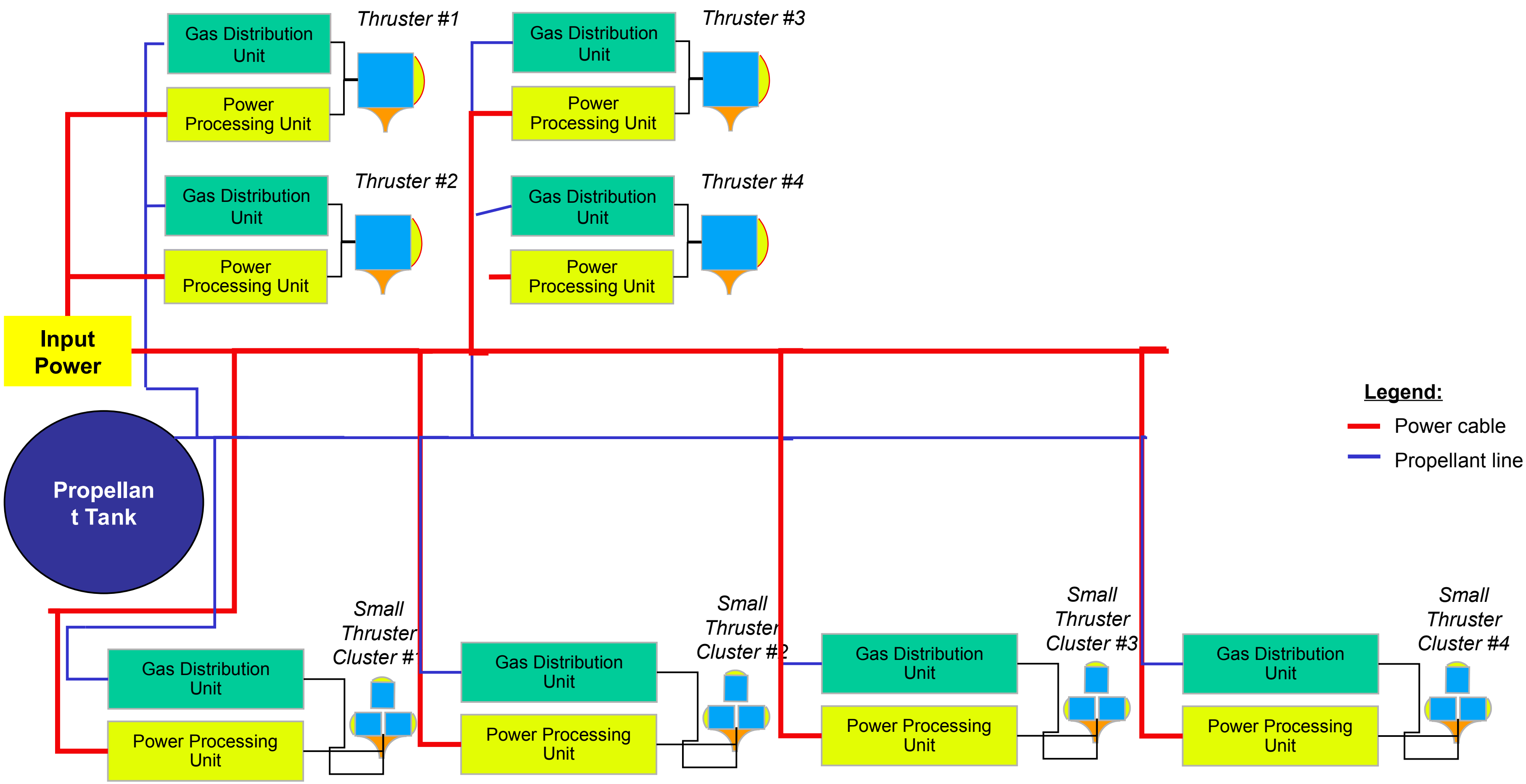
Station-keeping Propulsion:
4 - large High Isp Electric Thrusters
12 - small High Isp Electric thrusters

Aperture S/C



Station-keeping Propulsion:
4 - large High Isp Electric Thrusters
16 - small High Isp Electric thrusters

Science Spacecraft Propulsion Configuration



Schematic of Station-keeping Propulsion System

NASA RASC

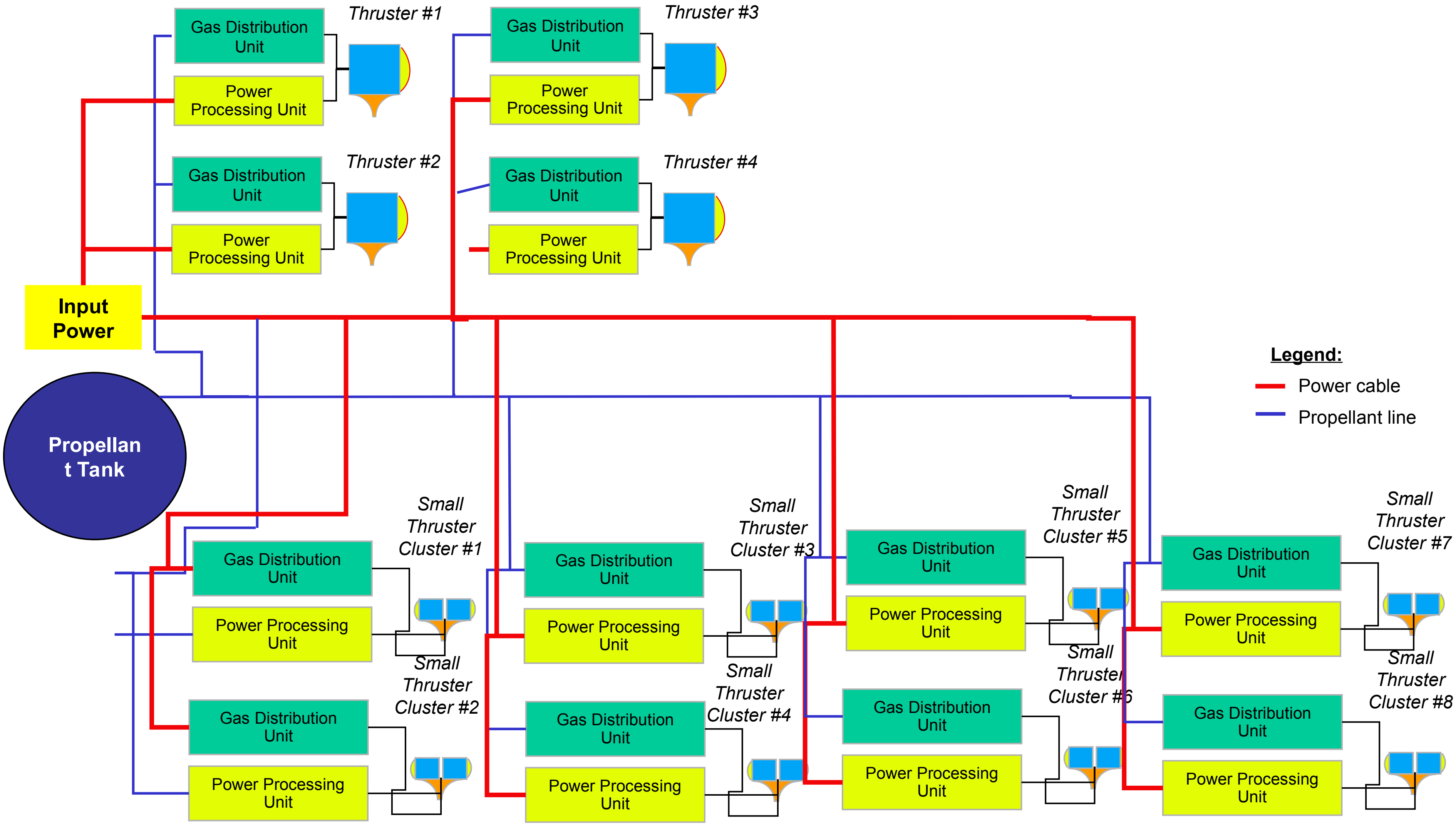
Science S/C Propulsion System

SCIENCE Spacecraft								
	Current Best Estimate				Future Best Estimate			
Item	Basis	Capability	Power (W)	Mass (kg)	Basis	Capability	Power (W), per thruster	Mass (kg)
Large Gridded Ion Engine		4 electric thrusters on s/c (notes 1,2,3)			Technology Projections guided by spacecraft mass limitations	4 electric thrusters on s/c (notes 1,2,3)		
	NSTAR, NEXT engines	2520 seconds specific impulse	1175	15.2	NSTAR, NEXT engines; HiPEP NRA engines	7600 seconds specific impulse	936.88	6.7
		64% thruster efficiency				90% thruster efficiency		
Power Processing Unit		94% PPU efficiency	75	13.0		98% PPU efficiency	19.12	8.3
		Power into Thruster (W)	1250			Power into Thruster (W)	956	
		Total Large Thruster System Mass (kg)		112.8		Total Large Thruster System Mass (kg)		59.8
		Specific Mass (kg/kWe)	22.6			Specific Mass (kg/kWe)	15.6	
Small Gridded Ion Engine		12 electric thrusters on s/c				16 small electric thrusters on s/c		
	NSTAR, NEXT engines	4535 seconds specific impulse	235	5.8	NSTAR, NEXT engines; HiPEP NRA engines	7500 seconds specific impulse	122.5	2.6
		64% thruster efficiency				90% thruster efficiency		
Power Processing Unit		94% PPU efficiency	15	4.2		98% PPU efficiency	2.5	1.8
		Power into Thruster (W)	250			Power into Thruster (W)	125	
		Total Small Thruster System Mass (kg)		120.0		Total Small Thruster System Mass (kg)		52.4
		Specific Mass (kg/kWe)	40.0			Specific Mass (kg/kWe)	34.9	
		Total Station-keeping Propulsion Dry Mass		232.8		Total Station-keeping Propulsion Dry Mass		112.2
Propellant Tank	5% tankage fraction (note 4)	Propellant Tank Mass		49.4	2.5% tankage fraction	Propellant Tank Mass		5.3
Propellant Load	Proprellant estimated for 6 years of operation (note 5)	Propellant Mass		988.8	Propellant load estimated for 10 years of operation	Propellant Mass		212.9

Note 1. Propellant distribution unit included in thruster mass
Note 2. Gimbal & support structure mass included in thruster mass
Note 3. Operational assumptions: No more than two large engines running at any time; small engines to be operated without large engines on;
Note 4. Xenon assumed to be stored supercritically in all cases
Note 5. Propellant loads are simple estimates based on ideal mass flow through an electric thruster assuming that two large and two small thrusters are operating continously during the mission duration

- Substantial hardware & propellant mass reduction required to meet performance targets
- Propellant load allowed to exceed 200 kg target to keep specific impulse levels < ~10,000 seconds
  - Resulting propulsion system mass small enough to keep Propulsion Wet mass under 400 kg target

Aperture Spacecraft



Schematic of Station-keeping Propulsion System

Aperture S/C Propulsion System

APERTURE Spacecraft								
	Current Best Estimate				Future Best Estimate			
Item	Basis	Capability	Power (W), per thruster	Mass (kg)	Basis	Capability	Power (W), per thruster	Mass (kg)
Large Gridded Ion Engine		4 electric thrusters on s/c (notes 1,2)			Technology Projections guided by spacecraft mass limitations	4 electric thrusters on s/c (notes 1,2,3)		
	NSTAR, NEXT engines	1785 seconds specific impulse	1175	15.2	NSTAR, NEXT engines; HiPEP NRA engines	7600 seconds specific impulse	980	6.7
		64% thruster efficiency				90% thruster efficiency		
Power Processing Unit		94% PPU efficiency	75	13.0		98% PPU efficiency	20	8.3
		Power into Thruster (W)	1250			Power into Thruster (W)	1000	
		Total Large Thruster System Mass (kg)		112.8		Total Large Thruster System Mass (kg)		59.8
		Specific Mass (kg/kWe)	22.6			Specific Mass (kg/kWe)	15.0	
Small Gridded Ion Engine		12 electric thrusters on s/c				16 electric thrusters on s/c		
	NSTAR, NEXT engines	3210 seconds specific impulse	235	7.0	NSTAR, NEXT engines; HiPEP NRA engines	7500 seconds specific impulse	107.8	2.5
		64% thruster efficiency				90% thruster efficiency		
Power Processing Unit		94% PPU efficiency	15	5.5		98% PPU efficiency	2.2	2.3
		Power into Thruster (W)	250			Power into Thruster (W)	110	
		Total Small Thruster System Mass (kg)		200.0		Total Small Thruster System Mass (kg)		76.4
		Specific Mass (kg/kWe)	50.0			Specific Mass (kg/kWe)	43.4	
		Total Station-keeping Propulsion Dry Mass		312.8		Total Station-keeping Propulsion Dry Mass		136.2
Propellant Tank	5% tankage fraction (note 4)	Propellant Tank Mass		32.8	2.5% tankage fraction	Propellant Tank Mass		5.6
Propellant Load	Propellant estimated for 2 years of operation (note 5)	Propellant Mass		657.0	Propellant load estimated for 10 years of operation	Propellant Mass		222.8

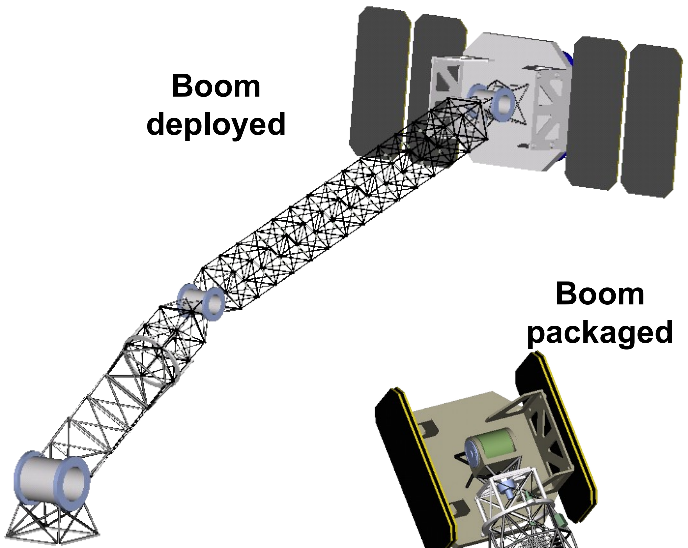
Note 1. Propellant distribution unit included in thruster mass
Note 2. Gimbal & support structure mass included in thruster mass
Note 3. Operational assumptions: No more than two large engines running at any time; small engines to be operated without large engines on;
Note 4. Xenon assumed to be stored supercritically in all cases
Note 5. Propellant loads are simple estimates based on ideal mass flow through an electric thruster assuming that two large and two small thrusters are operating continously during the mission duration

- Substantial propulsion hardware & propellant mass reduction required to meet performance targets
- Propellant load allowed to exceed 200 kg target to keep specific impulse levels < ~10,000 seconds
  - Resulting propulsion system mass small enough to keep Propulsion Wet mass under 400 kg target

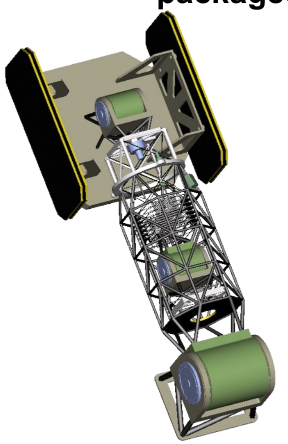
Alternate Thruster Configuration

- Configuration option studied at early stage
  - Assessment not completed
- Thruster(s) deployed on boom arms
  - Enable increased pointing range, thereby reducing number of engines on spacecraft
    - Could significantly reduce power requirements due to elimination of extreme thruster 'feathering' operations
    - Ensures no thruster impingement on critical spacecraft surfaces
  - Two booms envisioned to ensure balancing of disturbances induced by thruster operation
    - Preliminary assessment made using same thruster operating points as traditional configuration
      - Boom arm characteristics estimated from recent study; further refinement required
      - Design includes spare engines on each boom

Boom deployed

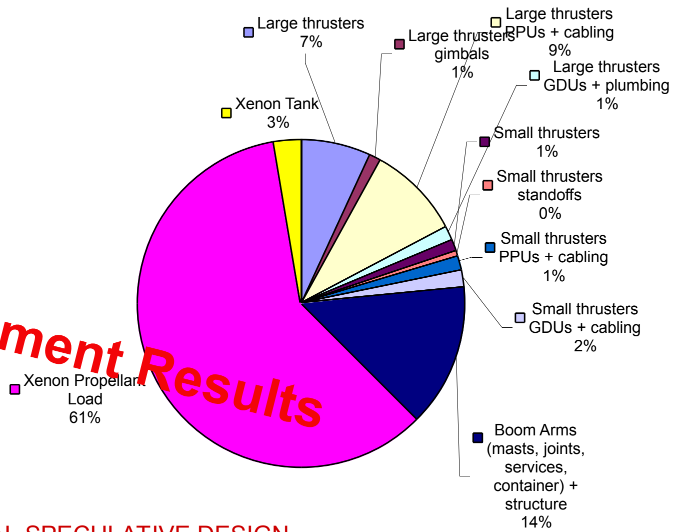


Boom packaged



Component	Mass
Large thrusters	84
Large thrusters gimbals	13
Large thrusters PPUs + cabling	112
Large thrusters GDUs + plumbing	18
Small thrusters	14
Small thrusters standoffs	4
Small thrusters PPUs + cabling	[illegible]
Small thrusters GDUs + cabling	20
Boom Arms (masts, joints, services, container) + structure	172
Xenon Propellant Load	725
Xenon Tank	35
Total Dry Mass	**490**
Total Mass	**1215**

Preliminary Assessment Results



Boom information to developed scaled version for this task obtained from "Final Report for the HPM and Mars Tug Solar Electric Propulsion Thruster Repositioning Arm Concept Study, NASA GRC / AFRL VS F29601-02-C-0087, bu M. Botke

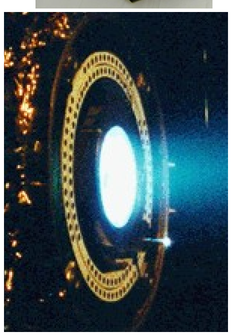
Station-keeping Propulsion Development Efforts

- Development programs required to provide thrusters for Current and Far-Term Best Estimate targets
- Significant technological progress required to meet Far-Term Best Estimate target
  - Performance target not on current development tracks
- Development program costs difficult to assess
  - Expect to to be greater than NEXT & HIPEP NRA development programs
  - <$20-25 M to TRL 3-4

Gridded Ion Thruster Roadmap

Power

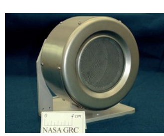
NSTAR 30 cm
2.5 kW
3100s TRL 9



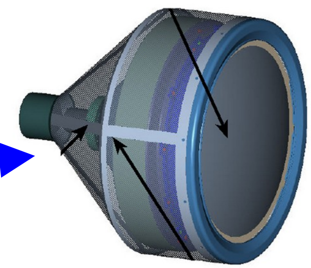
Deep Space One Proven

NEXT 40 cm
7 kW
4100s TRL 6

SubKW Lab Model
8 cm 0.3 kW
2500s TRL 4



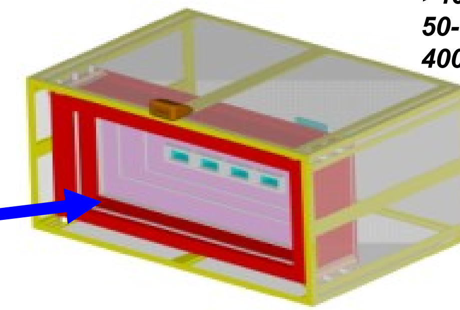
100 kW NEP-Class
Microwave
3300 cm^2 area
15-50 kW 6000-9000s TRL 3
(HiPEP)



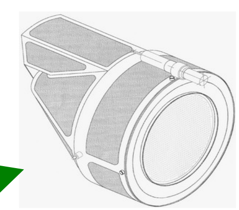
250 kW NEP-Class
Gridded Ion
50-200 kW
6000-9000s TRL 3
(NEXIS)

REP-Class
20 cm 0.1-0.8 kW
3000-4000s TRL 3

500 kW NEP-Class
Microwave
>4000 cm^2 area
50-200 kW
4000-12000s TRL 2



2nd gen REP-Class
20 cm 0.1-1.0 kW
3000-8000s TRL 1



Large Ion Thrusters
7600 - 9325 s
1-1.25 kW

Our Targets

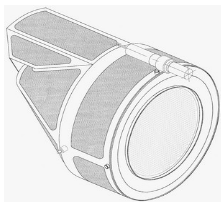
Small Ion Thrusters
8400 s
100-125 kW

0-5 years | **5-10 years** | **10-15 years**

Low Power Ion Propulsion Technology Road-Map options

	00	01	02	03	04	05	06	07	08	09	10	11	12		

2014



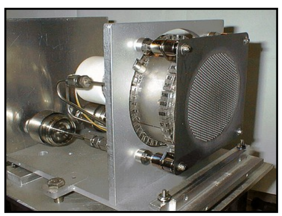
No Flow Cathode

Thermal and life limits assessed

Graphite Optics
30 kg Xe Throughput

300 W
3300 sec
56% Eff.
30 kg Xe Throughput

2011



Thermal and life limits assessed

Graphite Optics
30 kg Xe Throughput

300 W
2800 sec
49% Efficient
20 kg Xe Throughput

Our Targets

Large Ion Thruster
7600 - 9325 s
1-1.25 kW

Small Ion Thrusters
8400 s
100-125 kW

2008

0.5 sccm Cathode

Thermal and life limits assessed

Advanced Moly or Titanium optics
20 kg Xe Throughput

Regulated 28v PPU

300 W
2800 sec
49% Efficient
20 kg Xe Throughput

Glenn Research Center

Future

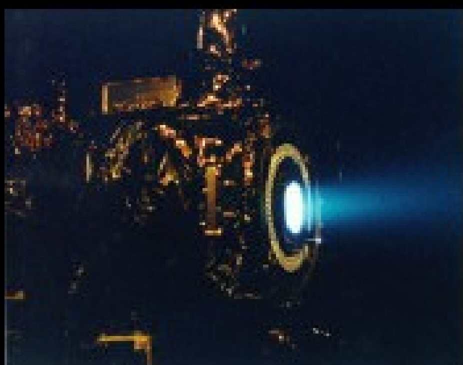
ION DRIVE

SOA

NSTAR 30 cm

- 2.3 kW
- 140 kg Xe throughput

SPACE SCIENCE →



SPACE SCIENCE →

Small Spacecraft
Planetary exploration
Commercial

5-YEAR *(to TRL-9)*

Next Generation 5-10 kW 40 cm

- 1-10 kW
- 550 kg Xe throughput

SPACE SCIENCE →

Large Spacecraft
Planetary exploration
Commercial/DOD

SPACE SCIENCE
HEDS →

Sub-kilowatt Ion

- 100-500 W, > 40% system efficiency
- 8 cm
- >12 kg Xe throughput

Micro S/C applications

SPACE SCIENCE →

10-YEAR *(to TRL-9)*

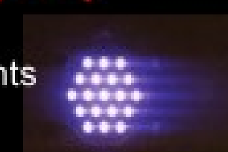
15 kW-Class High-Thrust Density Engine

- 5-15 kW
- >50 mN/kW

30 kW-Class High-Thrust Engine

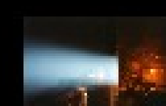
- Micro-wave plasma generation
- Carbon- based Ion optics
- Sub-6000 S specific impulse

30 kW-Class High-Isp Engine



- Alternate propellants
- >> 6000 S

Micro-Ion Engine



- < 50 W
- >25% efficiency, >1500 S

Recommendations

- High efficiency, high throughput Gridded Ion thrusters best candidate for station-keeping propulsion
  - Driven by significant power and mass constraints

- Technologies to invest in to achieve performance targets:
  - High voltage graphite grids
    - Low erosion/long-life
  - Discharge chamber advancement to meet requirements
    - Thruster efficiency increased to 90%
    - Low power & long life operation
  - Long-life plasma generation devices
    - Hollow cathode life issues
    - Efficacy of other approaches (I.e. microwave)

- At system level, develop high fidelity estimate for thruster operating profile, including spacecraft orientation effects
  - These will have first-order impact on propulsion requirements