Appendix I. NASA's Evolutionary Xenon Thruster (NEXT)

I.1 Starshade Propulsion

A key functional element of the starshade spacecraft is to move, within the Lagrange space, from observation state vector to observation state vector. On the order of 70-80% of the starshade spacecraft life cycle is spent in these translation maneuvers. This mission characteristically has a very large mission delta-V. With the current baseline New Worlds Observer concept, the translation maneuver delta-V for the primary mission is on the order of 7-8 km/s. Electric propulsion systems can execute this delta-V with significantly less propellant than a chemical propulsion system. The baseline concept requires approximately 900 kg of xenon propellant. Use of a bi-propellant chemical propulsion system, while reducing the mission delta-V, drives the propellant mass well above 10,000 kg. Such an approach is mass-prohibitive. Thus, considering findings from earlier studies and updates to analyses, the decision was made to baseline electric propulsion at the beginning of this study.

I.2 Requirements Flow-Down

The effectiveness of the Starshade Spacecraft propulsion system directly translates to science return. Key mission-level requirements that drive the Starshade Spacecraft propulsion system concept include:

1. The system shall be capable of detecting an Earth twin at Quadrature in a Solar System twin that is up to 10 (TBR) parsecs away.
2. The system shall be capable of finding at least 30 Earth twins if all target stars have such a planet.

These requirements drive the key elements of the telescope/starshade architecture, including distance between spacecraft, relative angles between spacecraft with respect to heliocentric space, starshade size and thus mass, and the number of observations that are required in the baseline mission. The current mission concept has determined a conceptual baseline for these parameters as documented in the Mission Design Laboratory study products. The key mission parameters that drive the Starshade Spacecraft propulsion system design are:

- Spacecraft dry mass: assumed to be 3523 kg based on MDL results, including contingency mass growth
- Telescope-to-Starshade Spacecraft separation distance: 80,000 km
- Minimum number of observations in the 5-year primary mission: 100
- Number of observation extensions in the 5-year primary mission: 30
- Slew angle, or the distance the Starshade Spacecraft must travel between observations: A function of the specific mission plan. Prior design reference missions indicate that the mission-average slew angle for coverage of high value targets is 20 – 25° (telescope slew angle), which translates to 28,000 to 35,000 km translation distances for the Starshade Spacecraft.
- Total ΔV capability of Starshade Spacecraft (assuming electric propulsion): 12 km/s

I.3 Electric Propulsion System Selection

A variety of electric propulsion systems were considered for use on New Worlds Observer. The best candidates that fit the possible range of performance parameters and technology readiness are summarized below.

NSTAR: NSTAR is a gridded ion thruster system that was developed for NASA deep space applications. It was successfully demonstrated on the New Millennium Program Deep Space 1 mission.[Ref. 1] This led to the selection of an NSTAR system for the Discovery-class Dawn mission, which is now on the way to the main belt asteroids Vesta and Ceres.[Ref. 2] With continued success on Dawn, the NSTAR system is at TRL9.

XIPS: XIPS is a gridded ion thruster system that was developed by industry for commercial geosynchronous satellite applications.[Ref. 3] The XIPS system is used for orbit-raising and on-orbit stationkeeping, and has two nominal throttle conditions associated with these functions. XIPS has been flown in two varieties, a 13 cm and 25 cm beam diameter thrusters. The XIPS-13 was used on Hughes (Boeing) 601 bus satellites, the XIPS-25 on Hughes (Boeing) 702 bus satellites. The 25 cm version was considered in this analysis. While the XIPS system is at TRL9 for it's current application, NASA standard practices dictate that it be re-rated as TRL5 because of the significantly different environments associated with deep space missions.[Ref. 4] Qualification of XIPS-25 for NASA deep space missions is being pursued.[Ref. 5] The technology readiness and qualification status of XIPS-25 for this mission would need to be further evaluated.

BPT-4000: BPT-4000 is a Hall-effect thruster that was developed by industry for commercial geosynchronous satellite applications. The BPT-4000 system is used for orbit-raising and on-orbit stationkeeping, and has two nominal throttle conditions associated with these functions. BPT-4000 has been qualified for this application (TRL8), and is planned to first fly on an upcoming advanced communications satellite. [Ref.6] NASA standard practices dictate that it be re-rated as TRL5 because of the significantly different environments associated with deep space missions.[Ref. 4] The technology readiness and qualification status of BPT-4000 for this mission would need to be further evaluated.

NEXT: NEXT is a gridded ion thruster system that is in technology development for NASA deep space missions.[Ref. 7] In many regards, it is an evolution of the NSTAR concept. The NEXT technology project is funded under the NASA Science Mission Directorate In-Space Propulsion Technology Project. It is completing the second phase of development, with the objective of reaching TRL6 for the critical elements of the ion propulsion system.

The critical performance parameters of these options are summarized in Table I-1. Parameters are stated at full power conditions, where most of the NWO propulsion operations are likely to occur.

Table I-1 Applicable Electric Propulsion System Characteristics

	NEXT	NSTAR	XIPS-25	BPT-4000
Thrust, mN	236	91	166	254
Specific Impulse, s	4190	3070	3550	2150
Input Power, kW	6.9	2.3	4.2	4.5
Xenon Throughput, kg	300 - 500	155 - 200	150	275 - 300

[Refs. 5, 8, 9, 10, 11]
Throughput values require additional research and referencing as applicable to NWO operating conditions. These values represent ranges considered in analyses below.

The four thruster choices were analyzed for the NWO reference mission, as defined by the following assumptions:

- Primary Mission Duration: 5 years
- Number of Observations: 100
- Telescope-Starshade Separation Distance: 80,000 km
- Average Distance per Translation Maneuver: 30,500 km
- Average Duration per Observation: 4 days

The analysis was performed assuming free-space maneuvers. Prior comparisons have shown this to be conservative with respect to high fidelity simulations of design reference missions, over-predicting required ΔV by 10-20%. All thrusters are assumed to be running at full power. In this analysis, it is assumed that the spare thruster is available to support extended mission operations. Comparisons were generated under two scenarios:

1. The initial wet mass and xenon load was constrained to match the MDL design solution of 5220 kg and 1220 kg respectively, with mission capability derived. In this case, number of targets observed was left to vary.
2. The initial wet mass and xenon load was allowed to vary such that 100 targets within the 5-year primary mission was accomplished, or for the XIPS-25 case, to achieve similar extended mission xenon reserves.

Scenario 1 results:

Table I-2 EP System Trade Results, Scenario 1

	BPT-4000	XIPS-25	NSTAR	NEXT
Primary Mission Xenon Mass, kg	1203	1004	1178	902
Extended Mission Xenon Mass, kg	18	217	43	319
Number of Targets Achieved	92	100	99	100
Thrusters/PPUs Operating During Translation Maneuvers	2	3	5	2
Thrusters Required for Primary Mission Lifetime	4-5	6-7	7-8	2-3
Thrusters/PPUs Required for Redundancy	1	1	1	1
Total Thrusters	5-6	7-8	8-9	3-4
Total PPUs	3	4	6	3
EPS Element Dry Mass, kg	147	243	251	178
Thruster Input Power Required, kW	9.0	12.6	11.6	13.8

In Table I-2, the EPS Element Dry Mass represents the total mass of the thrusters, PPUs, gimbals, and per-thruster feed system elements associated with the lower number in the total thruster range. Xenon tank and other feed system elements (that do not vary with thruster count) are not included, as this scenario assumes a fixed xenon load.
NEXT provides the best solution with efficient use of the available xenon, allowing the opportunity for extended mission operations, and the simplest propulsion system configuration, at the cost of higher power requirements.
BPT-4000 provides a solution that has a minimum power requirement, due to it's higher thrust-to-power, and a relatively simple system configuration. It is also lowest dry mass solution primarily due to the lower mass of the PPU relative to NEXT. This solution does not achieve the minimum number of targets, nor does it provide any extended mission capability, due to the specific impulse of the thruster and the mass constraints of this scenario. If the number of operating BPT-4000 thruster/PPU strings is increased to 3, at 13.5 kW input power, 96 targets can be accomplished with the baseline 1220 kg of xenon, improving the BPT-4000 mission capability only marginally.
While the specific impulse of the XIPS-25 provides efficient xenon use and extended mission capability, the poor lifetime capability of the thruster and lower thrust drives the system complexity to a prohibitive level.
The NSTAR solution is limited in effectiveness by the low power per thruster and limited thruster lifetime capability. The complexity of the resulting system is prohibitive.

Scenario 2 results

Table I-3 EP System Trade Results, Scenario 2

	BPT-4000	XIPS-25	NSTAR	NEXT
Initial Wet Mass, kg	5900	5350	5250	5220
Primary Mission Xenon Mass, kg	1901	1047	1248	902
Extended Mission Xenon Mass, kg	0	304	3	319
Number of Targets Achieved	100	100	100	100
Thrusters/PPUs Operating During Translation Maneuvers	2	3	5	2
Thrusters Required for Primary Mission Lifetime	7	6-7	7-9	2-3
Thrusters/PPUs Required for Redundancy	1	1	1	1
Total Thrusters	8	7-8	8-9	3-4
Total PPUs	3	4	6	3
Thruster Input Power Required, kW	9.0	12.6	11.6	13.8

Table I-3 illustrates the assessment results for scenario 2. The EPS element dry masses would be similar for this scenario, except that the BPT-4000 would be penalized with additional xenon tank mass.
The NEXT solution remains the same as a baseline solution. The BPT-4000 system requires a significant increase in xenon mass to achieve the minimum 100 target mission, with the associated increase in initial wet mass. This illustrates that the BPT-4000 approach is very sensitive to changes in this solution space. The additional xenon

throughput required also drives the system configuration complexity significantly. The XIPS-25 solution was modified to allow mass to grow to provide a similar extended mission xenon reserve as the NEXT baseline. The complexity of this system remains prohibitive, as for the NSTAR solution.

The results of these analyses illustrate that the NEXT ion propulsion is the optimum approach for the NWO mission concept currently baselined. The specific impulse of the NEXT thruster provides efficient use of propellant and provides significant extended mission capability with the selected xenon propellant load. The high power per thruster allows the translation maneuvers to be done with a reasonable number of thrusters operating. The long-life capability of each thruster minimizes the number of thrusters needed to accomplish the primary mission. The resulting system configuration is the simplest of all options considered and also provides the maximum opportunity for science return.

I.4 NEXT Background

The NEXT ion propulsion technology project is under development within the SMD In-Space Propulsion Technology (ISPT) Project. ISPT resides under the Planetary Science Division, where most NASA science mission use of electric propulsion is anticipated. The NEXT project was awarded a Phase 1 project, with an option for Phase 2 follow-on, in 2002 under a competitive NASA Research Announcement. The intent of Phase 1 was to establish the initial capabilities of the proposed technologies to meet the NRA requirements. Based on a successful Phase 1, Phase 2 was awarded in 2003. The defined objective of the Phase 2 project was to advance ion engine propulsion technologies at the component and system level to TRL5, with significant progress made toward TRL6. The required scope of the effort included thrusters, power processing units, propellant management, and other technology integrations. The NEXT team proposed and developed the 7 kW NEXT thruster, the PPU, the propellant management system (PMS) High Pressure and Low Pressure Assemblies, a new technology gimbal, and a Digital Control Interface Unit (DCIU) simulator to facilitate demonstration at the system level. The primary members of the NEXT project team are:

- NASA Glenn Research Center: technology lead
- NASA Jet Propulsion Laboratory: system integration lead
- Aerojet Corporation: thruster, PMS, and DCIU simulator
- L3 Communications Electron Technologies, Inc.: PPU

In addition, ATK (Swales) designed and fabricated the gimbal under the guidance of JPL, Applied Physics Laboratory and Goddard Space Flight Center have had supporting tasks, and University of Michigan, Colorado State University and Wright State University have supported thruster modeling and analysis under grants.

The technology development status of NEXT is described in section I.9 below.

I.5 NWO Starshade System Configuration

The NEXT system configuration for the NWO Starshade Spacecraft is driven by the thrust required to accomplish translation maneuvers associated with the 100-target primary mission, the number of thrusters needed to process the necessary xenon, and single fault tolerance requirements. The ion propulsion system configuration is shown in Figure I-1.

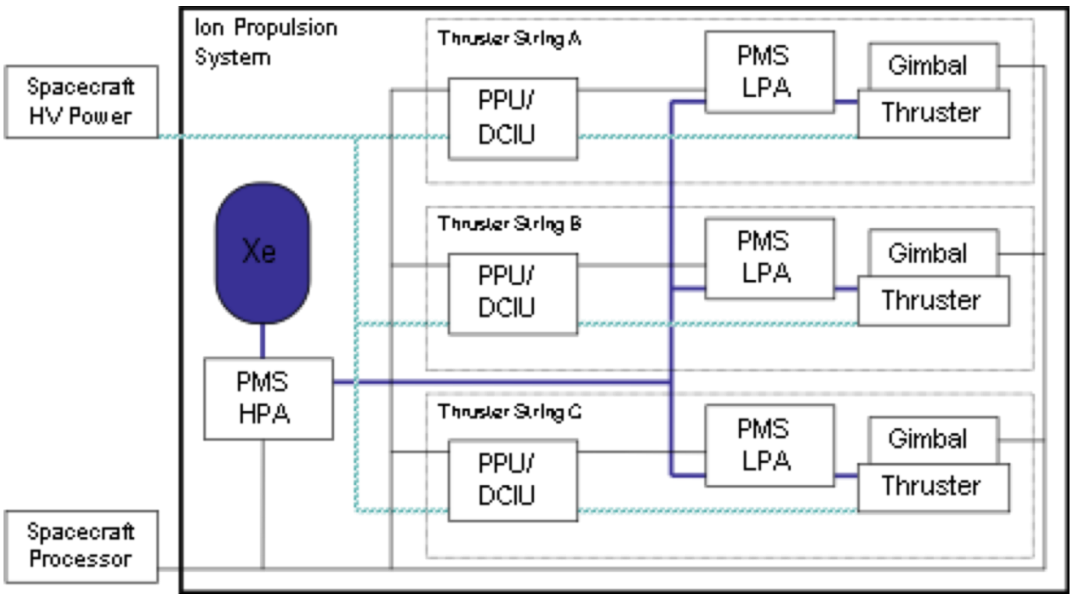

Figure I-1 NEXT Electric Propulsion System Configuration for the Starshade Spacecraft

With the projected mass of the spacecraft and planned telescope/starshade separation distance, two NEXT thrusters must be operated during translation maneuvers. A NEXT Prototype Model thruster is shown in Figure I-2. With only one thruster operating, the translation maneuver durations would increase, thus decreasing the number of target observations achievable in the 5-year primary mission. For example, a single NEXT thruster would accomplish less than 80 target observations (per the groundrules described in I.2). Two NEXT thrusters can process the xenon estimated to be necessary to complete the primary mission, as described in more detail in I.7 below. Thus, additional thrusters are not required for lifetime capability. A third thruster is required to provide single fault

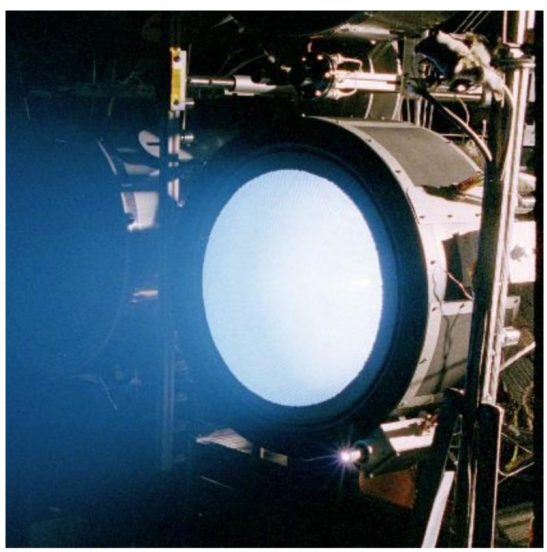
Figure I-2 NEXT PM Thruster in Acceptance Testing

tolerance. The current technical baseline assumes that the spare thruster and remaining capacity of the two primary thrusters is used for the extended mission phase.

Two PPUs are required to power the two operating thrusters, a third PPU provides redundancy. Each PPU can be cross-strapped to two thrusters, such that loss of a thruster or PPU does not negate use of the associated unit in that thruster string. Cross-strapping is not illustrated in Figure I-1 for clarity. The PPU incorporates the functionality of the DCIU, which can also be implemented in a separate unit. The DCIU element of the PPU interfaces to the spacecraft and controls the PPU and LPAs, thus controlling the NEXT thruster within that string. The NEXT EM PPU is shown in Figure I-3.

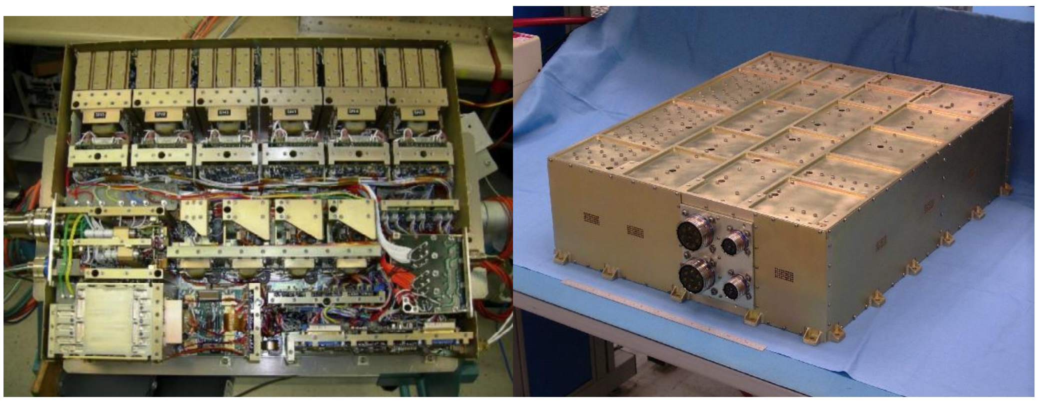

Figure I-3 NEXT EM Power Processing Unit

The propellant management system consists of a single xenon tank, a single NEXT High Pressure Assembly (HPA), a NEXT Low Pressure Assembly (LPA) for each thruster, and assorted service, purge and isolation components (not shown in Figure I.1). The single xenon tank was selected during the MDL definition study; multiple smaller tanks would serve adequately at likely higher mass. The HPA is internally redundant, such that the failure of a critical component does not result in loss of capability. The LPAs also have similar internal failure tolerance capability. The NEXT LPA (upper photo) and HPA EM assemblies are shown in Figure I-4. The HPA is controlled by the spacecraft; this function could also be accommodated in the PPU/DCIU.

Figure I-4 NEXT EM Propellant Management Assemblies

Each thruster has a gimbal to provide thrust vector control for both spacecraft orientation control and attitude control during translation maneuvers. The gimbal is controlled directly by the spacecraft, interfacing to the guidance, navigation and control system. Each gimbal has three actuator motors; the thruster/gimbal can continue to be operated after failure of one motor, though with a smaller range of motion.

A key configuration trade study is the placement of the thrusters on the Starshade Spacecraft, such that all translation maneuvers can be accomplished within the constraints of starshade orientation and full solar exposure of the solar arrays. Initial studies indicate that placement of all three thrusters on one side of the spacecraft, with sufficient gimbal authority, provides the necessary capability. This trade study must be further evaluated as design reference missions are developed.

The system configuration provides single fault tolerance at a minimum. Some failure modes may result in the loss of one “thruster string”, the thruster, gimbal, PPU, and PMS LPA required to operate one thruster. PPU/thruster cross-strapping and internal fault tolerance in the LPA and gimbal provide additional reliability. Additional configuration trade studies should be conducted early in development to establish the desired reliability/redundancy features.

I.6 Key Interfaces

Implementation of electric propulsion on a spacecraft has significant affects on other spacecraft subsystems. The most significant interface is that with the electrical power system (EPS). The electric propulsion system ultimately drives the sizing of the solar arrays and other elements of the EPS. The need to operate two NEXT thrusters at or near full power establishes a requirement that the EPS supply on the order of 14.7 kW of power to the IPS. Further analyses should be conducted to trade solar array size against throttled thruster operation. For example, operating the NEXT thrusters at 90% thrust would reduce the array size required at the expense of increasing the propulsion duty cycle during most translation maneuvers. Number of targets and xenon usage would not be primarily affected. These system level trades can drive out lowest cost and risk solutions.

Electric propulsion also affects interfaces with other elements of the spacecraft, including those summarized below:

- Thermal management: the spacecraft must accommodate heat rejection from the PPUs during powered operations. At full power, this can be on the order of 300 – 350 W of losses per PPU.
- The spacecraft processor interfaces to the DCIU to control and monitor the IPS. There are other additional direct control/data interfaces, such as tank and line heaters, ancilliary valve control, etc.
- The spacecraft GN&C system controls and monitors the gimbal to manage the thrust vectors in support of translation maneuver guidance and spacecraft attitude control.
- The spacecraft navigation system must be designed to support long duration propulsion operations.

I.7 Performance, Life and Margins

The critical elements of ion propulsion system performance for NWO are thruster performance, thruster life, and PPU efficiency. Additionally, throttling capability provides flexibility in implementing translation maneuvers effectively and efficiently.

I.7.1 Thruster Performance

The NEXT thrusters nominally will be operated at full power during NWO Starshade Spacecraft translation maneuvers. The expected thruster performance characteristics at full power at beginning of life include:

- Thrust: 236 mN
- Specific Impulse: 4188 s
- Efficiency: 70.8%
- Total xenon mass flow: 5.76 mg/s
- Input power: 6860 W

Testing of the first prototype model NEXT thruster provided results that met or exceeded these characteristics. [Ref. 8] Over the life of the thruster, thrust and specific impulse are maintained at the expense of input power (efficiency decreases); the projection for thruster efficiency after 300 kg throughput is 70.4%, resulting in an input power increase of only 50 W. The NWO Starshade Spacecraft solar array is sized for end-of-life power to accommodate this minor change.

I.7.2 Thruster Life

As described in sections above, NEXT thruster life capability is a significant factor in selecting NEXT for NWO. Long-life thrusters decrease the thruster count necessary to accomplish this high-ΔV mission. NEXT thruster life is being validated through test and analysis [Refs. 9, 12-15] . A long duration test (LDT) is being performed on a NEXT EM thruster, designated EM3. This thruster replicates to a high degree of fidelity the thruster components that are subjected to known wear mechanisms. The ion optics assembly is the first prototype model (PM) ion optics assembly produced by the NEXT thruster vendor, Aerojet, thus is flight-equivalent hardware. The discharge chamber shape and magnetic field design was fixed between EM and PM thruster designs. The surfaces and components of the neutralizer cathode assembly and discharge cathode assembly that are exposed to wear mechanisms are replicated in nearly all characteristics. The on-going EM3 LDT is thus a critical element in the overall thruster life validation.

Analysis of the LDT data to date, and supporting thruster modeling and analysis, indicate that the first failure will be reached at >750 kg xenon throughput (or xenon expended in propulsive operations). This first failure mode is pit-and-groove erosion of the downstream ion optics electrode surface, resulting in wear-through of the electrode and subsequent mechanical failure. Pit-and-groove erosion is caused by charge-exchange ions generated just outside the thruster sputter-eroding the electrode material. The full power condition is expected to be worst-case for this wear mechanism. Applying a 1.5X qualification factor, the projected mission capability for a NEXT thruster is in excess of 500 kg xenon throughput.

The LDT has exceeded 20,660 hours, 406 kg xenon throughput and 1.56 x 10^7 N-s total impulse as of February 28, 2009. Testing to date indicates that wear mechanism trends and changes in thruster operating characteristics are within expectations. The first 13,000 hours of the LDT was performed at full power, providing substantial trend data for the NWO nominal operating condition. The LDT will return to the full power condition after a sequence of throttled conditions. Extension of the testing at full power is planned as part of the NEXT thruster life validation for NWO, such that 100% of the necessary lifetime at full power, 450 kg xenon throughput, has been demonstrated by test. Failure to meet NEXT thruster lifetime objectives could result in the addition of a thruster, gimbal and feed system LPA to the IPS design, with an associated dry mass growth of less than 25 kg.

I.7.3 PPU Efficiency

PPU efficiency is important because of its impact on two spacecraft systems. High efficiency reduces the solar array size required to run a thruster at full power, and also reduces the PPU waste heat load that the spacecraft must manage. The PPU efficiency at the full power throttle condition and input bus voltage of 100V has been demonstrated to be 94.5% at a PPU baseplate temperature of 25° C, and 94.1 at 50° C for the EM PPU. Efficiency varies with input power, input bus voltage, and PPU temperature.

I.7.4 IPS Throttling

The NEXT system is designed with deep throttling capability for operations in a wide range of heliocentric distances with a fixed solar array size. The high voltage input power per PPU/thruster pair ranges from 680 to 7300 watts over the nominal throttle table. While the NWO Starshade Spacecraft will operate with generally fixed high voltage power to IPS, associated with operations at Earth-Sun L2, throttling capability may be beneficial. NEXT thrusters can operate with specific impulse greater than 4000 seconds over a thruster input power ranging from 2.5 – 6.9 kW. Thus, efficient xenon usage can be maintained under conditions of degraded solar array power output or losses in electrical efficiency. This also allows management of thruster life margins, by allowing operations at conditions better than worst case. NEXT can also be operated in lower power regimes with better thrust-to-power. If trip time between targets becomes an important factor, all three thrusters could be operated (with a fixed total system input power) at a lower power throttle setting with higher thrust-to-power to increase total system thrust by 15 - 20%.

I.7.5 IPS System Margins

The 2+1 NEXT system (2 thruster strings used for primary mission, with a third string for redundancy), with solar arrays sized to provide 14.5 kW high voltage power, is sized to perform the minimum mission of 100 targets in 5 years, with all spacecraft mass contingency growth, using 902 kg of xenon, with a mission translation maneuver ΔV of 7.5 km/s. To characterize the contingencies included in this design point, the electric propulsion and electrical power system performance is analyzed for the current best estimate (CBE) masses generated in the NWO MDL session. The CBE Starshade Spacecraft wet mass was estimated to be 4407 kg, including the 1220 kg xenon load and 476 kg chemical propellant load. Results are summarized in Table I-X.

Table I-4 NWO Starshade Spacecraft Margins

	Starshade Wet Mass, kg	HV Input Power, kW	Xenon Used, kg	Mission ΔV, km/s	Contingency	Overall Xenon Margin
MDL Baseline	5220	14.5	902	7.5	-	35%
CBE Min. Power	4407	**10.6**	904	9.0	36%	35%
CBE Min. Xenon	4407	14.5	**687**	6.6	31%	77%
CBE ΔV Margin	4407	14.5	687	**6.6**	13%	-

For the CBE wet mass, the minimum mission can be performed by a 2+1 system with an input high voltage bus power of approximately 10.6 kW using the same amount of xenon. This is modeled by throttling down the two NEXT thrusters to the minimum necessary to accomplish 100 targets in 5 years. Therefore, the baseline array sizing provides greater than 36% power contingency with respect to the CBE design baseline, ignoring additional contingency built into the array implementation.

At full IPS power, for the CBE wet mass, the minimum mission can be performed by a 2+1 system with only 687 kg of xenon used, for a translation maneuver mission ΔV of 6.6 km/s. The xenon contingency is thus greater than 31% with respect to the nominal mission expenditure; the 1220 kg xenon load provides an overall margin of greater than 77%. The ΔV contingency is greater than 13%.

The current Starshade Spacecraft design concept thus has substantial contingencies incorporated, in all cases in excess of standard MDL practices.

I.7.6 Sensitivity Analyses

Sensitivity analyses were performed to test the sensitivity of the NEXT configuration to variations in driving mission parameters. The parameters defined in section I.3 were used as a baseline, and the following parameters were varied independently, keeping other parameters fixed for each case:

- Initial Wet Mass
- Average Observation Duration
- Average Crossrange Distance
- Number of Observations for the minimum science mission

Note that in this analysis, as related to the margins analysis in section I.7.5, mass, power and propellant values are assumed that represent values after growth margins have been consumed. Also, these parameters are not likely to vary independently, but this analysis illustrates relative sensitivity. Figure I-5 illustrates the results of this analysis, assuming two NEXT thrusters operating at full power for all translation maneuvers.

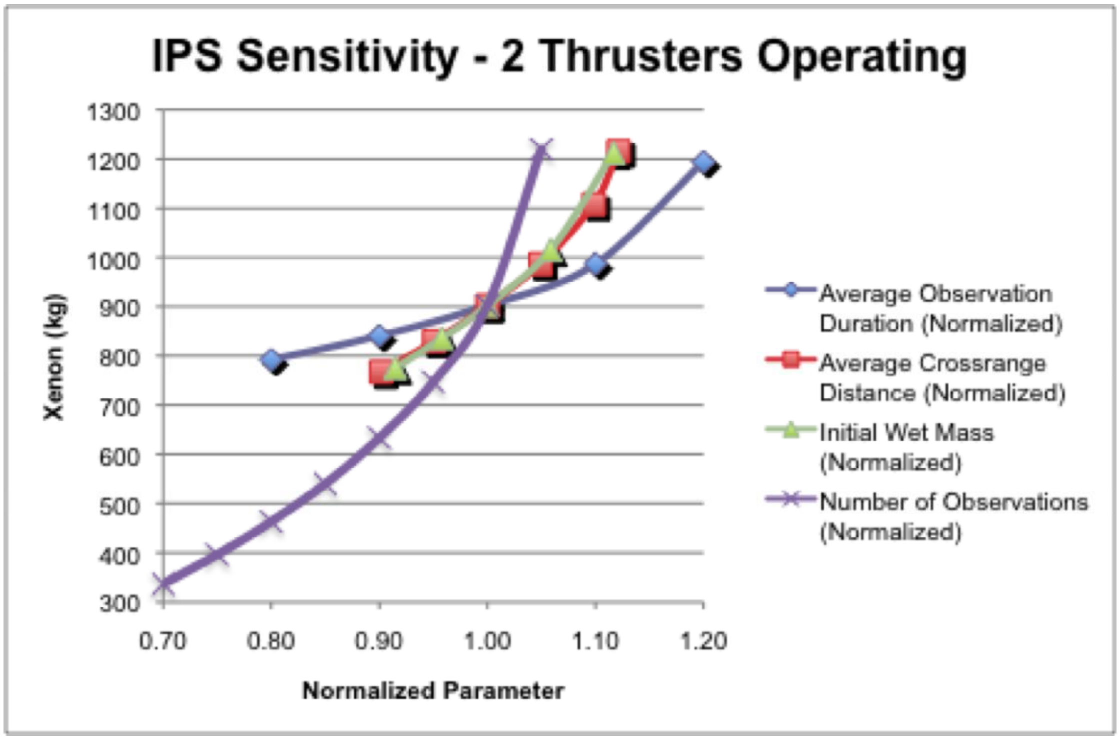

Figure I-5 Sensitivity Analysis Results – 2 Thrusters Operating at Full Power

In this analysis, the 1220 kg xenon load is retained as a constraint. With release of this constraint, results may vary. The most sensitive parameter is the number of observations required for the minimum science mission. This is caused by the resulting duty cycle required when targets are added or subtracted without changing primary mission duration. As targets are added, the IPS must operate for a higher percentage of the available time between observations, until there is insufficient time to execute the maneuvers with two thrusters at 105 observations. Increases in number of required observations is better mitigated by adding primary mission duration time, in which the asymptotic increase is significantly reduced. Average crossrange distance and initial wet mass have similar results in sensitivity. Note that the reference mass used is the mass including 30% growth. Average observation duration is the least sensitive parameter. These results led to consideration of use of three thrusters operating to reduce sensitivities. These results are shown in figure I-6.

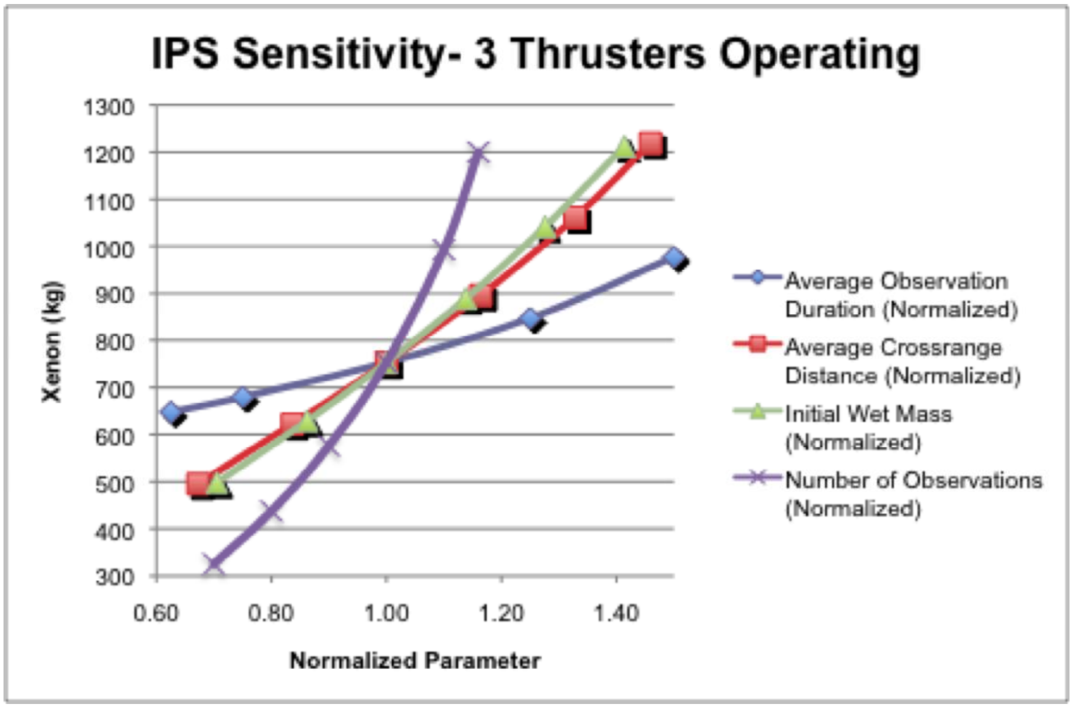

Figure I-6 Sensitivity Analysis Results – 3 Thrusters Operating at Full Power

The results show that three-thruster operations is much less sensitive to most parameters, with change on the order of 40% acceptable within the current xenon load. However, the number of observations that can be accomplished with the assumed xenon load is still a limiting factor.

These analyses illustrate that changes to the IPS configuration, by adding an operating thruster, might be considered if key mission parameters increase significantly beyond the present values, including growth contingency. As noted, increases in the number of observations necessary to accomplish the desired science may cause an increase in mission duration.

I.8 NEXT Operations

The operations concept associated with translation maneuvers and NEXT ion propulsion has a number of attributes that must be considered in the overall mission concept development. Electric propulsion is characterized by long duration propulsive events to accomplish desired spacecraft velocity changes; NWO is no different. The average duration of translation maneuvers for the reference mission described in section I.3 is 14.25 days. Of this time, approximately 4.8 days is spent accelerating the spacecraft, 4.6 days in coast, and 4.8 days decelerating into the target alignment state vector (representative average). The acceleration and deceleration durations are assumed to be continuous, but can be interrupted for communications or navigation periods.
The NEXT thruster requires about 6 – 10 minutes to start from an inactive (cold) state. This has negligible impact on the overall translation maneuver operations. If, however,

NEXT system operations are anticipated in the alignment capture phase, in which switching between thrusters may be necessary, start-up operations must be considered in more detail. There are additional operating modes of partial power, in which thrust is not provided, that allow quicker transition to full thrust, but these modes also consume xenon. Shutdown is relatively rapid and would not impact the overall spacecraft operations timelines.
In addition to nominal operations, the electric propulsion system will go through a thorough checkout after launch. This can be accomplished after solar array deployment, during spacecraft transfer to the L2 point

I.9 NEXT Technology Development Status

This section reviews the status of the NEXT technology development in relation to NWO mission requirements. Technology readiness and roadmap is addressed in Appendix R.

The motivation of the NEXT project is to develop a highly capable, ion propulsion system. The objectives were to develop an evolutionary design with strong heritage to a flight-demonstrated IPS. Advancements would address key limitations to SOA design (NSTAR), namely through increased throughput, increased power throttle range, increased performance and improved system mass. The status of the individual components is provided as well as the status of the system level demonstrations.

I.9.1 Thruster
A laboratory model 40-cm diameter ion thruster developed in 2001 provided the basis for the engineering and prototype-model ion thruster designs. GRC subsequently developed the EM design. Aerojet developed the PM design, under contract to GRC, with the objective to mature NEXT thruster design to ensure full-compliance with structural and thermal requirements and to improve thruster manufacturability. [Ref. 16] Aerojet delivered the PM1 thruster to GRC following flight-level design and fabrication processes.

GRC successfully completed performance acceptance testing followed by a comprehensive environmental test sequence at JPL. GRC and JPL completed two cycles of acceptance and environmental tests in order to resolve minor design issues with thruster rework. The reworked thruster used in the second cycle of environmental tests was designated PM1R. Thruster environmental testing included a thermal balance test to gather key thruster temperature maps over a wide range of operating and environmental conditions. [Ref. 17] Information was used to develop and validate a thruster thermal model and demonstrate temperature margins over a large temperature range. Vibration of the thruster/gimbal assembly to qualification-level vibration environments (10.0 Grms for two minutes in each axis) was completed with no changes in thruster performance functionality. [Ref. 18] Thermal-vacuum tests were completed to qualification levels with a lower temperature limit set < -120ºC (cold), and an upper temperature limit set > 215ºC (hot). The thruster was subjected to three cycles with hot and cold dwell and was started at both hot and cold temperature limits. [Ref. 18]

I.9.2 Power Processing Unit (PPU)

L-3 Communications completed the engineering model PPU. Initial functional testing integrated with a thruster was successful overall, but identified an issue with a low voltage output supply to the thruster. The supply was redesigned and successfully implemented in a PPU rework. Functional testing at vacuum, with the PPU baseplate temperature controlled at 25 and 50° C was successfully completed. [Ref. 19] The PPU was integrated into the NEXT System Integration Test prior to full environmental testing. During integration testing, the PPU suffered a part failure in the output circuit of the high voltage beam supply module. The PPU has been repaired and is back in performance/functional testing. After retest with the PM thruster, and completion of additional system integration testing objectives, the PPU will be sent to JPL for a comprehensive series of environmental tests. The environmental tests include qualification-level vibration tests with post-vibration functionality test, qualification-level thermal/vacuum test with post-thermal/vacuum functionality test, and electromagnetic interference/electromagnetic compatibility (EMI/EMC) tests. PPU environmental testing is planned to be complete in FY2009.

I.9.3 Propellant Management System (PMS)

Aerojet completed all engineering model PMS assemblies, including two High Pressure Assemblies (HPAs), with one flight-like assembly, and three Low Pressure Assemblies (LPAs) with one flight-like assembly. [Refs. 16, 20] The non-flight assemblies are identical except for use of lower-cost equivalent parts. All assemblies completed functionality tests. Flight-like LPA and HPA successfully completed qualification-level environmental tests. The environmental tests included qualification-level vibration tests (at 14.1 Grms for 2 minutes in each axis) and post-vibration functionality tests as well as qualification-level thermal/vacuum tests (+12º to +70ºC temperature range for three cycles). The EM PMS was delivered to NASA for use in system integration tests.

I.9.4 Digital Control Interface Unit (DCIU)

DCIU simulators were completed and are used in system-level tests. The simulator is laptop-based test equipment with EM-level PMS pressure loop control cards. The simulator is capable of operating a three-thruster string system. The DCIU simulator validates control algorithms and PMS control card and supports PPU input/output tests, PMS control during test, single-string and multi-string integration tests.

A brassboard DCIU card, designed for integration into the NEXT PPU, is in development through a separate task in the In-Space Propulsion Technology project. Production is currently in progress, with functional testing with the EM PPU, a simplified version of the NEXT PMS and a NEXT EM thruster planned in FY 2009. This product will serve as a departure point for development of the combined PPU/DCIU planned for the NWO system.

I.9.5 Gimbal

ATK (Swales Aerospace) designed and fabricated the breadboard gimbal. It is a flight-like design using JPL-approved materials with certifications. Stepper motors have a space-rated option. The gimbal successfully completed functionality tests with the PM1R engine. The gimbal passed two qualification-level vibration tests and low-level shock tests with minor issues. This establishes a baseline design, with few modifications needed to move into a qualification program. The NEXT gimbal in preparation for vibration testing with a thruster mass model is shown in Figure I-7.

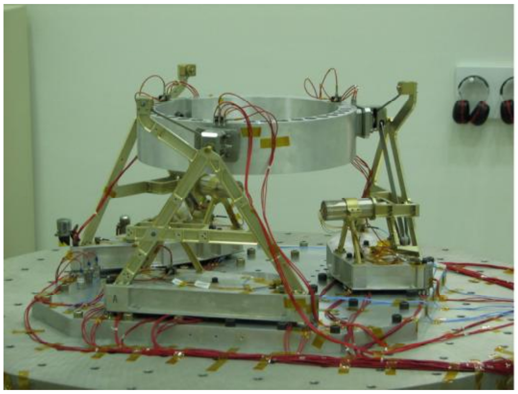

Figure I-7 NEXT Breadboard Model Gimbal with Thruster Mass Model

I.9.6 System/Integration Tests

The three test activities categorized as system-level tests are multi-thruster array tests, single-string system integration tests and multi-thruster integration tests. The objective of the multi-thruster array test was to assess thruster and plasma interactions with sensitivities to thruster spacing, gimbaled thrusters and neutralizer operating modes. The configuration included four GRC EM thrusters; three operating and one instrumented non-operating as well as an extensive suite of diagnostics to collect data for multi-thruster system modeling and analyses. The multi-thruster array test was completed in December 2005 and included single, dual, and triple thruster operations. Initial data indicate expected thruster performance was achieved and thruster operations were understood without significant sensitivity to system configuration. [Refs. 21-25]

The scope of the single-string system integration test is to verify that the integrated system of NEXT components meets the project requirements in a relevant environment. The primary objectives are to demonstrate:

- operation of the thruster over the throttle table with PPU and PMS,
- operation of system at off-nominal conditions, and
- recycle and fault protection operation.

The test configuration includes the PM thruster, EM PPU, EM PMS, as well as the DCIU simulator. The test was completed in September 2008, with additional PPU/thruster integration validation occurring after completion of the PPU part failure recovery and unit re-test. Results of the testing are in thorough analysis by GRC and JPL, to determine whether the elements function properly in a system configuration and comply with all system level requirements.

Multi-thruster Integration Testing was performed for a three-thruster, three-LPA system configuration. This test was completed successfully. Data analysis is in progress and will be included in the single-string system integration test results assessment.

I.9.7 Planned Work

The project is working towards a Phase 2 Project final review in the spring of 2009, which will accomplish the objectives of a Technology Maturity Assessment. The following project tasks are in work to support this review:

- PPU environmental testing
- Short duration wear test of the PM1R thruster
- Continuation of EM3 LDT
- Completion of project documentation
- Completion of analyses required to support requirement verifications

For the final review, a group of peers will present and review the entirety of the Phase 2 development activities to establish the TRL of the system. {Ref. 26] In addition, the group will identify, assess and prioritize any perceived risk reduction items so that the balance of project resources, available after the completion of all Phase 2 tasks, will be applied to ISPT-funded risk reduction activities in FY09/FY10. In addition to risk reduction work, ISPT will fund the EM3 LDT continuation through FY10. Additional LDT extension will likely be performed under NWO, as described in section I.7.2.

I.10 NEXT Flight System Development Plan

A development plan for the Starshade Spacecraft NEXT ion propulsion system was developed and integrated into the overall mission implementation concept during the MDL.

I.10.1 IPS Team

The development team for the ion propulsion system is planned to be composed of NASA Glenn Research Center and Starshade Spacecraft prime contractor team members. GRC's participation will ensure that the technology is correctly transferred to flight implementation with minimum risk due to design/hardware changes. The responsibility for each element would be determined through a make/buy process during the early phases of development. As a reference, the current model is for NASA GRC to develop the thrusters and PPUs for the flight system, and provide to the spacecraft prime for integration. The spacecraft prime would develop the xenon tank and feed system elements and the gimbal.

I.10.2 Hardware Development Approach

The NWO Starshade Spacecraft is assumed to be the first flight of NEXT technologies for the purpose of this development model. If NEXT is selected for other missions, tailoring of this approach is warranted.

With the initial transfer of NEXT TRL6 technology to a flagship-class flight project, a full hardware qualification program is warranted. The development model assumes a qualification build and test element for the thruster, PPU, xenon tank, feed system HPA and LPA, and gimbal. Qualification testing of the thruster will be performed jointly by the thruster vendor and NASA GRC, as large vacuum facilities are necessary for some tests. Qualification testing of the other system elements will be performed by the element vendor. In addition to the standard qualification test program, the following key tests will be performed:

- Thruster/PPU Integration Test: This test is critical in demonstrating successful functionality of the combined units. The test will be performed at NASA GRC.
- Thruster Wear Test: A wear test of the QM thruster will support validation that long duration testing performed on the earlier-generation thruster supports flight thruster lifetime verification. This test will be performed at NASA GRC.
- PPU/PMS Integration Test: This test will verify the interface between the DCIU functionality incorporated into the PPU and the feed system elements. This test will be performed at the spacecraft prime contractor.

A hardware sparing approach was defined to support the flagship-class criteria, as summarized below:

- Thruster: spare flight thruster, plus spare critical sub-assemblies including ion optics and hollow cathode assemblies. These sub-assemblies are the highest risk to receive damage in processing and testing. The QM thruster, with substantial testing performed, would require substantial refurbishment prior to use as a spare flight unit.
- PPU: spare flight unit. The QM PPU could be considered a spare with some additional risk.
- PMS LPA: spare flight unit, with additional spare critical components.
- PMS HPA: spare critical components.
- Xenon Tank: the QM is assumed to be the spare unit
- Gimbal: spare flight unit

The flight hardware would be delivered to the spacecraft prime contractor, after unit level acceptance testing, for final integration into the Starshade Spacecraft bus. An end-to-end propulsion system hot fire test is performed at the bus-level, prior to integration of the starshade and other payload items.

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