
Asteroid Initiative Discussion

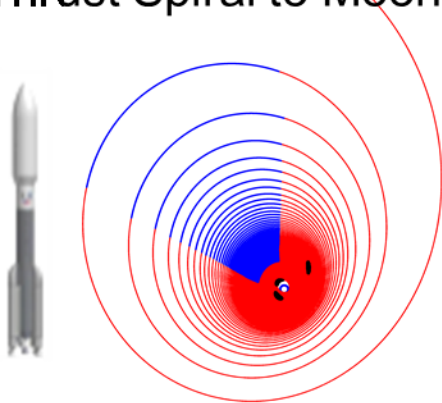
- Asteroid Redirect Mission – Point of Departure
(MSFC supported mission design and xenon propellant tank trades)
- Alternatives (Mission, propulsion*, capture)
(MSFC supporting all alternative teams at various levels)
- RFI: Locate, redirect, and explore an asteroid, as well as find and plan for asteroid threats
- Grand Challenge: “Final all asteroid threats to human populations and know what to do about them”

*Propulsion extensibility to Mars was weak

Point of Departure

1. Launch (2 Options)

1a. *Atlas V* – Low Thrust Spiral to Moon



1b. *SLS, Falcon Heavy* – Direct Launch to Moon or to Asteroid



4. Low Thrust Trajectory with Asteroid to Earth-Moon System

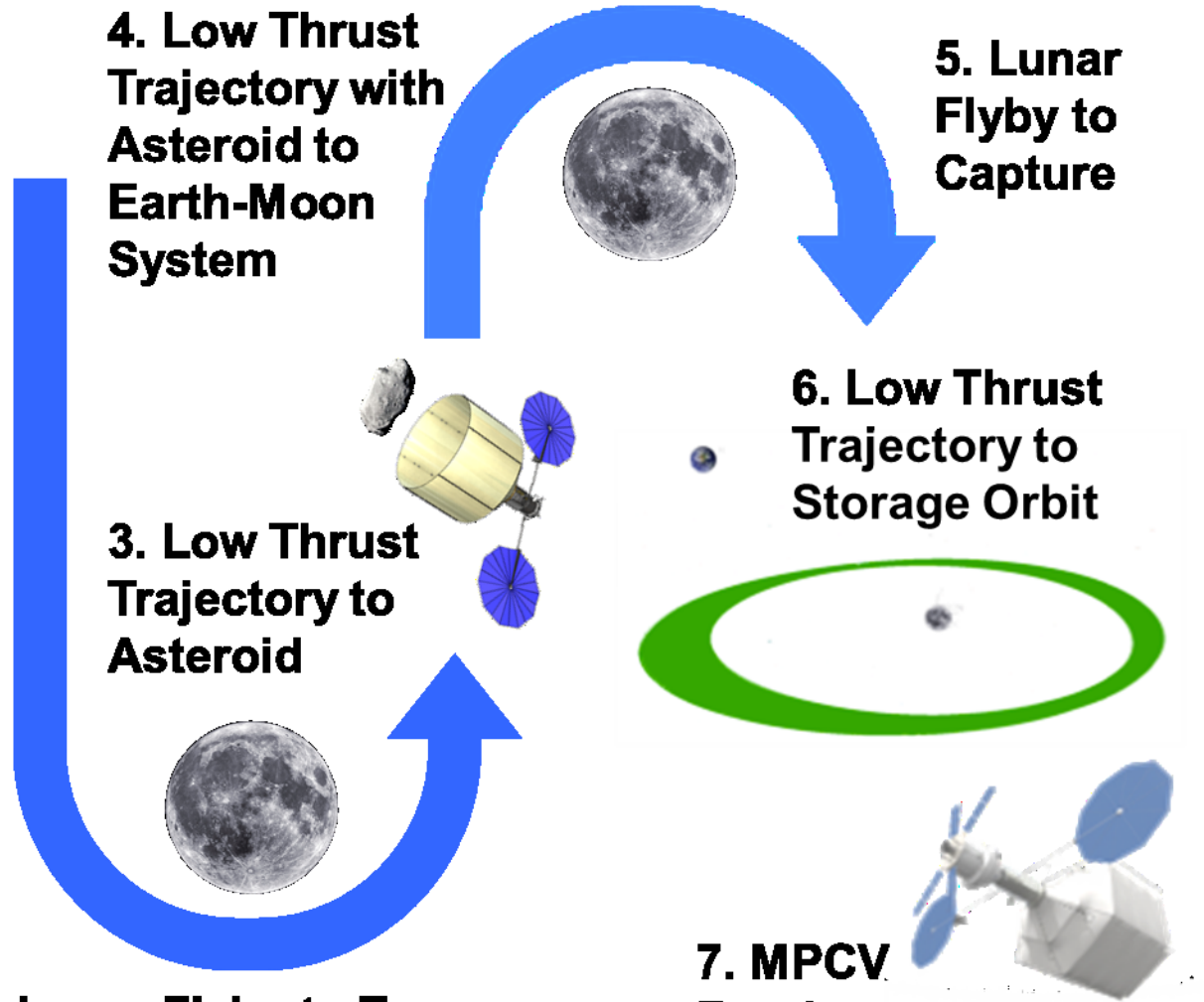
3. Low Thrust Trajectory to Asteroid

2. Lunar Flyby to Escape
(If Needed)

5. Lunar Flyby to Capture

6. Low Thrust Trajectory to Storage Orbit

7. MPCV Rendezvous



Three Key Aspects of the (ARRM) Mission

Observation Campaign

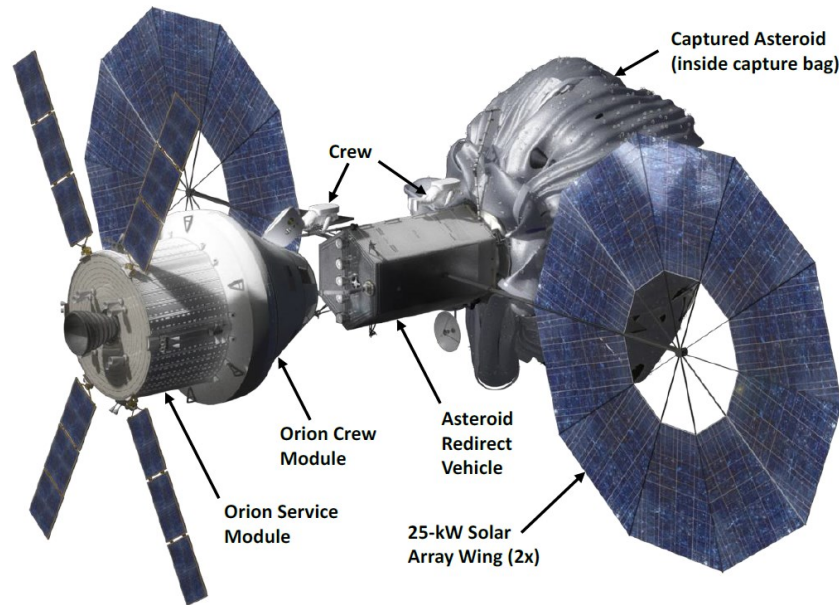
- Discovery and characterize targets

Asteroid Redirect Mission (ARM)

- Capture and return an entire NEA by 2025

Asteroid Redirect and Utilization Mission (ARUM)

- Rendezvous with an asteroid in cis-lunar space using SLS/Orion, inspect, sample, assess internal structure and resource potential



Small Bodies Assessment Group Findings

ARRM Mission Objectives: Objectives are not well defined. Level 1 requirements are not firm. Gerstenmaier stated an asteroid does not need to be returned. An independent Mission Definition Team to define the overall objectives and mission success criteria would be value added. Also concerns regarding management approach. Joint mission for HEOMD, STMD, and SMD. Who pays of over-runs? What if technology is de-scoped to reduce cost/risk?

Finding a target: Concerns of finding a viable target. Limited observations, targets have been lost (poor OCC), characterization is challenging and afterwards still leaves significant uncertainty in mass, size, tumbling, etc.

Planetary Defense: ARRM has limited relevance given the target size $<10\text{m}$.

Establishment of a Planetary Defense Office would more effectively interface with grand challenge entities and provide guidance for an asteroid redirect mission with respect to planetary defense objectives. MSFC is well positioned for a field office comparable to JSC's orbital debris office.

NEO Survey Telescope: A NEO survey telescope is a foundational asset in the critical path for NASA's primary objectives: human exploration, science, resource utilization, and planetary defense. However, a third part, outside of NASA's control, is in the critical path of meeting NASA's congressional mandate in addition to overarching objectives.

Schedule / Funding Profile: (Haven't been presented publicly). OSIRIS-REX is $>\$1\text{B}$, but ARRM is $<\$1\text{B}$. Funding begins in FY14 for a launch is FY17 or FY18 with subsystems that still require significant development. Schedule is unjustifiably aggressive. If we don't need to return an asteroid, why do we not need to return an asteroid by end of 2024? What is different from the COMPASS assumptions $\$2.6\text{B}$?

Target uncertainty and target characterization are the critical drivers.

Technologies Applicable for Asteroid Initiative

Technical requirements for asteroid initiative are still undefined.

However, the Asteroid Retrieval Mission or Alternatives is under consideration for a proposed multi-mission directorate activity specifically with Space Technology Mission Directorate (STMD) to demonstrate new technologies and operations.

New Technologies / Operations to be validated previously identified/planned by NASA:

- High power solar array technology^a
- High power solar electric propulsion^b
- NEO Proximity Operations^c
- Human NEO Interaction / Operations^d
- Asteroid capture/anchoring technologies^e

New Technologies / Operations potentially unique for baseline ARM or alternatives:

- Asteroid capture mechanism
 - Whole asteroid – likely a point design for a single mission
 - Piece of a larger asteroid – potentially applicable to future missions
- Planetary defense techniques

Asteroid initiative demonstrates a range of technologies currently under development and high priority objectives.

Mission unique technology/system development is also required.

Technologies Applicable for Asteroid Initiative

- a: TA03 Space Power and Energy Storage
 - 3.1.3 – High specific mass and high power density
 - 3.3.3 – Power distribution and transmission; increase D&T voltage
 - 3.3.5 – Power conversion and regulation; space qualify higher voltage components
- b: TA02 In-Space Propulsion
 - 2.2.1 – Electric Propulsion
 - Components for high capacity power processing units, understanding of wear mechanisms to full-length life tests are not always necessary, characterizing EP/spacecraft interactions, infrastructure to test high-power EP on the ground, demonstrating autonomous operation and control of high-power, large-scale EP systems in space.
- c: TA04 Robotics, Tele-Robotics, and Autonomous Systems
 - 4.1 Sensing and Perception, 4.3 Manipulation, 4.5 Autonomy, 4.6, Autonomous Rendezvous and Docking,
 - 4.6.3 – Docking and Capture Mechanisms / Interfaces
 - Enable grapple/capture of inactive, possibly tumbling bodies
- d: TA04 Robotics, Tele-Robotics, and Autonomous Systems, TA06 Human Health, Life Support, and Habitation Systems, TA07 Human Exploration Destination Systems
 - 4.4 Human Systems Integration, 6.2 Extravehicular Activity Systems, 7.1 In-Situ Resource Utilization,
 - 6.2.2 Portable Life Support System
 - Extended functionality, increased capability, reliability, and maintainability...long-term effect of dust on asteroids
- e: TA04 Robotics, Tele-Robotics, and Autonomous Systems, TA07 Human Exploration Destination Systems
 - 4.2.4 Small Body / Microgravity Mobility
 - 7.3.2 Surface mobility technology
 - 7.3.2.3 Berthing and Anchoring for application to NEAs

Non-exhaustive list highlights applicability / demonstration of NASA independently derived objectives and NRC recommendations. Also indicates known technology gaps.

Mission Design / Drivers

Target identification / characterization

- Asteroid mass uncertainty
 - Uncertainty in dimensions
 - Uncertainty in density
- Asteroid natural return date and V_{∞}
- Launch date and return date constraints

Dimensions Uncertainty ~30-40% for small NEAs

Density Uncertainty ~50% due to porosity

→ Mass factor of ~4 for most objects of this class

Multiple observations over months to years can resolve mass to ~50%.

Diameter (m)	Asteroid Mass (kg)		
	1.9 g/cm ³	2.8 g/cm ³	3.8 g/cm ³
2.0	7,959	11,729	15,917
2.5	15,544	22,907	31,089
3.0	26,861	39,584	53,721
3.5	42,654	62,858	85,307
4.0	63,670	93,829	127,339
4.5	90,655	133,596	181,309
5.0	124,355	183,260	248,709
5.5	165,516	243,918	331,032
6.0	214,885	316,673	429,770
6.5	273,207	402,621	546,415
7.0	341,229	502,864	682,459
7.5	419,697	618,501	839,394
8.0	509,357	750,631	1,018,714
8.5	610,955	900,354	1,221,909
9.0	725,237	1,068,770	1,450,473
9.5	852,949	1,256,977	1,705,898
10.0	994,838	1,466,077	1,989,675

Notional Mass Uncertainty.²

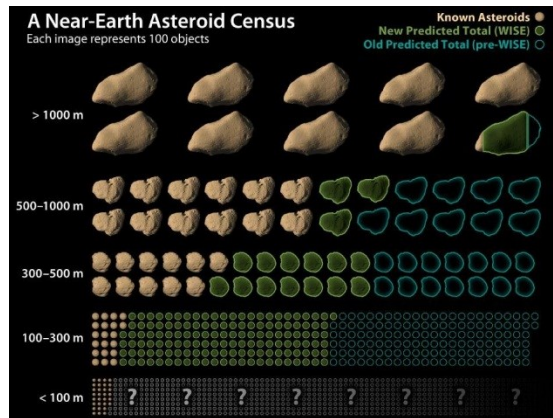


Image Credit NASA / JPL / Caltech

	Existence Proof Targets	Absolute Magnitude	Return Date	Return Mass
Whole Asteroids	2008 HU4	28.223	April, 2025	1300 MT
	2009 BD	28.213	June, 2023	1080 MT
	2011 MD	28.073	July, 2024	690 MT
Piece of Asteroid	1998 SF36*	19.2 (330m)	March, 2024	14MT
	1998 KY26	25.551 (30m)	November, 2025	67 MT
	2000 SG344	24.799	July, 2024	230 MT
	2000 SG344	24.799	September, 2029	3600 MT

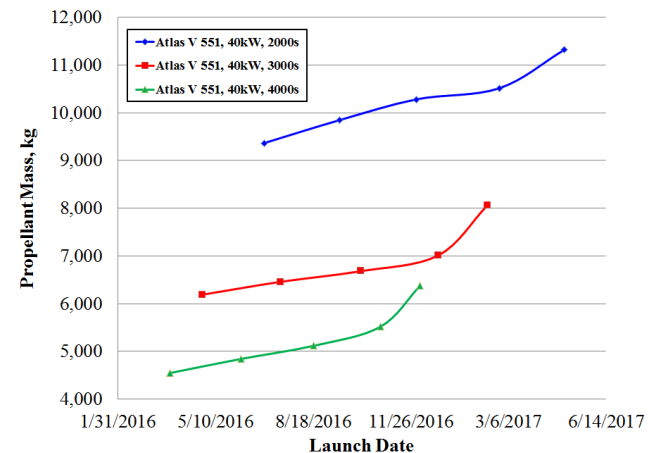
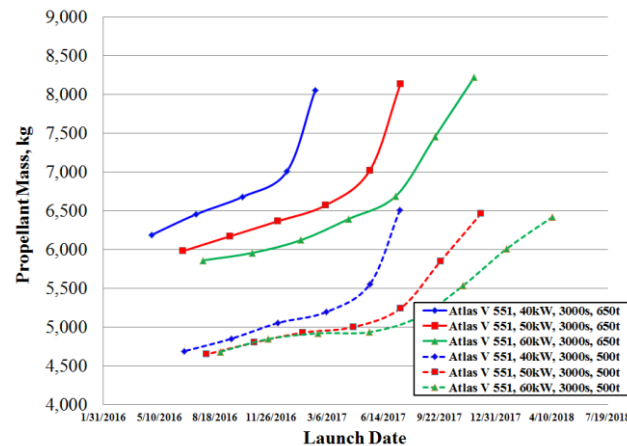
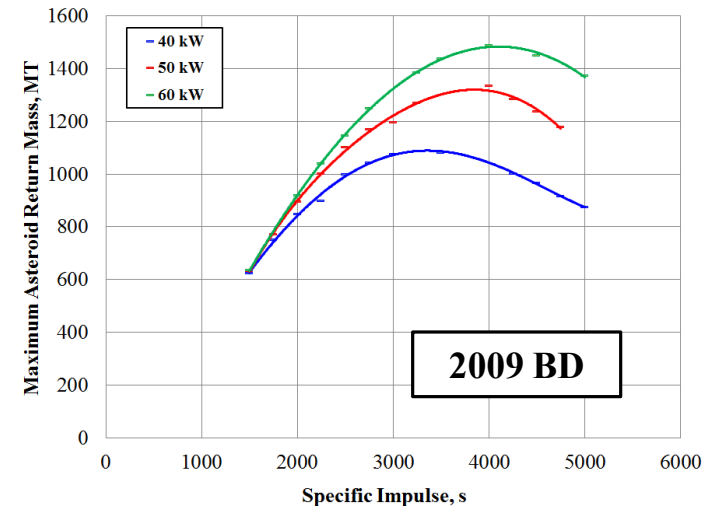
*Known Surface Boulders of this Scale

Target uncertainty and target characterization are the critical drivers.

Mission Design / Drivers

All results are target, dates, constraints specific:

- Propellant mass requirement increases with asteroid mass
- Propellant requirement increases with decreasing specific impulse
- Maximum asteroid return mass has an optimal I_{SP} (Increases with available power). For one case evaluated:
 - ~3250s at 40kW into the thruster (~3000s at 40kW into PPU)
 - ~3750s at 50kW into the thruster
 - ~4000s at 60kW into the thruster
- Shorter mission durations and launch/return date constraints increase propellant requirement



The mission drivers are target specific with system trades for power and propulsion.

Propulsion

(Requirements / Drivers / SOA)

Requirements:

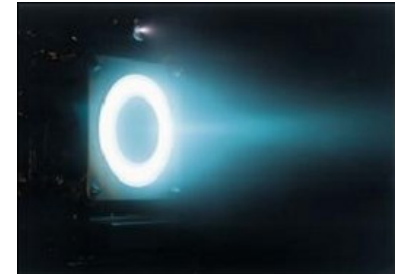
40-50kW Input power, ~3000s Specific Impulse, system $\eta > 60\%$, over 0.7AU to 1.3AU³ and ~10,000kg of Xenon throughput capability².

- Assumed 4x 10-12.5kW input power per propulsion string²
- Assumed to be Hall thruster technology

SOA:

Aerojet BPT-4000 Hall thruster

- 2076s Specific Impulse
- 4.5kW



Drivers:

Launch and departure time constraints, target orbital characteristics and properties

Gaps from SOA:

3000s Specific Impulse at 10-12kW with stated lifetime goals

Life testing methodology:

Standard practice would take >10 years at 80% duty cycle for 150% Life demonstration

Life test facility background pressure – High 10^{-6} Torr at NASA GRC

Carbon deposition / impact to life testing



Additional Comment:

Power Processing Unit (PPU) / System Development Schedule:

Historically long development times

Production unit delivery schedule is 24-30 months due to EEE parts lead times

Production unit ordered today with delivery 1 year prior to launch is launch NET July, 2017

Propulsion

(Recent Relevant Work)

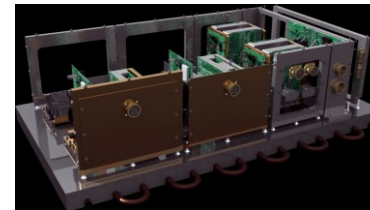
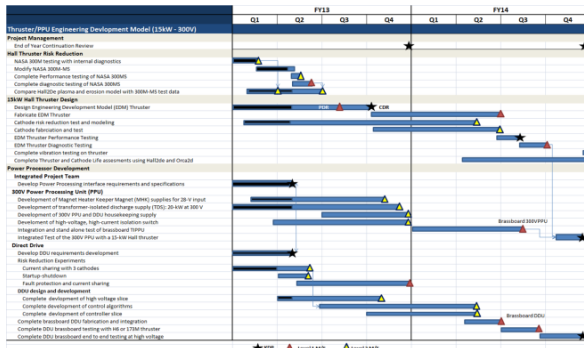
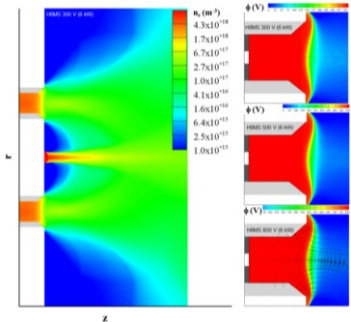
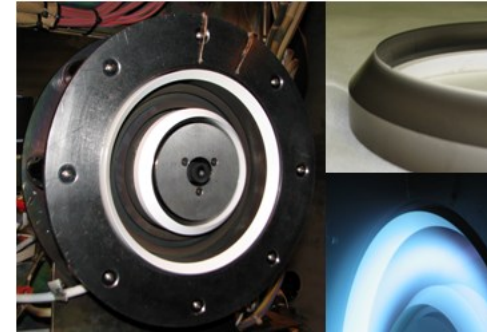
Game Changing Development: Space Power Systems Project – Electric Propulsion Technologies⁵

Goal's:

- Develop high power Hall thruster (15kW-class) and system components for 30kW class (2000s)
- Pursue high input voltage (i.e. 300V) PPU/DDU system compatible with Hall thruster and advanced solar array development
- Life commensurate with mission (~ ???kg per thruster)

Path Forward:

- Designing and building 15kW EDU at GRC
- Incorporating recent AFRL and NASA thruster designs
 - Developing large set of test data related to high power thruster performance
 - Developing physics-based models of performance and key failure modes
 - Designing and building high input voltage PPU (300V) EDU at GRC
- Designing and building high input voltage Direct Drive (300V) EDU at GRC with test at JPL
- Integrating Thruster EDU and PPU and DDU for test by end of FY14



Potentially applicable propulsion system development underway with FY14 integrated testing.

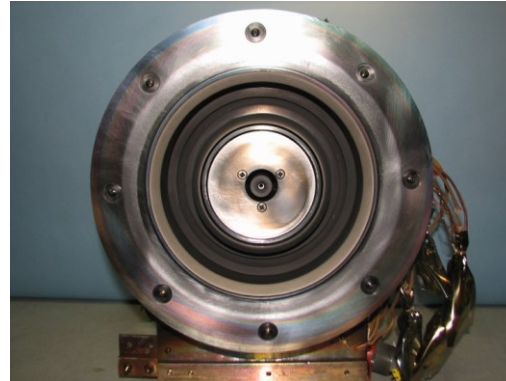
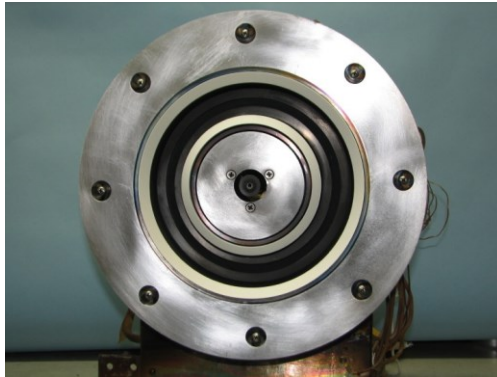
Propulsion

(Recent Relevant Work)

JPL H6 Magnetic Shielding Testing and Analyses⁶

Under STMD, H6 Hall Thruster with Magnetic Shielding (H6MS) tested > 100 hours at 3000s and 9kW
Steady-state thermal characterization completed at 9kW (High power density)

Tested at Owen Chamber (JPL) – Background Pressure 1×10^{-5} Torr



H6MS before (left) and after (right) 113 hours at 3000s 9kW operation.

Agreement with performance and life expectation using physics based modeling
Quartz-crystal microbalance and witness plates measured $0.0025 \mu\text{m/h}$ carbon deposition. (Projected life > 30,000 hours)

Performance measured: ~386mN of Thrust
Calculated: ~3000s Specific Impulse
~62% Efficiency

H6MS laboratory thruster demonstrated performance and predicts lifetimes commensurate with Asteroid Initiative goals.

Propulsion

(Recent Relevant Work)

12kW Hall Thruster Development Occurred through 2009 under Air Force Transformational Satellite Communication Systems (TSAT) Program

Initiated development of an integrated Hall system

- Thruster
- Cathode
- Power Processing Unit
- Xenon Flow Controller

Demonstrated 1100s – 2300s specific impulse (Higher I_{SP} possible)

Completed 2,600 hour cathode life test

Completed 400 hour thruster life test; predicted > 20,000 hour life

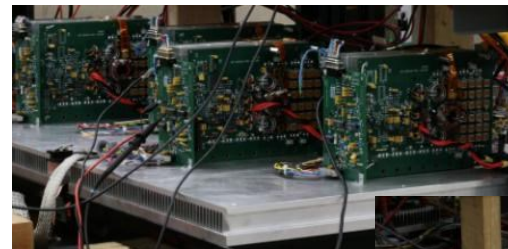
Completed flight thruster and cathode design

Completed structural and thermal analyses

Completed 12kW bread-board PPU

Initiated Engineering Model PPU design / potentially ready for flight design effort

Thruster may be available for life testing with minimal start-up schedule



Significant progress previously demonstrated towards 12kW class thruster.

Propulsion

(Recent Relevant Work)

Commercial Hall thruster designed and built by Busek w/ USAF funding (TRL 5)

Testing at Busek (T-8), AEDC (12V) and NASA-GRC (VF5)

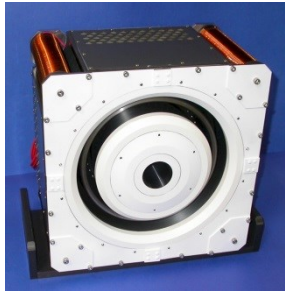
Highly throttle-able from 5 to 20 kW

Total Isp > 2500 s at P > 10 kW, 500 V (Isp > 3000s possible)

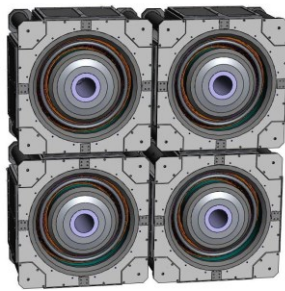
Peak thrust ~ 1.1 N

Total efficiency is 60-64 % at P > 10 kW and Isp > 2300 s

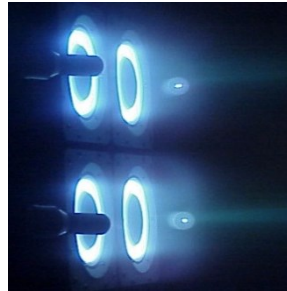
Predicted lifetime >> 20,000 hrs



Single Thruster: BHT-20K



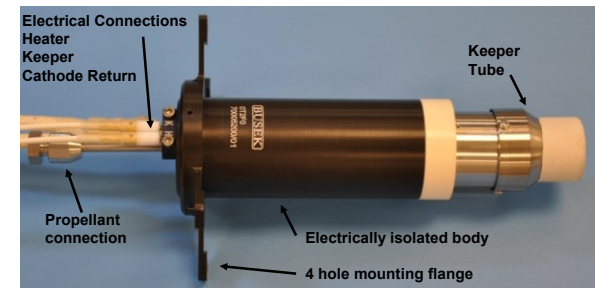
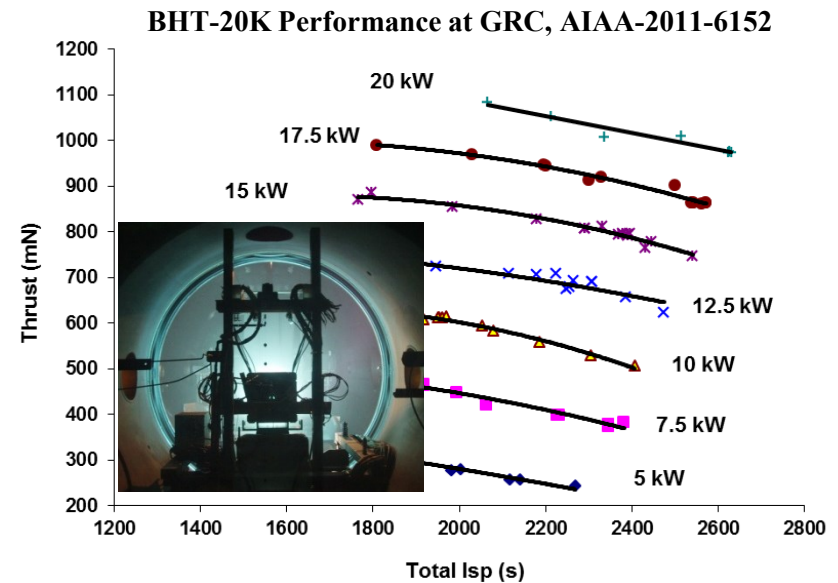
Cluster: 40-80 kW
Fully redundant at 40 kW



Busek & U. Michigan Cluster
Demonstration

- High efficiency, high input voltage PPU under development
 - 3.5 kW, 80-160 V input, 200-700 V output breadboard demonstrated
 - Modular architecture → P > 10 kW

PPU
Components



Busek
Hollow
Cathode

- Flight model center-mounted hollow cathode developed
 - NASA based Ba-W electron emitter
 - >250 hrs demonstrated w/ thruster operating at 20 kW, 200-600V
 - Lifetime > 33,000 hrs predicted at current >100A (L-3 ETI model)

Engineering/flight model system being developed under NASA funded programs

Power

(Requirements / Drivers / SOA)

Requirements: 40-50kW Power Generation with availability no later than June, 2018³

Desired: Specific Power > 125W/kg
 Stiffness > 0.1 Hz
 Acceleration Limit: > 0.1g
 Stowed Stiffness: ?? > 25Hz
 Stowed Volume: Configuration Dependent

Drivers: Array voltage, cell efficiency, specific power, packaging and stowage density

Gaps: All specifications have been demonstrated at lower absolute power, and lower specific power

The higher power COMSATS are >20kW

Standard voltages ~100V

Technology efforts:

- Higher voltage
- Low cost Inverted Metamorphic Multijunction (IMM) cell production
- Etc.

Technology paths identified to achieve higher performance solar power, but none appear to be required.

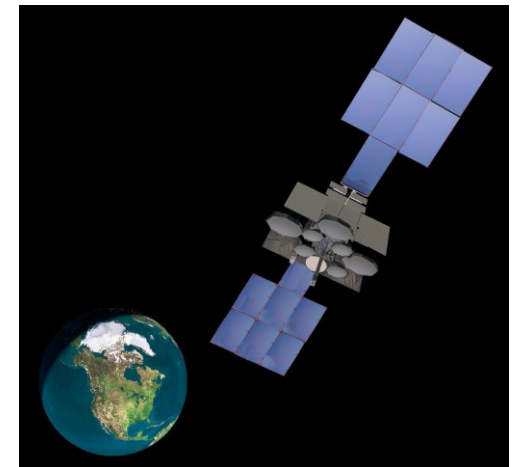
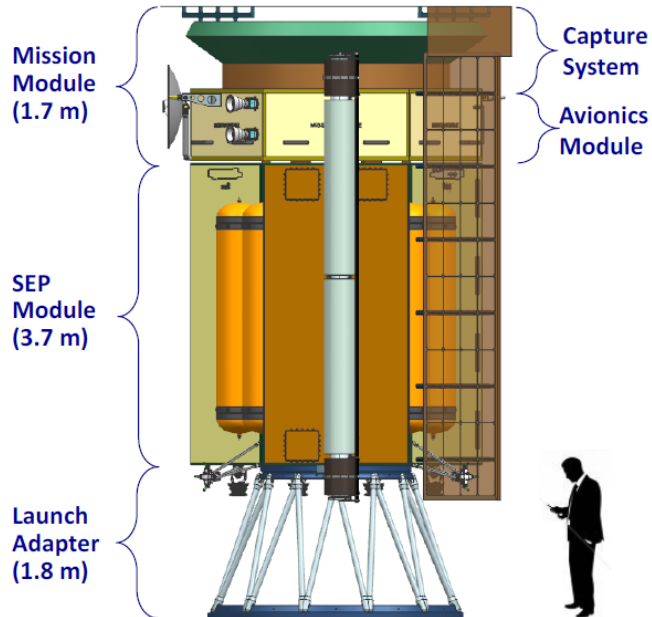
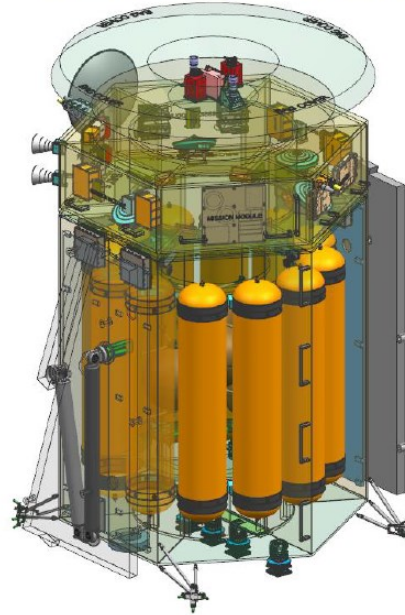


Image Credit Boeing

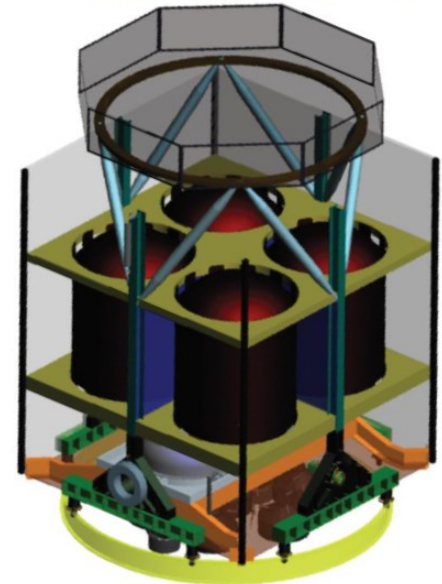
Propellant Tanks



12-Tank Configuration
Seamless Al-lined COPVs



4-Tank Configuration
Welded-Al liner COPVs



Xenon acquisition is NOT an issue

Power

(Recent Relevant Progress)

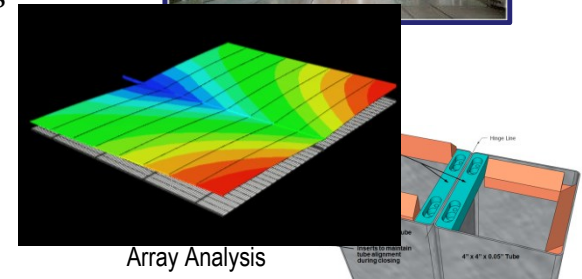
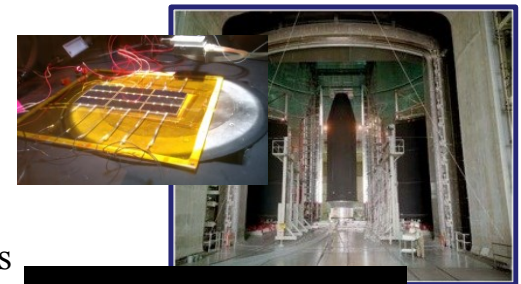
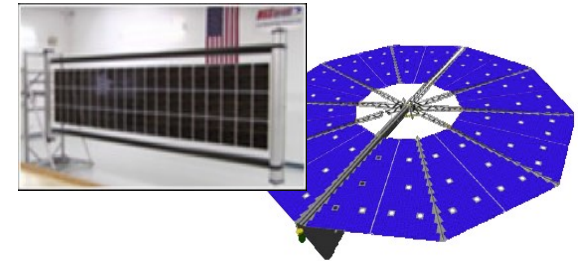
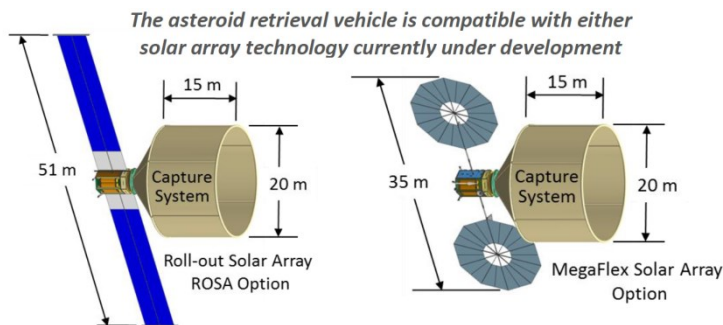
Solar Power Technology Development (NASA – Game Changing)⁷

Goal's:

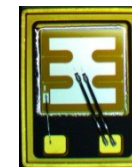
- Develop reliably deployable high power solar arrays (30kW-class)
- Operate at high voltage (160-300V) with high strength/stiffness
- Stowed volume commensurate with mission (> 80kW/m³ for 50kW class)

Path Forward (FY13/FY14 Activities):

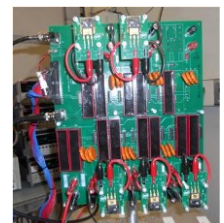
- Designing and building 30kW-class Solar Array EDUs
 - MegaFlex and Mega-ROSA designs
 - Coupon plasma testing for electric thruster environment
 - Thermal-vacuum testing planned for spring 2014
- Developing analysis models and tools to evaluate very large solar array designs
- Destructive single-event upset testing planned for summer 2013
 - SiC transistors, diodes, bridge drivers, and gate drivers



Array Analysis



Parts Characterization



Solar array system options currently under development through STMD, and potentially other options, are compatible with ARM requirements.

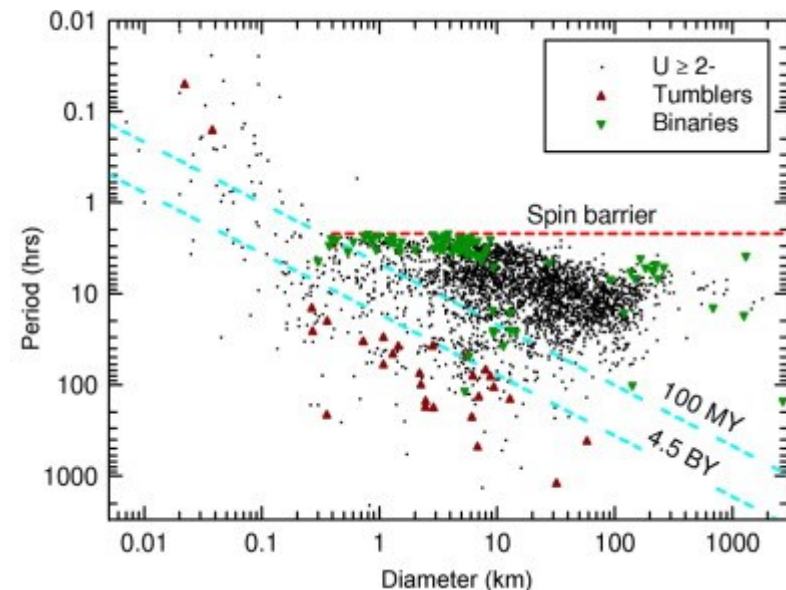
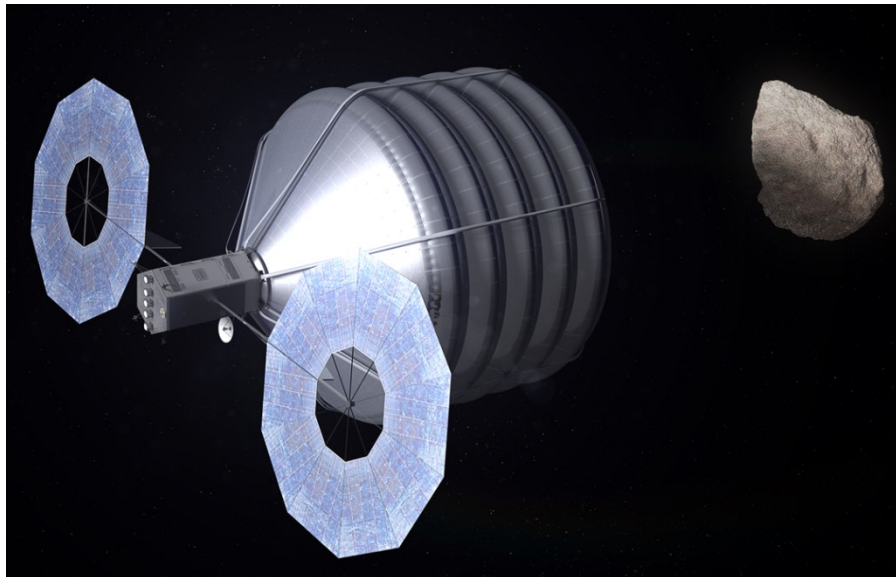
Capturing / Anchoring

Requirements: Capture up to 1000MT asteroid with assumed worse case dimensions of 5m x 12.5m and spin rates < 2 rpms while limiting spacecraft accelerations to $< 0.1g$ (Assumes solar array is limiting structure)

Drivers: Mass, spin state and aspect ratio of the target: Faster spin rates and tumbling requires mitigation of forces transmitted to the spacecraft through the capture mechanism. Ground verification and validation approach.

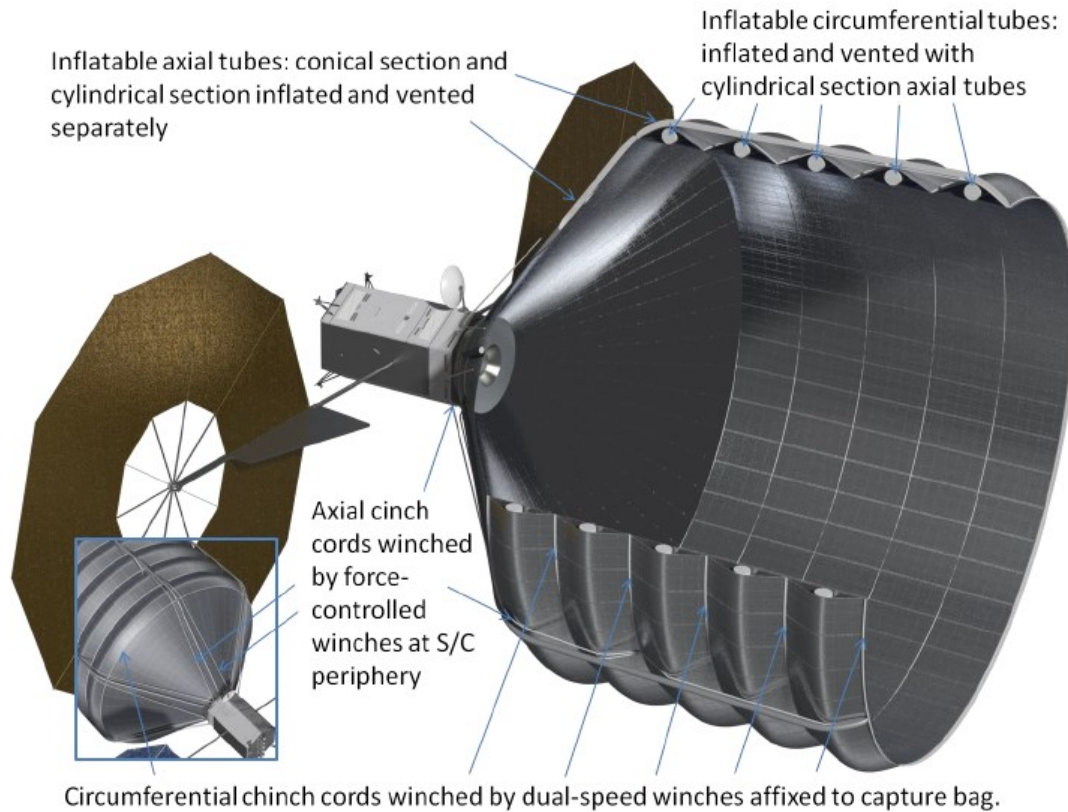
Capture System Concept:

- Capture bag formed of cylindrical barrel section 15 m diameter and conical section attached to S/C.
- Inflatable exoskeleton to deploy bag after arrival at asteroid.
- Inflatable elements in cone to form passive cushion between asteroid and S/C.
- Circumferential cinch winches close cylindrical section around asteroid.
- Axial cinch winches control motion to limit S/C acceleration to $\sim 0.1g$, based on asteroid rotation < 2 RPM.

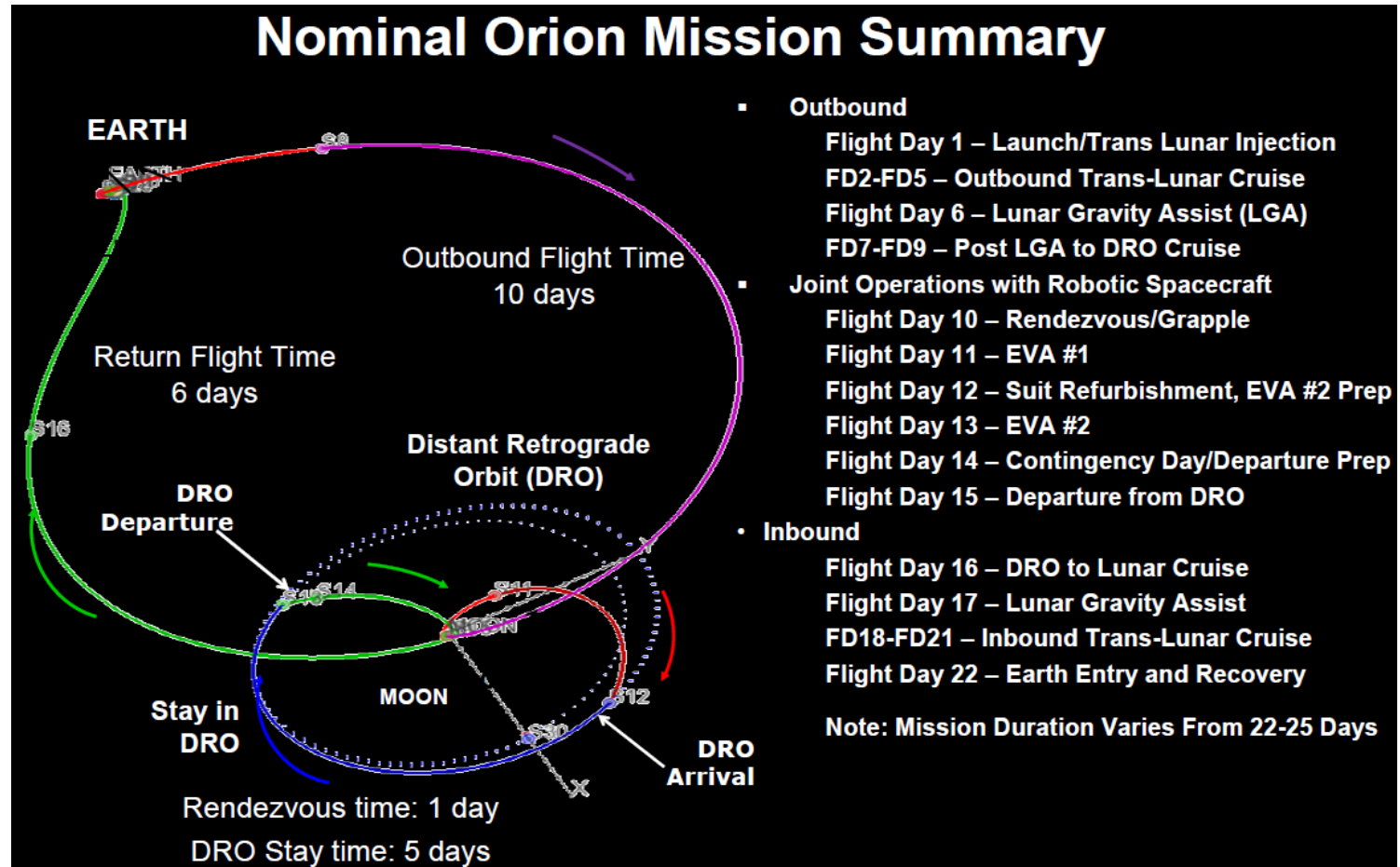


Capturing / Anchoring

Axial cinch winches control motion to limit S/C acceleration to ~ 0.1 g, based on asteroid rotation < 2 RPM.



Human Interfaces / Operations¹⁰



Human interaction / EVAs within the planned Orion and HEOMD development capabilities.

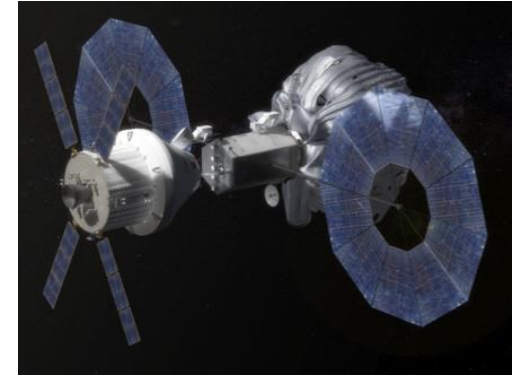
Human Interfaces / Operations¹¹

Requirements:

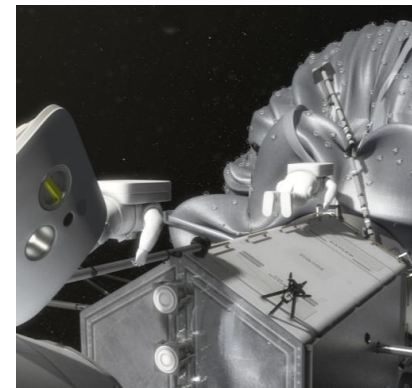
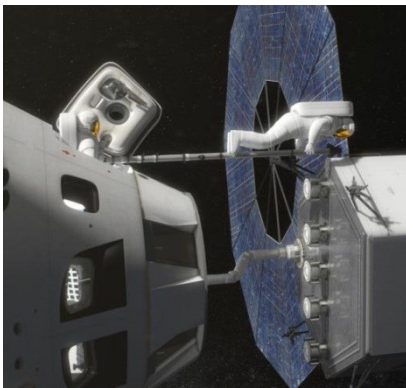
- Deliver the Multi-Purpose Crew Vehicle (MPCV) to the distant retrograde orbit
- Perform the asteroid Extra Vehicular Activities (EVAs)

Drivers:

- Mission Duration (20-30 days)
 - Advanced life support not required (90+ day missions)
- Autonomous Rendezvous and Docking
 - Flight tested on STS-134 via STORM
 - Docking system already under development under ISS
 - EVA system already under development under Advanced Exploration Systems (AES)



Detailed exploration systems development plans will be presented at Mission Formulation Review scheduled for July 30th



Asteroid initiative demonstrates planned exploration systems capabilities with extensibility to future missions, but does not appear to add any new requirements to SLS or MPCV.

(This is because NASA is looking beyond EM2)

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