

Asteroid Retrieval Propulsion and Flight Dynamics Concepts

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This paper discusses a spacecraft design concept and mission optimization for missions to 12 different asteroids. Mission concepts with different electric propulsion systems were considered for optimization by the Evolutionary Mission Trajectory Generator (EMTG) code. The optimization was conducted to find the latest possible launch to reach said asteroids using engine models with both variable thrust and specific impulse. A range of propulsion systems, powers, launch vehicles, and target asteroids were studied. Results are presented for the required trajectories and the required propellant.

Nomenclature

ARM	= Asteroid Retrieval Mission
D4H	= Delta 4 Heavy
EMTG	= Evolutionary Mission Trajectory Generator
EP	= Electric Propulsion
FH	= Falcon Heavy
GSFC	= Goddard Space Flight Center
Isp	= Specific Impulse (s)
JPL	= Jet Propulsion Laboratory
KISS	= Keck Institute for Space Studies
Mdot	= Mass Flow Rate
MDL	= Mission Design Lab
NASA	= National Aeronautics and Space Administration
NES	= Natural Earth Satellite

I. Introduction

An asteroid retrieval mission is being considered by NASA to return material for use and study. The study by the Keck Institute for Space Studies (KISS) was released in 2012, outlining a fast trip to the asteroid 2008 HU4 to return that asteroid to a stable lunar orbit for the purpose of studying it and harvesting the *in situ* resources.¹ This study assumed a generic electric propulsion (EP) system of 40 kW, with a specific impulse of 3000 seconds. The total launch mass was 18,000 kg, and returned an asteroid of approximately 500,000 kg, for a “mass yield” (defined as the asteroid mass divided by the spacecraft mass) of 28:1.

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The fastest way to get to an asteroid is via a direct launch. A direct launch avoids long spiral trajectories with damaging effects on electronics, reduces the amount of propellant required to reach the asteroid, and consequently reduces the dry mass required to hold that propellant. The mission modeling effort described here examines direct launch mission concepts to a range of asteroids, including 2006 RH120, 2007 UN12, 2008 EA9, 2008 HU4, 2008 UA202, 2009 BD, 2010 UE51, 2010 VQ98, 2011 BL45, 2011 MD, 2011 UD21, and 2013 EC20.

II. Methodology

Three principal variables were considered for each asteroid in this study. A number of possible targets were considered using a range of engines that are close to flight readiness, three launch vehicles (the Atlas V 551, the Falcon Heavy, and Delta IV Heavy), and powers ranging from 20 to 80 kW.

In this study we considered missions to ten candidate targets described in a recent paper by Yarnoz *et al*: 2006 RH120, 2010 VQ98, 2007 UN12, 2010 UE51, 2008 EA9, 2011 UD21, 2009 BD, 2008 UA202, 2011 BL45, and 2011 MD.² We also examined 2013 EC20, a recently discovered target candidate³, and 2008 HU4, the target of the original KISS ARM study; but no solutions were found for these bodies. The absolute magnitude of each asteroid was acquired from the JPL Small Body Database Browser⁴ and the diameter of the asteroid was then calculated using the formula²,

$$D = \frac{1329}{\sqrt{p}} 10^{-0.2 \cdot H} \quad (1)$$

where D is the diameter, H is the absolute magnitude, and p is the geometric albedo of the asteroid. A value of $p = 0.22$ was used for all of the asteroids.

Next, the mass of each asteroid was determined using the computed diameter and an assumed density of 2800 kg/m³. Table 1 shows the derived parameters for the asteroids in this study.

Table 1 Asteroid Properties

Body	Absolute Magnitude	Calculated Diameter (m)	Calculated Volume (m ³)	Calculated Mass (t)
2006 RH120	29.527	3.5	23	64
2007 UN12	28.741	5.1	68	190
2008 EA9	27.735	8.0	272	762
2008 HU4	28.223	6.4	139	388
2008 UA202	29.44	3.7	26	72
2009 BD	28.213	6.5	141	394
2010 UE51	28.311	6.2	123	344
2010 VQ98	28.2	6.5	143	401
2011 BL45	27.162	10.5	601	1682
2011 MD	28.073	6.9	171	478
2011 UD21	28.483	5.7	97	271
2013 EC20	29	4.5	47	133

In order to optimize the interplanetary phase of the missions, the matching parameters for the cislunar arrival phase (the end condition for the interplanetary phase) were calculated first for each mission. The propellant mass necessary to perform the cislunar phase of the mission was computed for each combination of asteroid and spacecraft size. This was done using the rocket equation where 1) the spacecraft mass included the mass of the asteroid, 2) the specific impulse was assumed to be maximum for each available thruster, and 3) velocity change was assumed to be 150 m/s. One hundred-fifty m/s was chosen as a conservative figure for the ΔV necessary to insert the asteroid and spacecraft into a distant retrograde orbit relative to the Moon. Finally, the cislunar propellant mass was added to the spacecraft dry mass and used as a known minimum system final mass for the interplanetary trajectory optimization (the mass needed for the final phase of the mission).

A mission study was conducted in the NASA GSFC Mission Design Lab (MDL) to determine a single point dry mass. This “generic” spacecraft includes the capture mechanism of the KISS study, a single maximum electric propulsion system mass, as well as complete functional redundancy applied to all of the other subsystems, and was sized to contain up to 12,000 kg of xenon in 8 tanks. The dry masses used for all of the optimization cases were based on two single point designs at 40 kW and 80 kW, and the power mass was varied. The solar array mass increases disproportionately at 80 kW due to using two 40 kW MultiFlex arrays. The dry masses are shown in Table 2.

Table 2 Spacecraft Margined Dry Mass and Number of Engines

Power level (kW)	20	40	60	80
Number of NEXT Engines	3	5	9	12
Number of BPT-4000 Engines	4	8	12	16
Number of H6MS Engines	2	4	5	7
Number of NEXIS Engines	1	2	3	4
Number of BHT20K Engines	1	2	3	4
Margined Dry Mass (kg)	5191	5453	5717	6935

All low-thrust trajectory data were generated with the EMTG code.⁵ Global optimization was performed within EMTG by modeling the problem using the Sims-Flanagan transcription, a medium-fidelity numerical method that is very fast. In the Sims-Flanagan transcription, each phase of the mission was discretized into time intervals, and the total impulse applied during each time interval was approximated by a discrete impulse placed at the center of the time interval. The trajectory was propagated between intervals by solving Kepler's problem. The Sims-Flanagan transcription simplifies the need for numerical integration and results in significant reduction in computing cost in exchange for some accuracy.

The EMTG model is comparable to other broad-search low-thrust tools used in the industry (MALTO, GALLOP, PaGMO, etc). EMTG was used previously to address orbit optimization for JIMO and Bepi-Combo. The optimizer was modified to find the latest launch dates for specified asteroid masses. Accordingly, the objective function used in the EMTG runs was to find the latest possible launch date that returned the asteroid while meeting the final mass constraint.

The power for the thrusters is modeled as an inverse square relation to the radial distance from the Sun, with the solar flux condition set at 1 AU. The models all assume a 90% electric propulsion duty cycle throughout. This is consistent with periodic communications with Earth and trajectory adjustments. The power model also assumes a 2% degradation rate per year.

Other assumptions used as input to the EMTG optimization include having an earliest possible launch date of January 1st, 2018, a stay time at the asteroid of between 90 and 500 days, and a maximum Earth-Moon system return velocity of 1.5 km/s.

Engine models were derived for this study based on fixed efficiencies so that the optimizer can vary both the thrust and specific impulse simultaneously. The engines included in this study are the NEXT and NEXIS gridded ion engines and the BPT4000, H6MS, and BHT20K Hall effect thrusters. The thrust and mass flow curves used for the engine models are shown in Figures 1-3. EMTG uses the mass flow rate to model the specific impulse. The models for NEXT and the BPT4000 were obtained from Oh *et al.* and Hofer, respectively.^{6,7} The performance values for the BHT20K were taken at a discharge voltage of 500 VDC, and for the H6MS, the discharge voltage was 800 VDC.

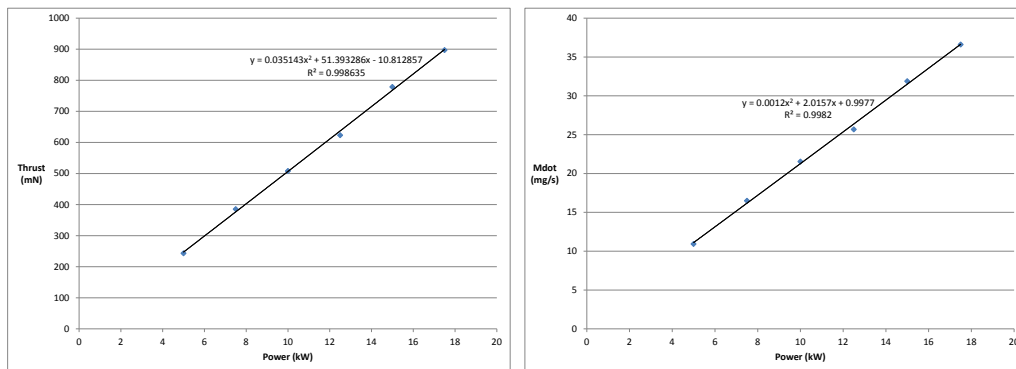


Figure 1 Thrust and mass flow rate for the BHT20K engine⁸

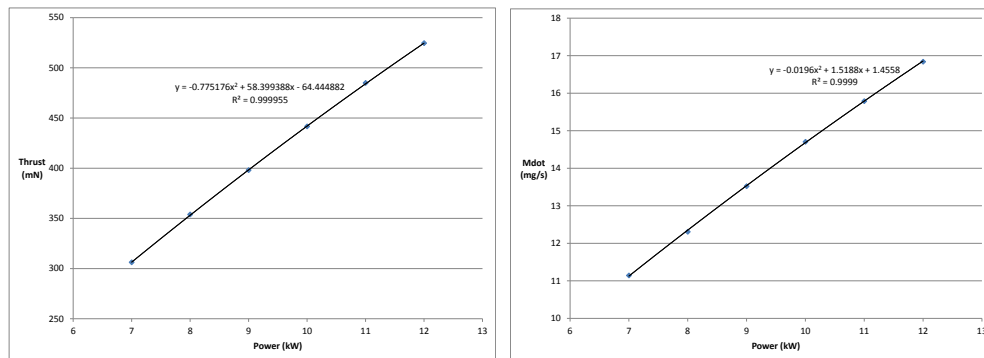


Figure 2 Thrust and mass flow rate for the H6MS engine⁹

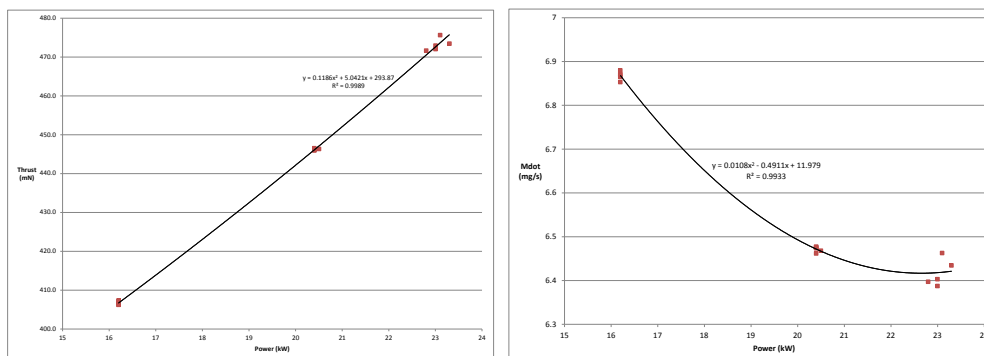


Figure 3 Thrust and mass flow rate for the NEXIS engine¹⁰

III. Results

EMTG was then run for ten of the twelve targets. The asteroids 2008 EA9 and 2011 BL45 were eliminated because they were too large to be plausible retrieval targets. Each asteroid was run for each of the 20 combinations of power system and thruster and each of three launch vehicles: Falcon Heavy, Delta 4 Heavy, and Atlas V 551. Sixty total cases were run for each asteroid, or 600 cases in all. EMTG was run for eight hours for each case in batches of 60. In most cases the best solution was found in minutes, but extra time was devoted to reduce stochastic optimization convergence errors. EMTG's autonomy was very important in this study. Each batch run required only a few minutes to set up and no user interaction for the duration of the run. Missions were found for 6 of the targets.

A. Launch Dates

Launch date results for the six asteroids are shown in Figures 4 through 9. These are the only results that closed from the EMTG analysis.

There are a significant number of missions that close with 20 kW of power to all but 2007 UN12, including cases with the H6MS, BPT4000, BHT20K and NEXT engines. No missions closed with the Atlas V 551 launch vehicle.

Higher power missions did not always produce the latest return dates, due to the increased dry masses of these systems. The mission configurations with the latest launch dates were all with the H6MS on the Delta 4 Heavy.

The asteroid 2006 RH120 was captured for a year near the Earth in 2006. It is part of a class of objects, Natural Earth Satellites, or NESs, that have already *temporarily* been captured in cislunar space. Per Granvik *et al.*, there is always statistically at least one such object of at least 1 meter diameter in temporary orbit around the Earth at all times.

All of the missions were optimized to return in either November or December of 2025, per the constraint.

B. Spacecraft Propellant Masses

Total propellant masses for the spacecraft (including both the interplanetary and cislunar phases) for the six asteroid missions that closed are shown in Figures 10 through 15. All of the propellant masses for the interplanetary phase were between 1100 kg and 6100 kg. The propellants for the cislunar phase varied between 140 kg and 2123 kg. The propellant used to produce the 150 m/s ΔV to capture in cislunar space is a relatively small fraction of the propellant total for all of the missions. The lowest interplanetary propellant missions were all with the NEXIS engine, though the power level and launch vehicle varied.

The mass yields (asteroid mass returned divided by the spacecraft mass launched) for these missions are driven primarily by the mass of the asteroid returned. The smaller asteroids produce the smallest mass yields. The highest yield was 48 with the NEXIS engine at 60 kW for the asteroid 2010UE51.

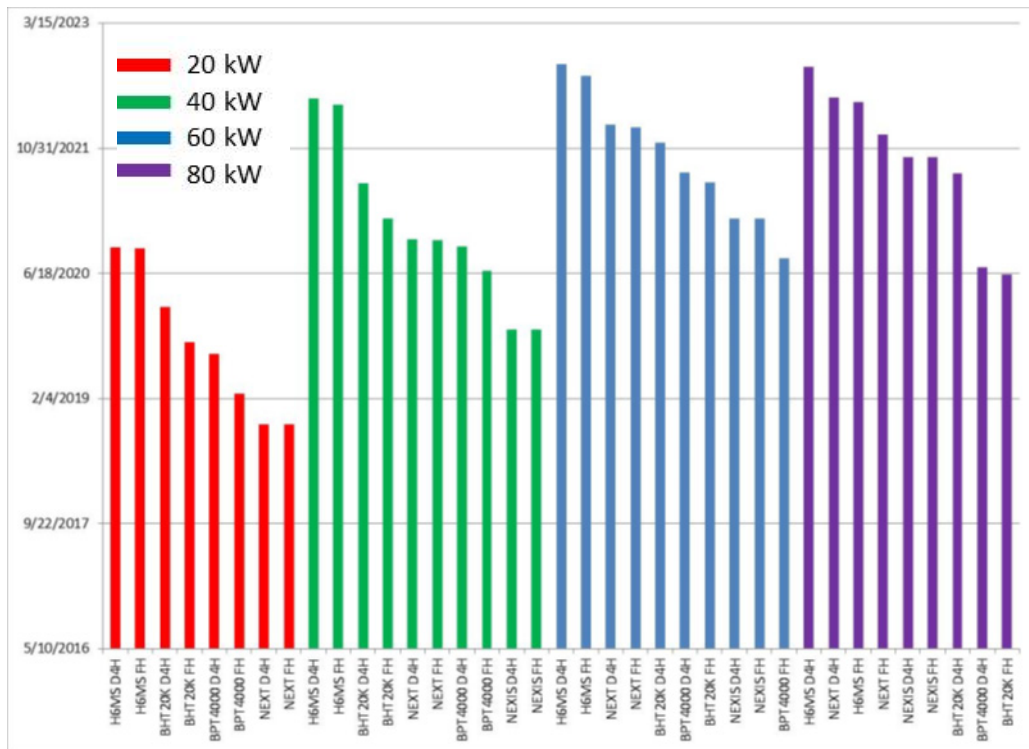


Figure 4 Launch Dates for Asteroid 2006 RH120

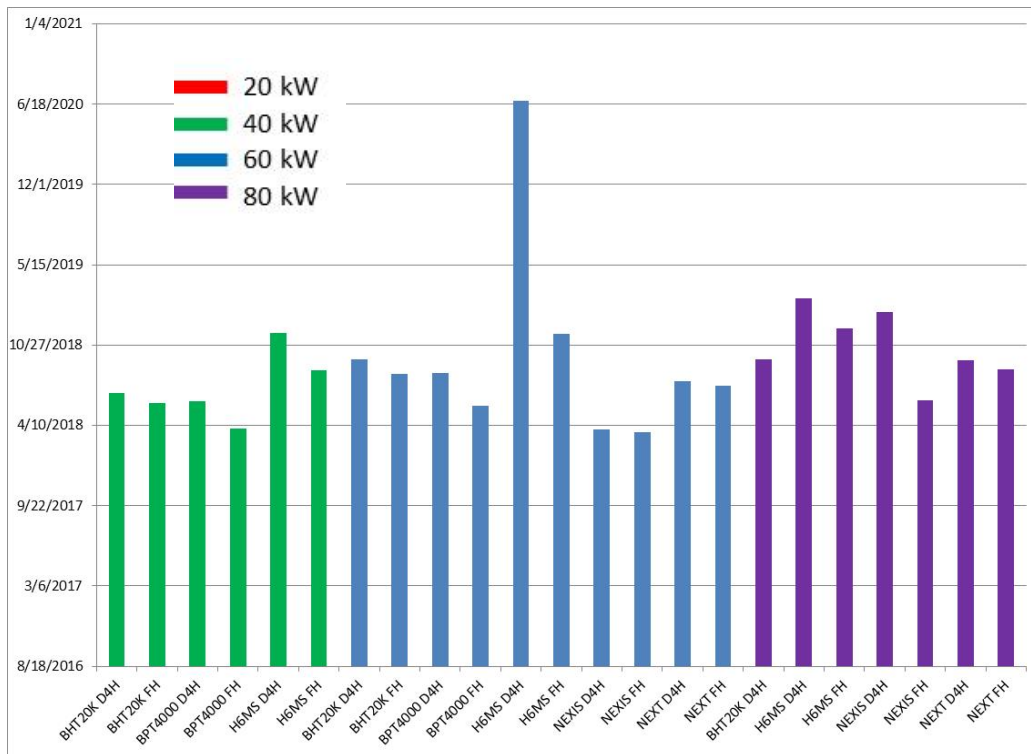


Figure 5 Launch Dates for Asteroid 2007 UN12

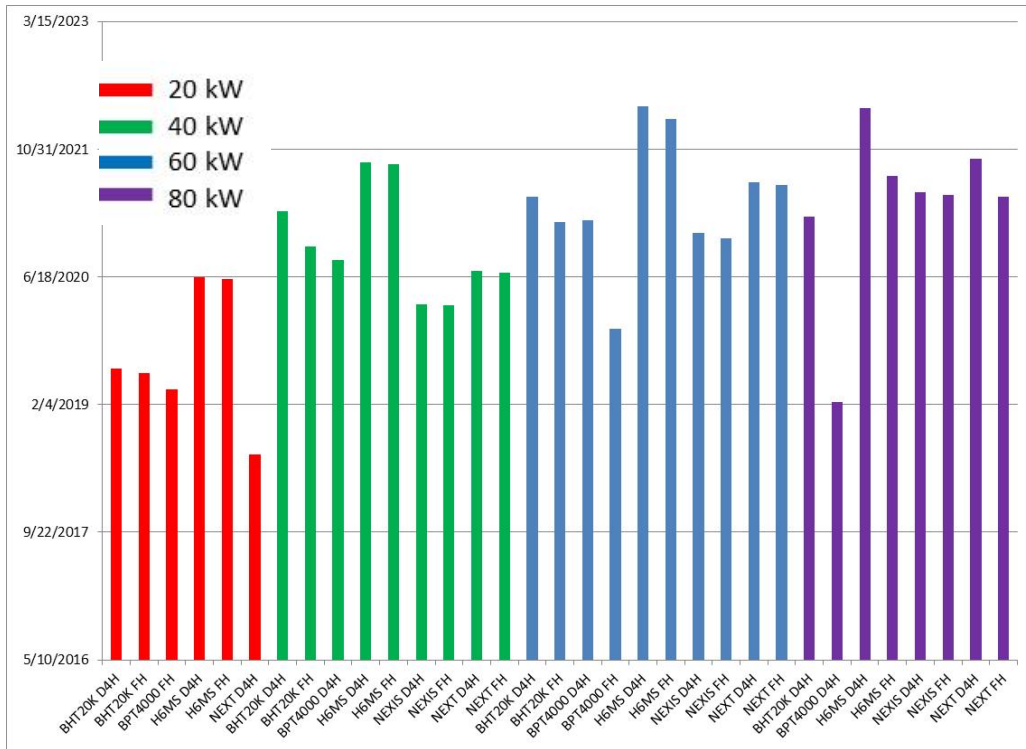


Figure 6 Launch Dates for Asteroid 2008 UA202

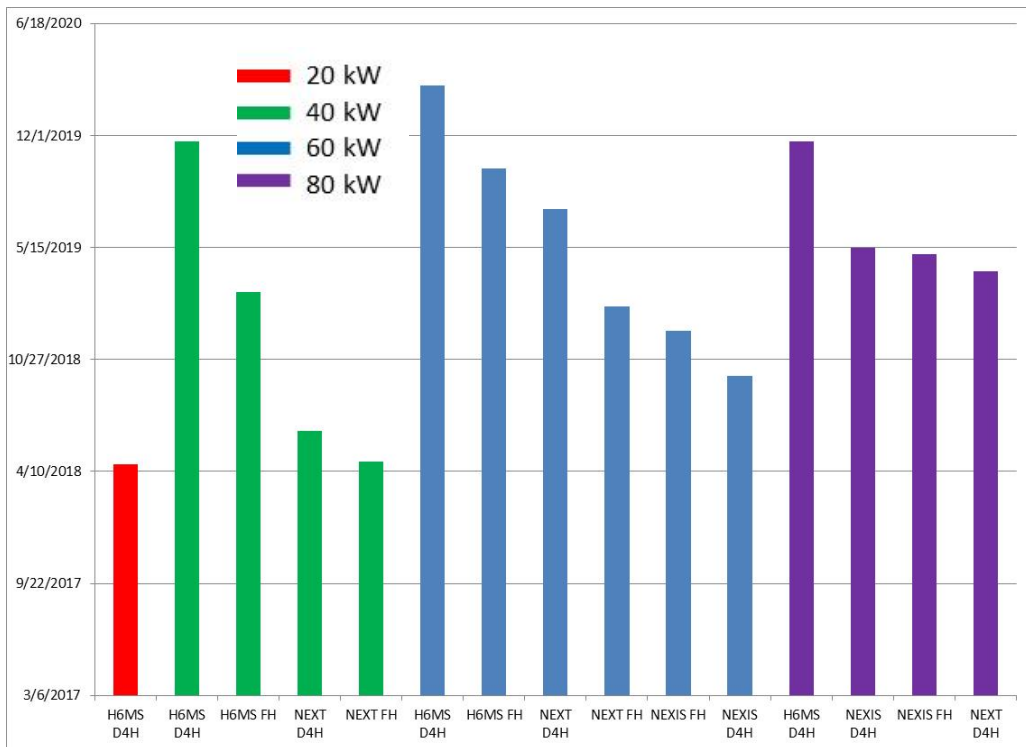


Figure 7 Launch Dates for Asteroid 2009 BD

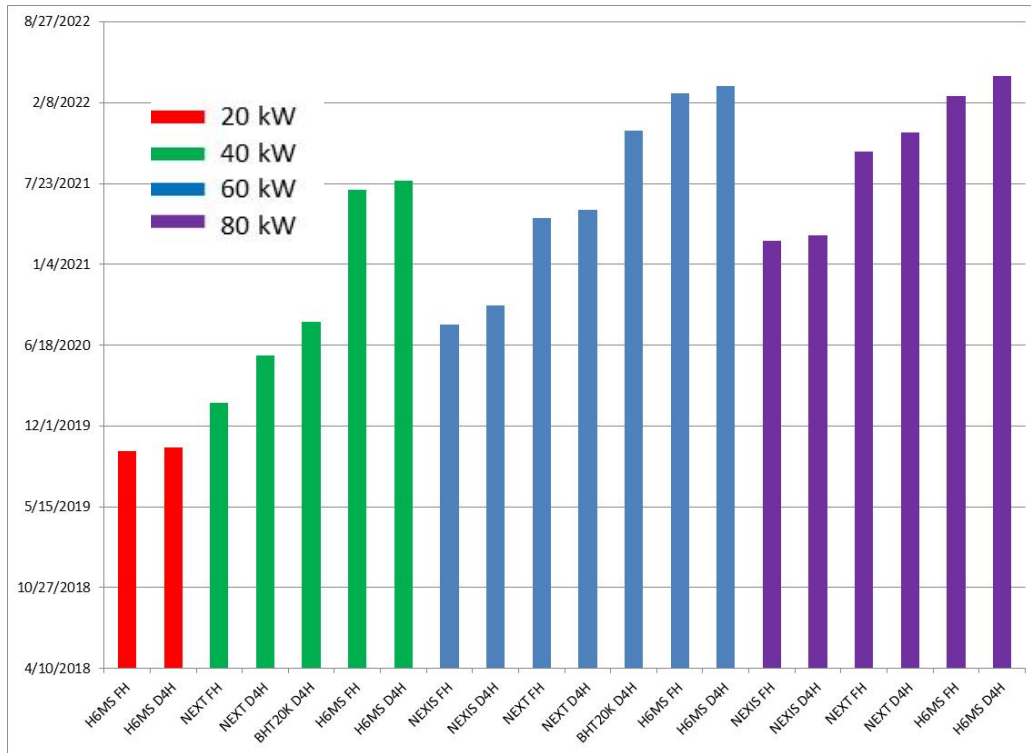


Figure 8 Launch Dates for Asteroid 2010 UE51

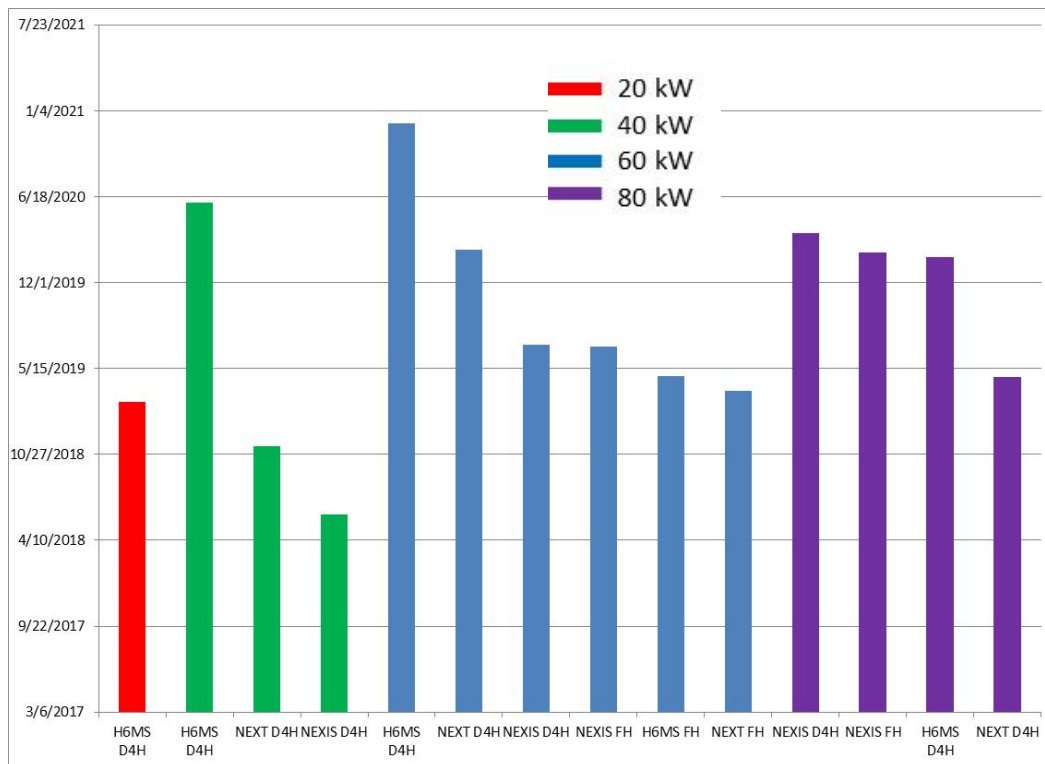


Figure 9 Launch Dates for Asteroid 2011 MD

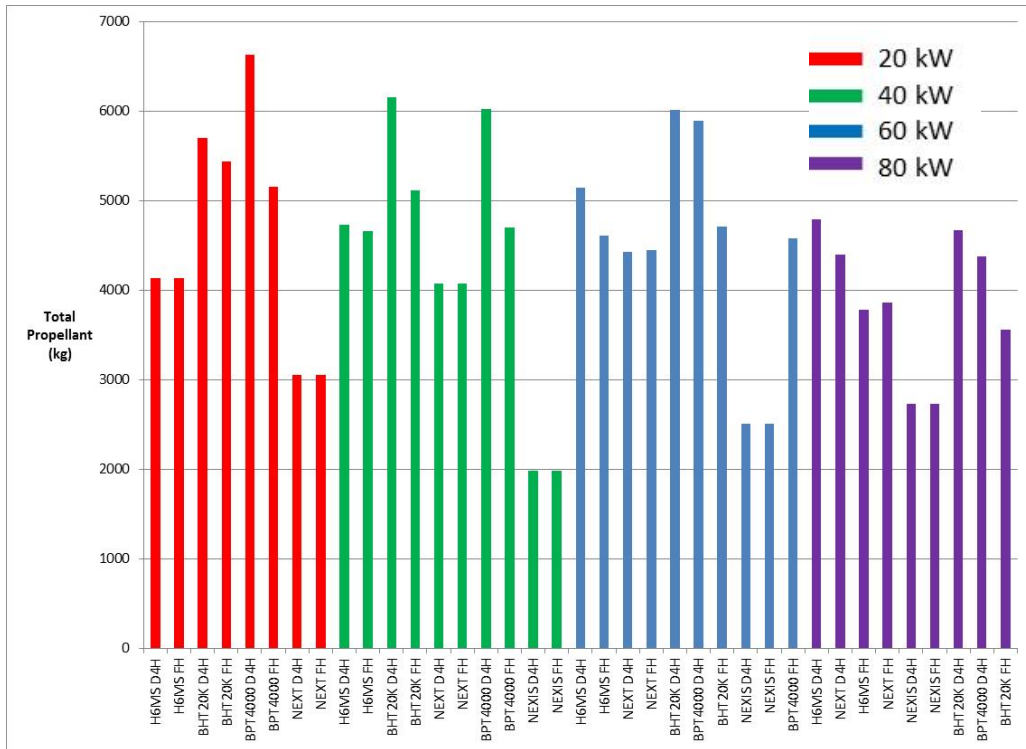


Figure 10 Total Propellant Mass for 2006 RH120

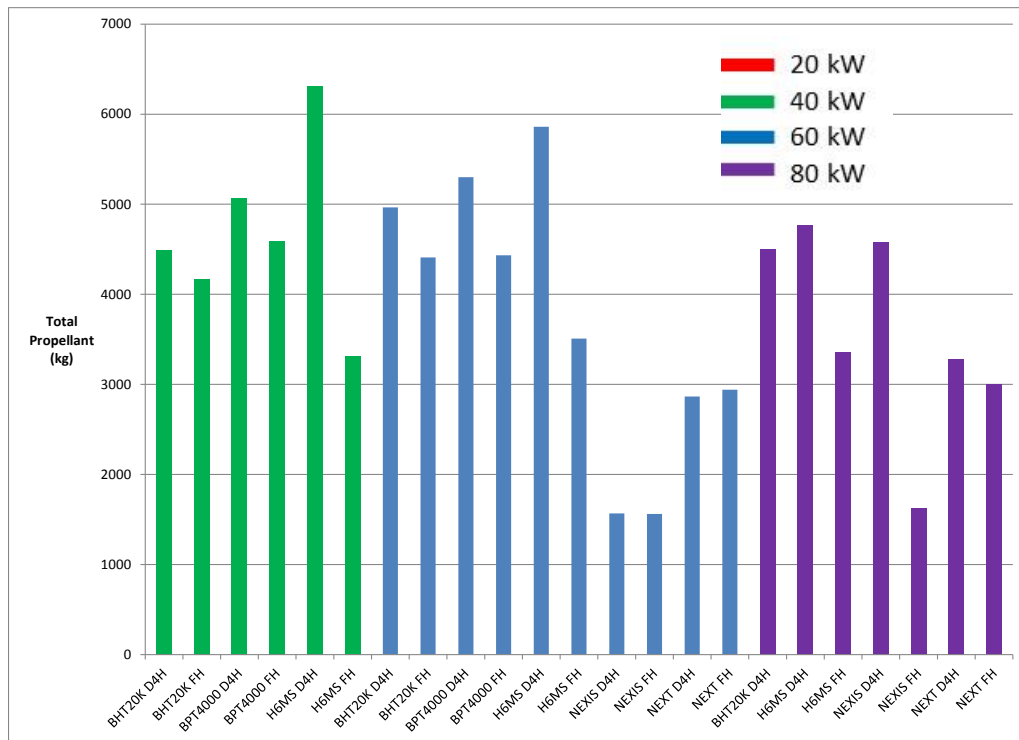
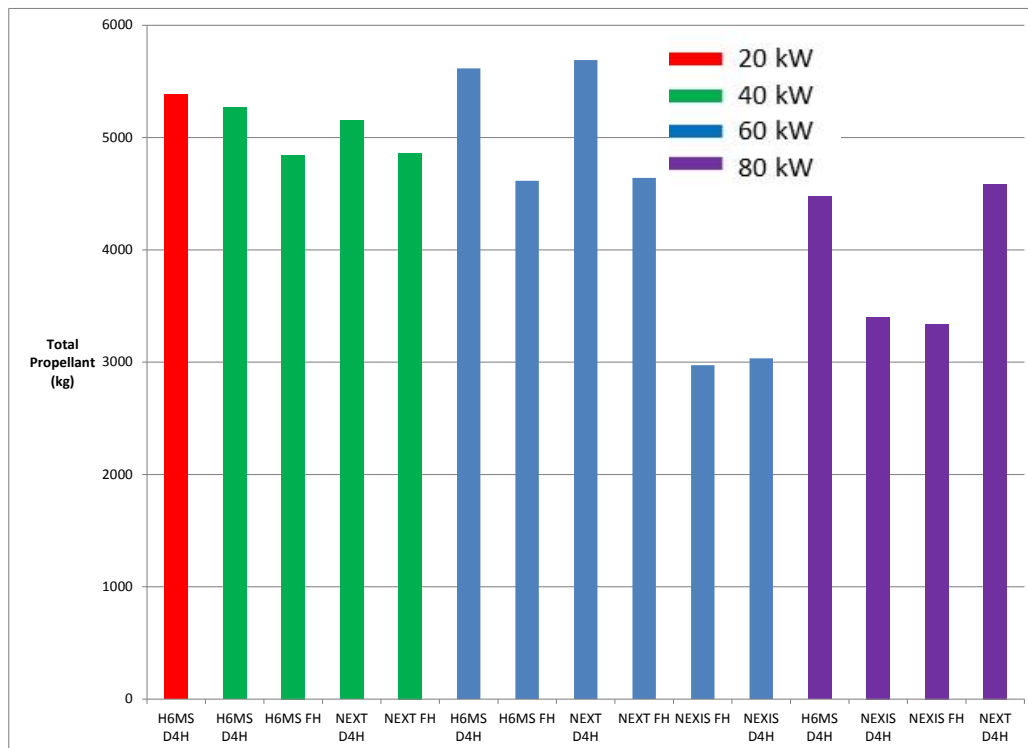
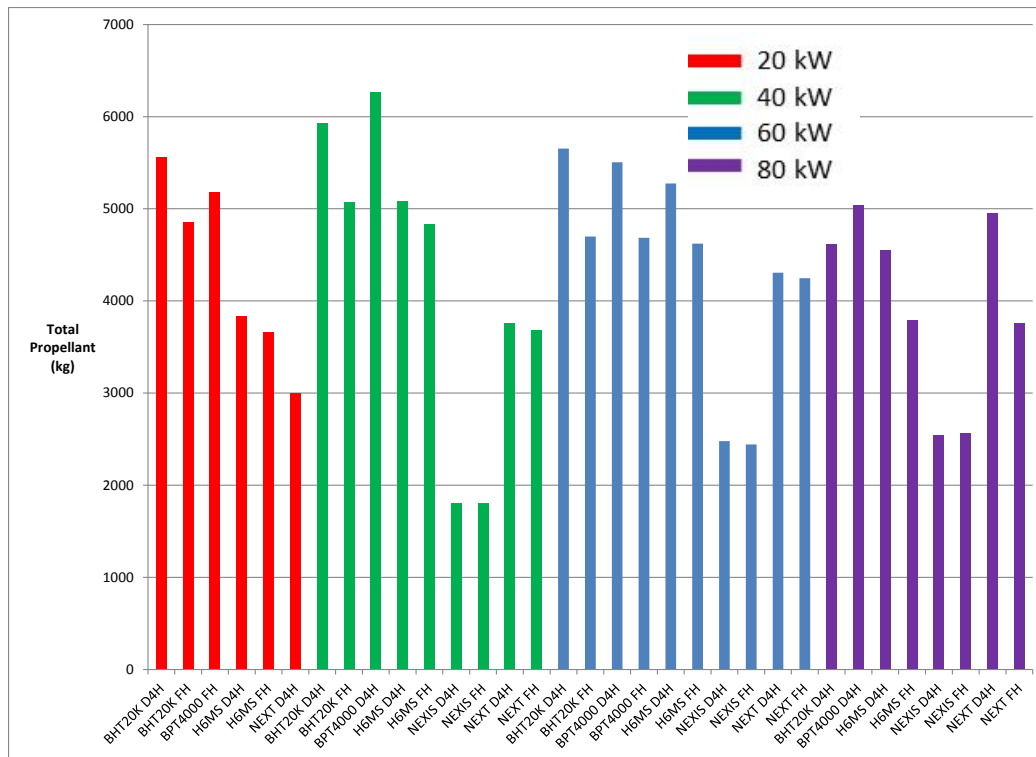


Figure 11 Total Propellant Mass for 2007 UN12



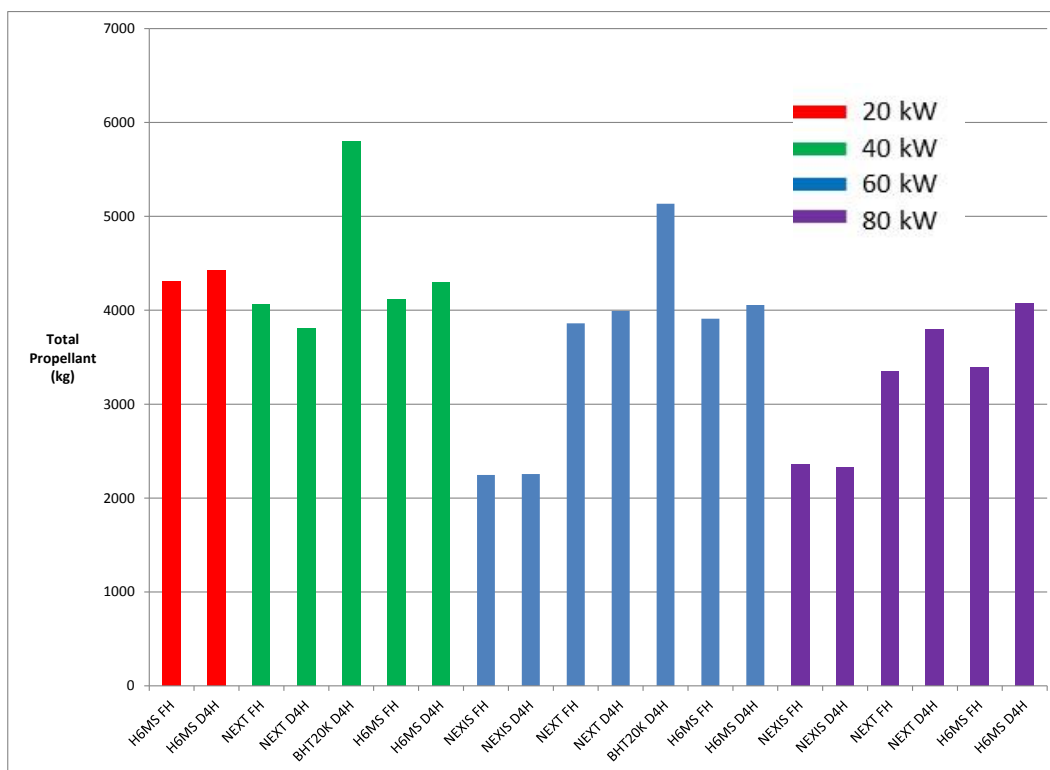


Figure 14 Total Propellant Mass for 2010 UE51

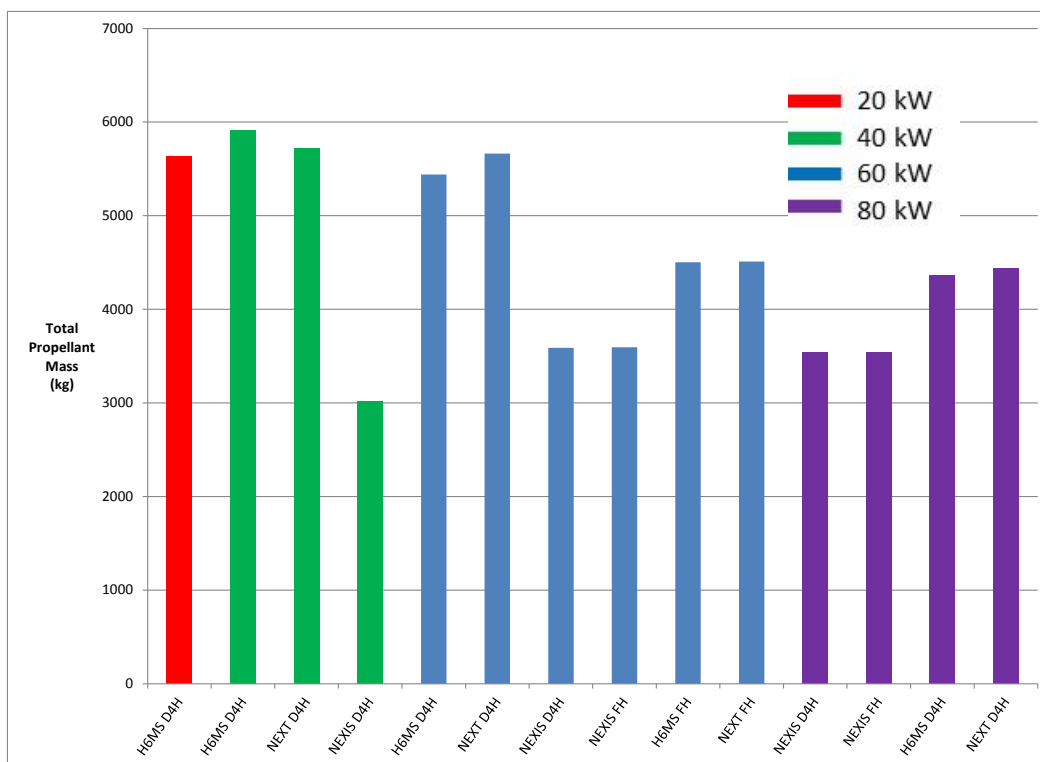


Figure 15 Total Propellant Mass for 2011 MD

C. Orbital Example

An example of one of these trajectories is shown in Figure 16. This trajectory is for a mission to 2006 RH120, launched on a Delta 4 Heavy, propelled by an H6MS propulsion system, with 60 kW power at 1 AU. These trajectories demonstrate that EMTG autonomously optimizes coast periods and throttling of both thrust and specific impulse, as shown in Figure 17. As typical for all of these missions, the trajectory to the asteroid comes in closer to the Sun and coasts. The optimizer does not make use of the significant excess power available closer to the sun and actually costs during much of the time of close approach to the Sun.

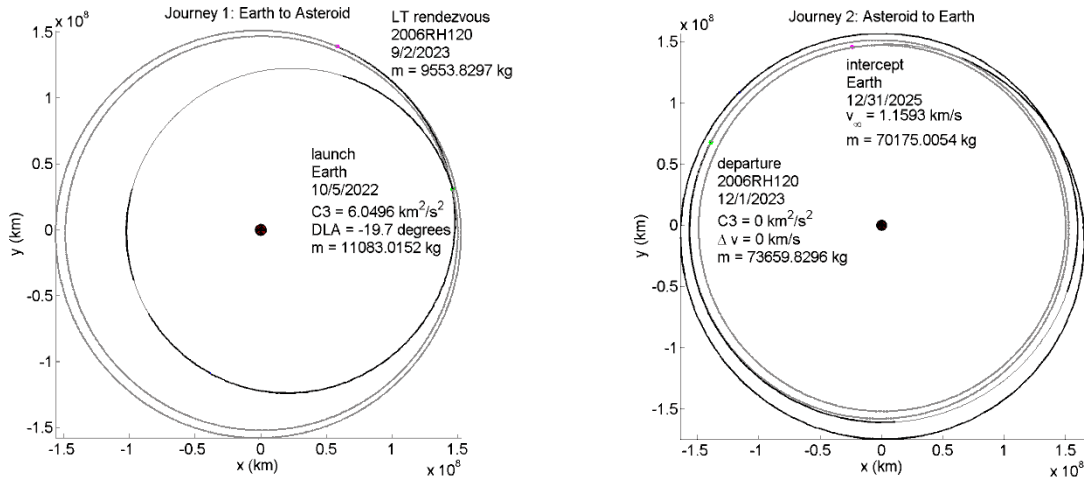


Figure 16 Trajectories for a mission to (left) and from (right) 2006 RH120

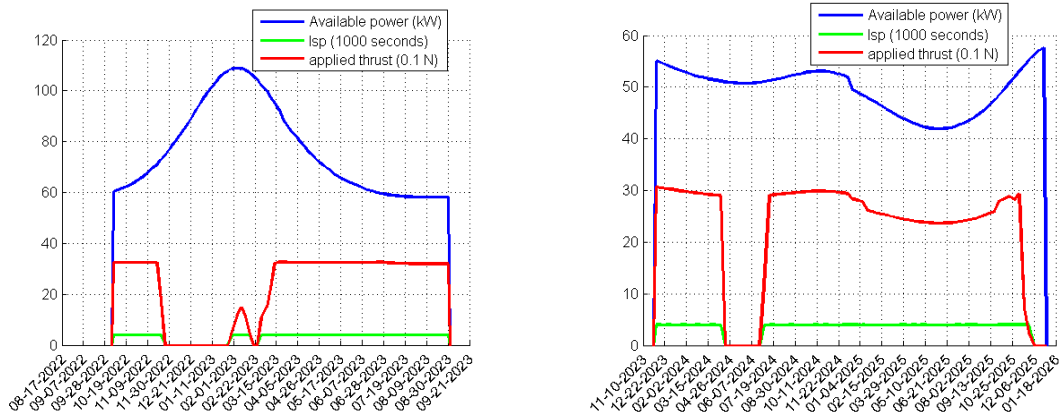


Figure 17 Power available, thrust and specific impulse for a mission to (left) and from (right) 2006 RH120

IV. Conclusions

A summary of the principal results is given in Table 3. Missions are possible that launch as late as 2022, and there are also missions that are possible with power subsystems sized to 20 kW.

Table 3 Summary of Results

Body	Mission Status	Latest Launch	Closes at 20 kW	Minimum Total Propellant (kg)	Minimum Propellant Configuration
2006 RH120	Closed	10/2/2022	Yes	1982	40 kW NEXIS FH
2007 UN12	Closed	6/26/2020	No	1562	60 kW NEXIS FH
2008 EA9	Too Large	-	-	-	-
2008 HU4	Did Not Close	-	-	-	-
2008 UA202	Closed	4/16/2022	Yes	1806	40 kW NEXIS D4H
2009 BD	Closed	2/29/2020	Yes	2973	60 kW NEXIS FH
2010 UE51	Closed	4/14/2022	Yes	2247	60 kW NEXIS FH
2010 VQ98	Did Not Close	-	-	-	-
2011 BL45	Too Large	-	-	-	-
2011 MD	Closed	12/6/2020	Yes	3017	40 kW NEXIS FH
2011 UD21	Did Not Close	-	-	-	-
2013 EC20	Did Not Close	-	-	-	-

The mission configurations with the latest launch dates were always with the H6MS on the Delta 4 Heavy. There are also multiple missions possible with both the NEXT and BPT4000 engines, the propulsion systems with the highest technology readiness levels. Of particular interest, there are 20 kW missions possible to 2008 UA202 and 2006 RH120 with both the NEXT and BPT4000 engines that launch in 2018/2019.

Using the “yield” is not a valid way to compare these missions with respect to the net mass gain from these missions, though many of the missions discussed here produce better “yields” than the KISS study. Including the launch vehicle mass (733 mt for the Delta 4 Heavy, and 1,400 mt for the Falcon Heavy) produces a fractional yield for all of the missions that actually close.

The class of NES objects, as exemplified by 2006 RH120, is a critical population for a potential asteroid retrieval mission. Although asteroid 2006 RH120 is no longer in a temporary capture, a mission to permanently capture an asteroid that is *already* temporarily captured is much less costly than the missions discussed here. There are obvious benefits to identifying this class of objects to determine possible impact events, and a priority should be placed on identifying other objects in this class before they enter cislunar space.

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