VASIMR® Solar Powered Missions for NEA Retrieval and NEA Deflection

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Abstract: High power Solar Electric Propulsion (SEP) technology using VASIMR® engines can dramatically reduce mission cost, when factoring in the time cost of money, and duration for Near-Earth Asteroid (NEA) retrieval and deflection missions. The current paper compares the 2008 HU_4 asteroid retrieval mission using a 40 kW Hall thruster array with SEP-VASIMR® missions. The capabilities of 400 kW SEP-VASIMR® system were also studied for a NEA deflection mission with an orbit similar to 99942 Apophis.

Nomenclature

C	=	cost [$]
I_{sp}	=	specific impulse [sec]
M	=	mass [kg]
P	=	power (as output from solar panels) [kW]
r	=	interest rate of time value of money [%]
T	=	mission time [years]
α	=	specific mass [kg/kW]
β_T	=	tank-to-propellant mass ratio
η	=	efficiency
ΔV	=	velocity change, Delta V [km/s]

Abbreviations

AARC	=	Ad Astra Rocket Company (or Ad Astra)
DC	=	Direct Current
DDT&E	=	Design, Development, Test & Evaluation
EP	=	Electric Propulsion
ESOI	=	Earth Sphere Of Influence
GEO	=	Geostationary Earth Orbit
HET	=	Hall Effect Thruster
HW	=	Hardware
KISS	=	Keck Institute for Space Studies

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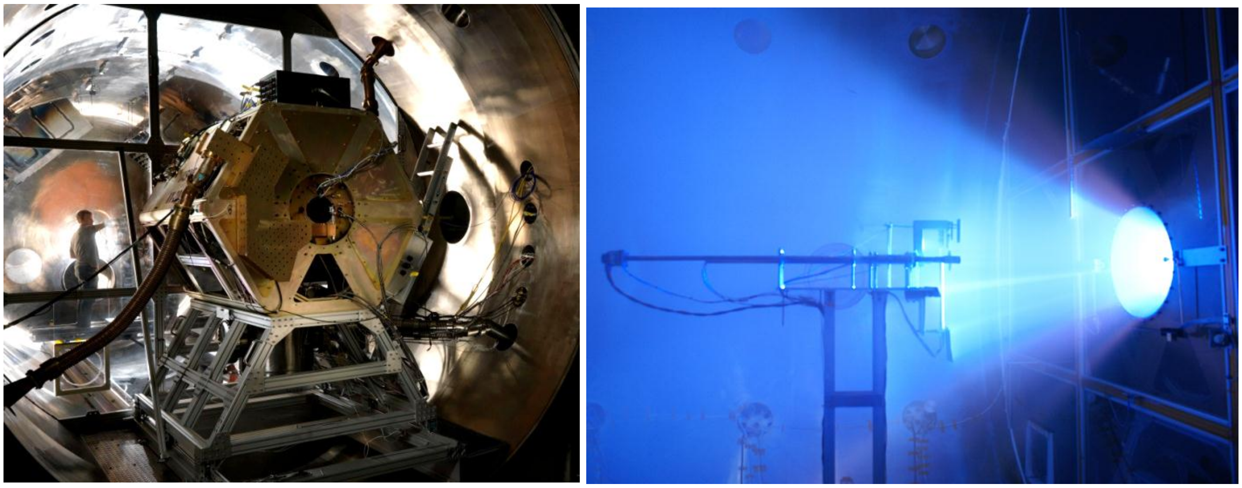

Figure 1: VX-200 engine (left) and 200 kW argon plume (right)

LEO = Low Earth Orbit
L1 = Earth-Moon Lagrangian L1-point
NEA = Near Earth Asteroid
PDR = Preliminary Design Review
PM&D = Power Management and Distribution
PPU = Power Processing Unit
RF = Radio Frequency
SEP = Solar Electric Propulsion
TRL = Technology Readiness Level
VASIMR® = Variable Specific Impulse Magnetoplasma Rocket
VF-200™ = VASIMR® Flight unit at 200 kW input power
VX-200 = VASIMR® Experimental device at 200 kW input power

I. Introduction

THIS work presents the advantages of the Variable Specific Impulse Magnetoplasma Rocket (VASIMR®) technology to move an observed near-Earth asteroid (NEA) from its present position to high lunar orbit by means of a high power (>100 kW), solar electric propulsion (SEP) space tug. It also discusses asteroid deflection capabilities of the technology. Ad Astra Rocket Company (AARC) has demonstrated a VASIMR® rocket prototype, the VX-200 (Fig. 1), running with argon propellant at 200 kW[1,2] in its Houston vacuum chamber. The company has executed more than 10,000 reliable firings of this engine to date. First stage operation with krypton was also demonstrated in 2012. On June 26, 2013, after more than a year of planning and preparation, a team of Ad Astra engineers and physicists, along with NASA engineers participating as part of a technical interchange, completed the company's first formal preliminary design review (PDR) of the VF-200™ engine,[3] a 200 kW "proto-flight" engine to be tested in space.

The high power scalability of the technology forms the basis of attractive missions. The VASIMR® propulsion system is electrodeless (with reduced component wear and increased lifetime) and has an inherent high power density and high specific impulse (I_{sp}), with no thruster scalability concerns for total powers of up to 1 MW. VASIMR® systems is more efficient, and uses more economical propellants, such as argon (~$5/kg) and krypton (~$300/kg), than conventional Hall and ion thrusters, which typically operate with much rarer and expensive xenon (~$1000/kg). Such flexibility results in significant cost savings for testing and operation.

II. VASIMR® Performance Prediction

Experimental studies with the VX-200 experimental VASIMR® rocket prototype demonstrated greater than 70% thruster efficiency[1,2] using argon propellant at 200 kW (Fig. 2, left). The thruster efficiency, η_T, is defined as a ratio of the jet power P_{jet} to the Radio Frequency (RF) Power P_{RF}:

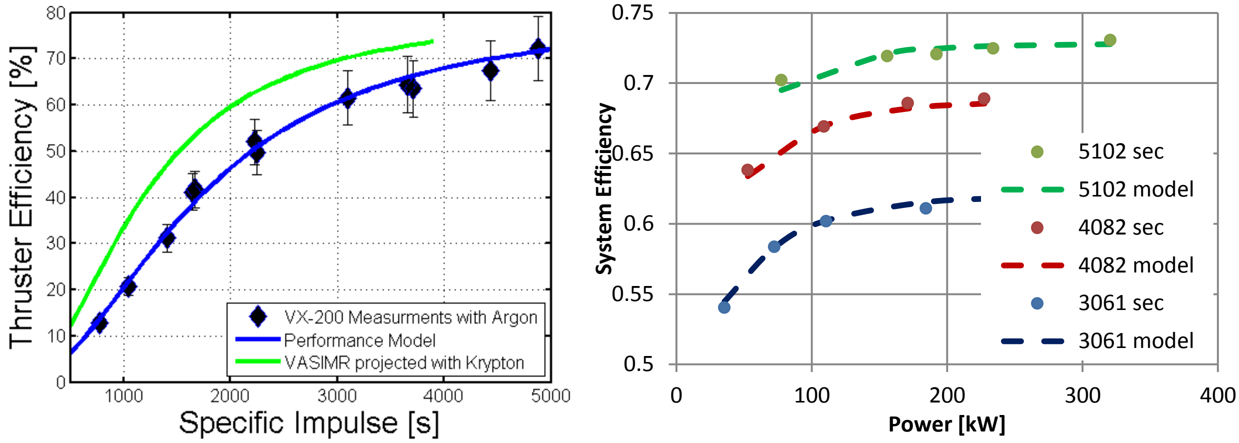

Figure 2: VX-200 measured and predicted performance data for thruster efficiency (left) and predicted system efficiency for VF-200™ (right)

$$\eta_T = \frac{P_{jet}}{P_{RF}}. \tag{1}$$

Computer simulations[4] used to design the VX-200 device were verified with the measured data of VX-200. The simulation code has now been used for the VF-200™ engine design with power level ranging from 30 to 300 kW and an analytical fit of the simulated data was performed, as shown in Fig. 2 (right). The system efficiency, shown in Fig. 2, is a ratio of the jet power to the total input Direct Current (DC) power generated by solar panels during a space mission:

$$\eta = \frac{P_{jet}}{P}. \tag{2}$$

The analytical fit for the system efficiency in the following exponential form:

$$\eta(I_{sp}, P) = \eta_{max} - e^{-a_1 I_{sp} + a_2} - e^{-a_3 P + a_4}, \tag{3}$$

$3000\ s < I_{sp} < 5000\ s$, $30\cdot(I_{sp}/3000)^2\ kW < P < 250\ kW$, within 1% has an average error (root-mean squared) less than 0.3% with a maximum asymptotic efficiency $\eta_{max} = 0.79$ and constants $a_1 = 0.0005$, $a_2 = -0.24596$, $a_3 = 0.01948$, $a_4 = -1.90013$.

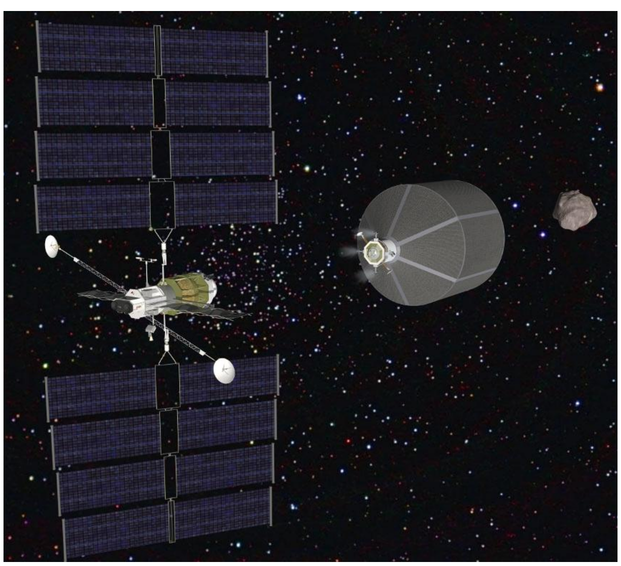

Figure 3: Concept of a SEP asteroid tug with a VASIMR® engine for NEA retrieval mission.

III. NEA Retrieval mission

The mission architecture is based on the recent Keck Institute for Space Studies (KISS) 1300 t, 2008 HU_4 asteroid retrieval mission,[5] but, instead of a 40 kW Hall thruster operating with xenon gas, a range of more powerful (100 - 400 kW) VASIMR® propulsion systems are considered, operating with either argon or krypton propellant.

By restricting the SEP technology using the Hall Effect Thruster (HET), the KISS study produces 10-year mission, costing $2.6B in 2012 dollars, without considering the time value of money, which over a 10 year mission for delivery of the asteroid, would result in a significantly increased cost over the KISS estimate. This study concludes that an increase in

SEP power from 40 kW to a range between 100 and 400 kW would result in lower cost, faster delivery (see Fig. 6), and also with considerably less risk regarding the actual return mass (unknown) of the asteroid. Although clusers of low power (< 5 kW) Hall thrusters are at high technology readiness level (TRL),[6] VASIMR® thrusters and Power Processing Units (PPUs) are at a TRL of 4-5, while Hall thrusters and PPUs for > 50 kW today are at an equivalent TRL of 2-5.

Potential commercial and scientific interests motivate the asteroid capture mission, as near Earth asteroids are potential sources of large quantities of raw materials, and can serve to study the evolution of the solar system. A typical mission would involve four stages: Launch into Low Earth Orbit (LEO) (options include the Delta IV, Atlas V, and Falcon 9 launch systems), transfer to NEA orbit, de-rotation and capture of the NEA, and return to the Earth-moon system. Transfer to NEA includes spiraling from LEO to Earth Sphere Of Influence (ESOI) with $\Delta V_{LEO\text{-}ESOI} = 6.6\ km/s$ and heliocentric transfer from ESOI to NEA with $\Delta V_{ESOI\text{-}NEA} = 2.8\ km/s$, as assumed by the KISS study for 2008 HU_4 in 2022). Return of NEA to ESOI assumes $\Delta V_{NEA\text{-}ESOI} = 0.17\ km/s$ (as for 2008 HU_4 in 2024). The specific parameters impacting the various mission phases are described in detail in Fig. 6.

In order to demonstrate advantages of the SEP-VASIMR® technology for the NEA retrieval mission, several models were created to describe the cost and mass of a specific mission as a function of power, specific impulse, and asteroid mass. These models are used to compare a mission with SEP-VASIMR® propulsion system with an identical mission utilizing Hall Effect Thrusters. Further, the models are used to find optimum values of power and specific impulse for a mission returning an asteroid of arbitrary mass (although the limited launch capacity of existing launch vehicles places a cutoff on the maximum asteroid mass which can be returned with certain values of power and specific impulse).

The results of this report depend on the impact of certain cost assumptions incorporated into the analysis: First, a present value of cost, *PV*, is compared to a future cost value, *FV*, which is a function of mission time, *T*. The difference is referred to as the time cost of money, described by an interest rate, *r*, assumed to be 20%. This parameter describes the growing opportunity cost of increases in the total mission time, which becomes especially important for missions aiming to harvest asteroids for their raw materials. The opportunity cost of waiting for a return on investment is:

$$C_{FV}[\$] = C_{PV}[\$]\ e^{r\,T[years]}. \tag{4}$$

The total mission time is a function of power, specific impulse and NEA mass, and for low power missions, which corresponds to long mission times, the time cost of money becomes substantial (see Fig. 6). The up-front costs listed in this paper are modeled after the cost model from the KISS study (Ref. 5, page 40). Design, Development, Test & Evaluation (DDT&E) costs for the VASIMR® spacecraft are assumed to be the same as that of a Hall Effect Thruster, while hardware (HW) costs for the VASIMR® system scale with power. The cost of power system hardware, which includes the cost of solar panels, grows as:

$$C_{HW,\,P}[M\$] = c_P * P[kW]. \tag{5}$$

In the power cost Eq. (5), the constant $c_p = 1.51\ M\$/kW$ is chosen such that the cost agrees with the value given in the KISS study (Ref. 5, page 40). The cost of the thruster hardware is assumed to be proportional to the square root of power. All other spacecraft costs (everything besides power system and propulsion system) are assumed to remain constant, with values taken from the KISS study.[5] Other cost-impacting parameters include the mission operations cost, which is proportional to mission time, and the launch cost, which depends on the choice of launch vehicle. Launch vehicles examined in this report are the Falcon 9 ($54M), Atlas V ($288M), and Delta IV ($300M) rockets.

In addition to assumptions regarding mission costs, this report also makes certain assumptions in a mission mass model. Maximum launch mass depends on the launch vehicle used, with the Delta IV being the heaviest-lift rocket examined (22.95 t), followed by the Atlas V (18.8 t) and Falcon 9 (13.1 t). The mass of the spacecraft is assumed to be a sum of masses of the power system, thruster, capture mechanism, chemical propellant, Electric Propulsion (EP) propellant and propellant tank. The power system, including the solar panels, is assumed to have mass M_p proportional to power:

$$M_P[kg] = \alpha_P * P[kW] + M_{PM\&D}[kg]\,. \tag{6}$$

The KISS study assumes the specific mass for the power system to be $\alpha_P = 21\ kg/kW$, and mass of Power Management and Distribution (PM&D) $M_{PM\&D} = 235\ kg$. VASIMR® power system is assumed to follow the same

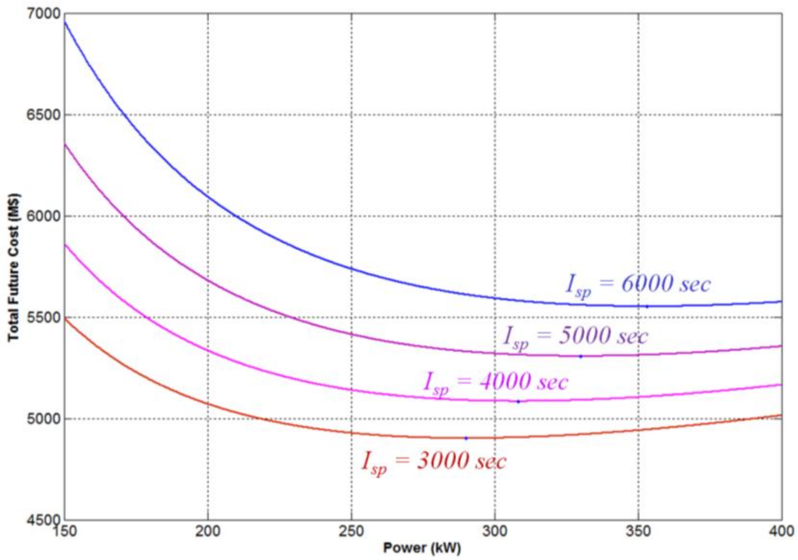

Figure 4: Mission cost versus Power and Specific Impulse.

model. The mass of the propulsion system is based on specific power ratios of VASIMR® technology, and in the study is held virtually constant at 1.1 t, despite recent evidence suggesting a much lower thruster mass is possible.

The mass of the capture vehicle is assumed lie primarily in a cylindrical container that fits around the target NEA. The size, and mass, of this cylinder therefore depends on the square of the radius of the asteroid, which results in a capture system mass of:

$$M_C = A_C\, M_{NEA}^{\;2/3}, \tag{7}$$

which is scaled to agree with the value listed in the KISS report[5] for a 1300 t asteroid. The mass of propellant required to de-spin the NEA is also considered; with the simplifying assumption that the asteroid is roughly spherical, it is straightforward to show that the required propellant required to de-spin the asteroid is:

$$M_{DS,pr} = A_{DS}\, M_{NEA}^{\;4/3} \tag{8}$$

with the constant adjusted to agree with the value in the KISS report.[5] Finally, the fuel tank mass is computed as a function of propellant mass (which is derived directly from the rocket equation), using the same scaling factor of 4% tank pass per fuel mass as used in the KISS report:[5]

$$M_{pr,T} = \beta_T\,(M_{ch,pr} + M_{EP,pr}). \tag{9}$$

The Copernicus code[7] was used to reproduce NEA retrieval mission trajectories using both SEP-HET and SEP-VASIMR® technologies. The mission segment times and segment Delta-V's values were verified to within a 1% error.

Several MATLAB programs were written to minimize the cost in terms of specific impulse and power (I_{SP}, power) as a function of asteroid mass. Mission performance was examined for the asteroid's mass ranging from 200 to 2000 tonnes, the specific impulse ranging from 3000 s to 6000 s (I_{SP}), and for solar power ranging from 100 to 400 kW (P).

Since thrust is inversely proportional to I_{sp}, higher I_{SP}'s lead to longer mission times, but with increased capability to return more massive asteroids. Figure 4 demonstrates the mission cost as a function of power values and specific impulse. For every I_{sp} value, there is an optimal power level, corresponding to minimal mission cost. For power values that are too low, the mission cost is higher than optimal because of the slower mission time. For power values that are too high, the mission cost is higher than optimal because the increased up-front hardware cost to support the mission.

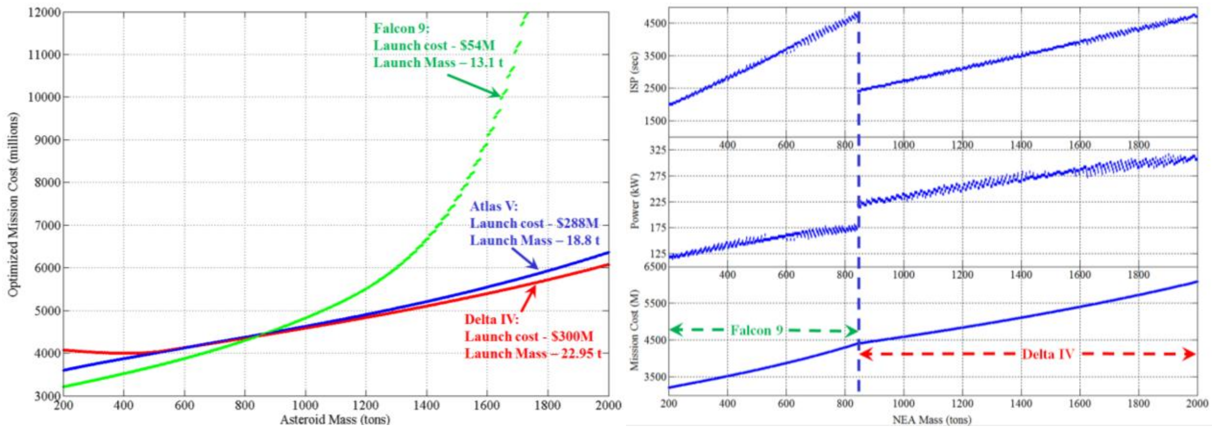

Figure 5: Mission cost versus Asteroid mass and Launch vehicle option. Discontinuities occur in the right hand plot when the launch vehicle is changed.

For low Isp values, the mission time and mission cost go down, but the increased propellant usage drives the initial mass of the spacecraft up and that mass is limited by the maximum launch- mass for the selected launch vehicle. Figure 5 demonstrates VASIMR® mission cost (at optimal power and specific impulse values), as a function of NEA mass for different launch vehicles. Since the Falcon 9 launch option is the cheapest but has a relatively low launch mass capability to LEO, it produces the lowest mission cost for relatively low values of asteroid return mass. For higher asteroid mass values, the minimal mission cost is found using the increased launch mass capabilities of the Delta IV Launch option.

Figure 6 summarizes the mass and cost values for 1300 t NEA retrival mission from this analysis, comparing the original KISS study option with different VASIMR® options. From these results, in terms of future cost, the optimal power level is 255 kW with a specific impulse of 3400 sec using the Delta IV launch vehicle. Thus, even though it is more expensive up front, the VASIMR® technology is more cost-effective in terms of the time cost of money because it can complete the mission in significantly less time. The VASIMR® technology can also reduce the mission risk with respect to unknown mission parameters, especially the mass of the asteroid to be returned.

The higher power capabilities of the VASIMR® technology also allow for missions to retrieve asteroids with shorter synodic periods and/or increased mass, expanding the range of possible NEA that can be retrieved. The lower up-front costs of relatively low-powered clusters of HETs are complimentary to VASIMR® systems if the return mass is relatively small, well known and if extended mission times do not significantly increase the mission cost.

Name	KISS	VF-150	VF-200	VF-300	VF-400	VF-255
Power	40 kW	150 kW	200 kW	300 kW	400 kW	255 kW
Propellant Type	Xenon	Argon	Argon	Argon	Argon	Argon
Specific Impulse (Isp)	3000 sec	3000 sec	3000 sec	4000 sec	5000 sec	3400 sec
Efficiency	60%	61%	61%	68%	73%	65%
Propulsion System Mass (KISS pg. 26)	1.0 t	1.0 t	1.0 t	1.0 t	1.0 t	1.0 t
Power System Mass (KISS pg. 26)	1.1 t	3.3 t	4.4 t	6.5 t	8.5 t	5.5 t
Asteroid Capture System Mass	0.2 t	0.2 t	0.2 t	0.2 t	0.2 t	0.2 t
Tank Mass (4% of propellant, as in KISS)	0.5 t	0.6 t	0.6 t	0.4 t	0.4 t	0.6 t
Spacecraft Dry Mass (KISS pg. 26)	5.3 t	7.7 t	8.7 t	10.6 t	12.6 t	9.8 t
Mass in LEO (KISS pg. 26)	18.9 t	22.2 t	23.6 t	21.6 t	21.6 t	23.0 t
Delta V (KISS pg. 29)	6.6 km/s	6.6 km/s	6.6 km/s	6.6 km/s	6.6 km/s	6.6 km/s
Propellant Used	4.03 t	4.72 t	5.03 t	3.54 t	2.87 t	4.37 t
Time	2.3 yrs	0.7 yrs	0.6 yrs	0.4 yrs	0.4 yrs	0.5 yrs
Heliocentric Delta V (KISS pg. 29)	2.8 km/s	2.8 km/s	2.8 km/s	2.8 km/s	2.8 km/s	2.8 km/s
Propellant Used	1.41 t	1.65 t	1.76 t	1.29 t	1.08 t	1.56 t
Time (w/50% coasting)	1.8 yrs	0.5 yrs	0.4 yrs	0.3 yrs	0.3 yrs	0.4 yrs
NEA Stay Time (days)	90	90	91	92	93	94
Total Propellant to NEA	5.4 t	6.1 t	6.5 t	4.7 t	3.9 t	6.1 t
Total Time to NEA	4.3 yrs	1.5 yrs	1.2 yrs	1.0 yrs	0.9 yrs	1.1 yrs
NEA Mass (KISS)	1300.0 t	1300.0 t	1300.0 t	1300.0 t	1300.0 t	1300.0 t
Heliocentric Delta V (KISS pg. 29)	0.17 km/s	0.17 km/s	0.17 km/s	0.17 km/s	0.17 km/s	0.17 km/s
Propellant Used	7.7 t	7.7 t	7.7 t	5.8 t	4.6 t	6.8 t
Time (w/25% coasting)	6.0 yrs	1.6 yrs	1.2 yrs	0.9 yrs	0.8 yrs	1.0 yrs
Chemical Propellant (KISS pg. 29)	0.4 t	0.4 t	0.4 t	0.4 t	0.4 t	0.4 t
Total EP Propellant Used	13.1 t	14.1 t	14.5 t	10.6 t	8.6 t	12.7 t
Total Mission Time	**10.1 yrs**	**3.1 yrs**	**2.4 yrs**	**2.0 yrs**	**1.8 yrs**	**2.0 yrs**
Power System (KISS pg. 40)	$251M	$417M	$492M	$643M	$794M	$575M
Thruster (KISS pg. 40)	$224M	$288M	$308M	$342M	$371M	$328M
Spacecraft (KISS pg. 40)	$1,243M	$1,472M	$1,568M	$1,753M	$1,933M	$1,671M
Payload cost (KISS pg. 40)	$93M	$93M	$93M	$93M	$93M	$93M
Contractor Fee (10% without PL)	$115M	$138M	$148M	$166M	$184M	$158M
Spacecraft w/fee (KISS pg. 40)	$1,357M	$1,610M	$1,716M	$1,919M	$2,117M	$1,829M
NASA (15% of SC, KISS pg. 41)	$204M	$242M	$257M	$288M	$318M	$274M
Phase A (KISS) (KISS pg. 41)	$68M	$81M	$86M	$96M	$106M	$91M
Mission Ops (KISS pg. 41)	$116M	$51M	$45M	$41M	$40M	$42M
Launch Vehicle: Atlas 551(KISS) or Delta IV	$288M	$300M	$300M	$300M	$300M	$300M
Reserve (30%)	$610M	$685M	$721M	$793M	$864M	$761M
Total (minus propellant)	**$2,643M**	**$2,969M**	**$3,125M**	**$3,438M**	**$3,744M**	**$3,297M**
Propellant (Xe: $1000/kg, Ar: $5/kg)	$13M	$0.07M	$0.07M	$0.05M	$0.04M	$0.06M
Total+Propellant with 20% Time Cost of Money	**$19,980M**	**$5,495M**	**$5,074M**	**$5,091M**	**$5,364M**	**$4,948M**

Figure 6: Analysis results and rough cost model, including time value of money assessing the effects of VASIMR® technology on the KISS study NEA retrieval mission.

IV. NEA Deflection Mission

Another important application of the VASIMR® technology is an asteroid deflection mission, which recently attracted attention because of the Chelyabinsk meteorite event and the 2012 DA_{14} fly-by in February 2013. It is generally agreed[8] that the impact of a 60 m asteroid could destroy an area approximately the size of New York City.

Ad Astra Rocket Company has evaluated the applicability of its 400 kW solar electric propulsion (SEP) "space tug" in a concept named Viento™ to successfully deflect an imaginary medium-sized asteroid in a direct impact scenario with Earth. Viento™ is equipped with two dual-core, VF-200-class engines operating at 200 kW each.

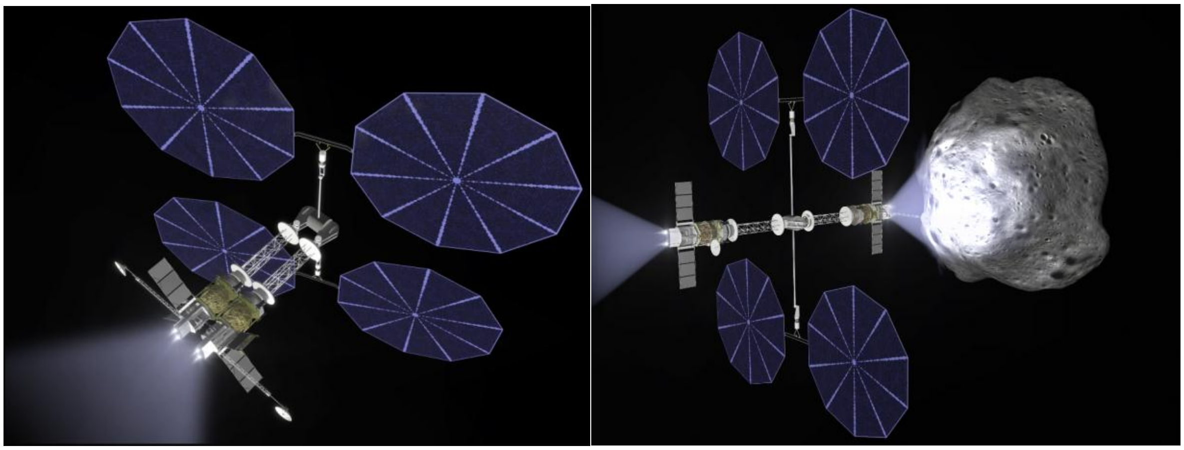

Figure 7: Concept of the spacecraft with two 200 kW VASIMR® engines configured in two modes: additive propulsive mode for fast transit to asteroid (left) and opposing tandem mode (right)

The Viento™ configuration is assumed to have two modes, shown in Fig. 7: 1) an additive translation mode to provide high speed capability to initially reach the target asteroid and 2) a deflection mode with its two nacelles oriented in opposing directions to utilize the plasma exhaust of one of the engines to gently "blow" on the asteroid to impart momentum and alter its trajectory, while the other engine, with proper gimballing and auxiliary spacecraft attitude control, maintains the spacecraft in a stable position, hovering adjacent to the asteroid without actually landing.

The asteroid, 99942 Apophis discovered on June 19, 2004, is a 270 m diameter boulder with a mass estimate of approximately 40 million tons, although this mass is uncertainwithin a factor of 3, which is to say statistically that its actual mass should lie somewhere between 13 and 120 million tons. We imagine a similar smaller asteroid, which we call "Khan," to be a 7 million ton, 150 m diameter body in an Apophis-like orbit that is slightly modified to set it up for a direct impact with Earth on April 13, 2029, instead of the near-miss that will actually occur with Apophis in 2029.[9] For these assumptions, Khan is in a nearly circular orbit with a period of 323 days that crosses Earth's orbit every year on April 13 as it heads inbound toward perihelion. In this imaginary scenario, if not deflected, Khan will impact Earth with an energy release of 131 megatons in 2029, causing a major regional disaster.

Ad Astra's Viento™ carries out the deflection campaign in four phases: 1) departure on August 13, 2019 from Earth-Moon L1 (EML1) and a 305 day propulsive translation to a rendezvous with Khan on June 13, 2020; 2) a five-year active deflection period, ending on June 13, 2025, where the spacecraft is configured to hover adjacent to the asteroid while pushing on it with the other engine; 3) a four-year passive loiter period at Khan, ending on March 19, 2029, while Viento™ awaits an optimal return opportunity and 4) a 40 day return maneuver, which brings Viento™ back to its point of origin at EML1.

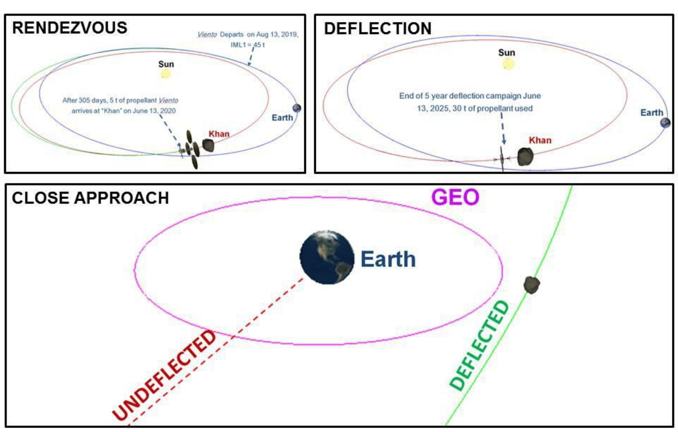

Figure 8: Deflection trajectories and close approach geometry before and after deflection

The VASIMR® deflection capability is determined by the power level, the deflection time and the size and mass of the asteroid. At the 400 kW level used in this study, the deflection of a 7,000,000 t asteroid is readily facilitated within the allotted time from a direct impact at the center of the Earth out to six Earth radii (GEO sattelite distance). In this mission, the initial mass ofViento™ at L1 is 45 t. It includes the power and propulsion system with specific mass of α = 10 kg/kW (total mass of 4 t), and a tank and structure mass of 5.4 t. The mass of propellant is 35.6 t, of which 5.0 t will be used for L1-NEA transfer, 30 t for the NEA deflection and 0.6 t

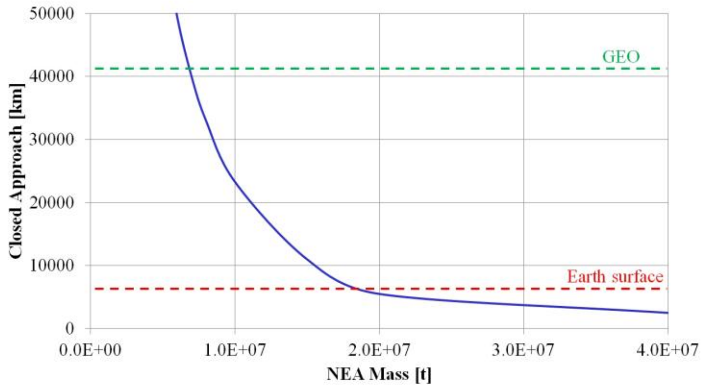

Figure 9: Analysis results for the NEA deflection mission with two 200 kW VASIMR® engines.

to return Viento™ to L1.

As shown in Fig. 9, larger asteroids, with a mass up to 20,000,000 t, may also be deflected just enough to avoid a collision.

V. Conclusion

This work compared the 2008 HU4 asteroid retrieval mission using a 40 kW Hall thruster array with SEP-VASIMR® missions. In terms of future cost, for the optimal power level of 255 kW with a specific impulse of 3400 sec, a SEP-VASIMR® mission is four times more cost-effective than the HET-mission described by the KISS study, because it can complete the mission five times faster. The increased power and variable specific impulse capabilities of the VASIMR® technology also allows a much broader range of asteroid orbits to be engaged with reduced risk regarding the unknown (within a factor of 3) mass of the asteroids. The capabilities of a 400 kW SEP-VASIMR® were also demonstrated for a NEA deflection mission with an orbit similar to 99942 Apophis. It was found that a 400 kW VASIMR® mission can successively deflect an otherwise impacting NEA with a mass of up to 7M t, such that it will miss Earth at the distance of approximately one GEO radius.

VI. References

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