Ad Astra's VASIMR® Space Tug
Near Earth Asteroid (NEA) Retrieval Mission

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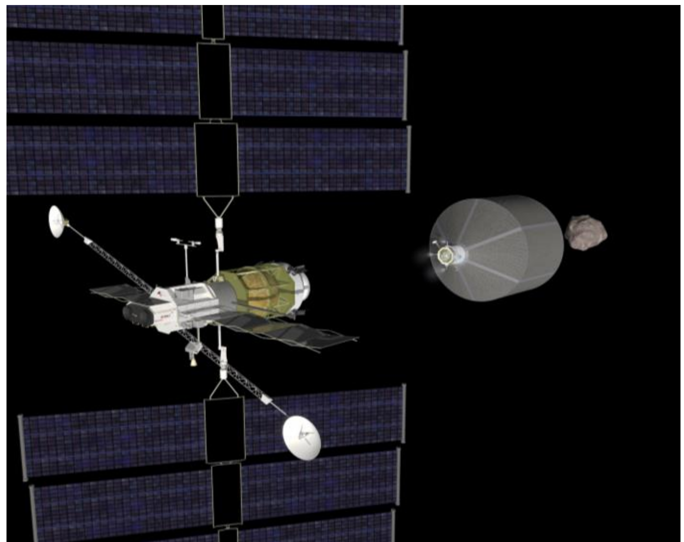

Figure 1: Concept of a 200 kW VASIMR® engine adapted to KISS study NEA retrieval module

Ad Astra Rocket Co (Ad Astra), developers of the VASIMR® electric propulsion engine, presents the advantages of its propulsion technology to move the known 1300 t, 2008HU4 NEA asteroid from its present position to high lunar orbit by means of a high power (> 100 kW), solar electric propulsion (SEP) space tug. The mission architecture is based on the recent Keck Institute for Space Studies (KISS) asteroid retrieval study[1], but, instead of a 40 kW Hall thruster, operating with xenon gas, it considers a more powerful (100 - 400 kW) VASIMR® propulsion system, operating with either of two significantly cheaper propellants: argon or krypton. Ad Astra maintains a VASIMR® rocket prototype running with argon propellant at 200 kW with greater than 70% thruster efficiency[2] in its Houston vacuum chamber. The company has executed more than 10,000 reliable firings of this engine to date. Initial operation with krypton was demonstrated on the VX-200 in 2012.

By confining the SEP technology to the Hall thruster, the KISS study produces a significantly underpowered, 10-year mission, costing $2.6B in 2012 dollars, not including the cost of the xenon propellant or a consideration for the time value of money. Assuming reasonable 20% interest rate, the future cost of the KISS mission is increased to about $20B. **Ad Astra's study concludes that an increase in SEP power from 40 kW to 100 – 400 kW would result in lower cost and faster delivery (see Fig. 2). A 255 kW VASIMR® would result in a 4x future cost improvements and a 5x reduction in the mission time[3].** Although low-power Hall thrusters (< 5 kW) are at high technology readiness level (TRL), for >100 kW, both VASIMR® and Hall thrusters are today at an equivalent TRL of 3-4[4]. High power scalability however, leading to more attractive missions, favors the VASIMR® propulsion system with its electrode-less design (expected to reduce component wear and increase lifetime) and inherent high power density and high I_{sp}, with no thruster scalability concerns at total

[1] J. Brophy, et al. Asteroid Retrieval Feasibility Study, Keck Institute for Space Studies, Pasadena, CA, Apr 2 2012. http://kiss.caltech.edu/study/asteroid/asteroid_final_report.pdf.
[2] B. Longmier, et al. VASIMR VX-200 Performance Measurements and Helicon Throttle Tables Using Argon and Krypton, IEPC-2011-156, 32nd International Electric Propulsion Conference, Wiesbaden, Germany, Sept 11-15, 2011. http://www.adastrarocket.com/Ben_IEPC11-156.pdf
[3] A. V. Ilin VASIMR® Solar Powered Missions for NEA Retrieval and NEA Deflection, IEPC-2013-336, 33rd International Electric Propulsion Conference, Washington, DC, Oct 6-10, 2013.
[4] "NASA Space Technology Roadmaps and Priorities" http://www.nap.edu/catalog.php?record_id=13354#toc NRC p. 122

power of up to 1 MW. Moreover, VASIMR® systems use more economical propellants, such as argon (~$5/kg) and krypton (~$300/kg), than conventional Hall and ion thrusters, which operate with much rarer and expensive xenon (~$1000/kg). Such flexibility results in significant operational cost savings.

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 2: Copernicus trajectory analysis results and rough cost model, including time value of money assessing the effects of VASIMR® on the KISS study NEA retrieval mission.

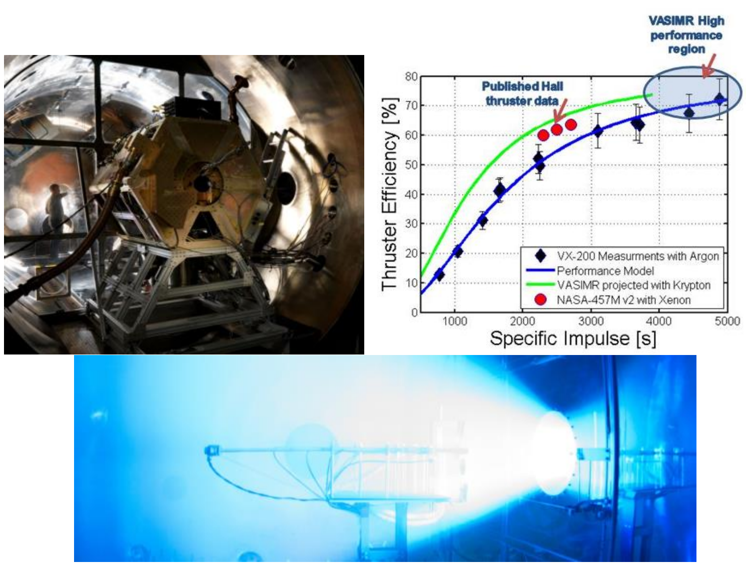

Figure 3: 2011 VX-200 performance data, VX-200 engine, and VX-200 plume at 200 kW