ASTEROID CAPTURE FOR SPACE SOLAR POWER

A PROJECT PLAN

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This project plan describes the approach, technologies, timing, and challenges of capturing the asteroid 99942 Apophis, turning its ores into useful products, and building both an initial constellation of Solar Power Satellites and a permanent orbiting habitat for the workers. Estimates include an overview of the equipment and workers to be launched from the Earth, the number of launches required, a proposed timeline, the direct project costs, and potential profits.

Asteroid Capture for Space Solar Power: A Project Plan focuses on a specific technical approach which enables us to capture an asteroid into Earth orbit using gravitational slingshots around the Earth and the Moon.

The key enabling point is that small orbital changes in advance of a pending gravitational slingshot are greatly amplified, enabling us to effect changes much larger than our existing technologies would otherwise allow.

So why capture an asteroid? The main reason is to gain convenient access to its resources. Even a relatively resource-poor low-iron, low-metal LL chondrite such as Apophis contains 27 megatons of resources including 20% iron, significant quantities of water and other volatiles in the form of hydrated minerals, and oxygen to burn.

We should not forget that capturing an asteroid into a stable Earth orbit eliminates a threat to the planet and our civilization. Merely deflecting an asteroid with a bull's eye on the Earth simply postpones the problem for our children to address.

Key assumptions include:

- Using Apophis locks us into a timeframe around its close approach on April 13, 2029.
- Launch pricing and capabilities are based upon SpaceX Falcon Heavy launch vehicles (announced but not yet built, let alone flown).
- 2011 prices, not adjusted for inflation or cost-of-money.
- Worker launch costs (including supplies) initially average $24M/person, but in a mid 2030's timeframe human-rated transports will be built that can transport 30 to 100 people per launch into LEO at a price of $1,000,000 per ton (also per person).
- Costs do not include in-space worker salaries, partly because they are small compared to launch costs, but also because they may be offset by fees for room & board, sales of real estate, etc. and are thus difficult to quantify. Some workers would volunteer; others may require a significant premium.
- Only R&D costs expected to be directly attributed to a commercial venture are included. Thus technology research costs are ignored, but mission specific R&D costs are included.
- All income is assumed to be from solar power satellite energy sales at a wholesale price of three cents per kilowatt hour, ignoring tourism, the sales/rentals of housing and retail space, sales of propellants or habitats to outside parties, product placement, tie-ins, naming rights, or any other potential revenue sources.

Phase I: Capture Apophis into Earth Orbit

- The Asteroid Capture project begins in 2027 with construction (in LEO) of a space tug.
- The tugship launch from Earth orbit occurs in October of 2027, using a lunar slingshot which adds velocity and matches the inclination of Apophis.
- Five months of thrust and 3 km/s of delta-V later, the tugship matches speed and docks with Apophis.
- Over the next 10 months, an acceleration of 1.0 cm/s per month is applied (a total of 10 cm/s delta-V), followed by coasting for another 3 months. The resulting 200 second delay in reaching the intersect with the Earth's orbit reduces the gravitational slingshot and subsequent delta-V by 1.5 km/s (a factor of 15,000 gain).

- This major slingshot is the near-Earth approach on April 13, 2029 and is tailored to target an orbital capture via Earth & Lunar slingshots a year later. These dates are driven by orbital dynamics.

The deep-space mission duration is approximately 30 months, plus time to spiral out to the Moon, and more time for the final spiral back down into LEO.

TUGSHIP COST SUMMARY:

A large tugship using ion thrusters and powered by solar panels is to be assembled in LEO from modular components. The components to be launched include:

- The core crew quarters with life support and the tools needed to grapple the asteroid.
- 100 tons of fuel and sufficient thrusters to achieve 200 Newtons of thrust.
- 10 megawatts of solar panels (a 200x200 meter array may generate 12 megawatts).
- The components total 250 tons, requiring 5 Falcon Heavy launches ($600M); cost of equipment is another $1.5B. This cost is lower than many large space-based projects because of the extensive use of modular components assembled by humans in space (reducing the need for first-time perfection).

The tugship must be assembled in LEO, and then crewed for the deep-space mission:

- Launch in-orbit assembly crew: 1 launch @ $100M, plus another launch of a construction shack & supplies ($500M), probably another $1B for training, tools, supplies, & support staff. 12-18 person-months of assembly is required.
- Separately launch the mission crew & supplies (one launch @ $100M)
- The capture mission duration is a little over 30 months; with recycling of water & oxygen, supplies for a crew of 4 masses six tons.

Total capture cost: $3.8B.

PHASE II: LAUNCH MINING & MANUFACTURING TOOLS

Once we've captured the asteroid, we need to exploit it. Mining & Manufacturing is a big unknown, in that we don't yet know how best to do mining, smelting, refining, and manufacturing in microgravity conditions, plus we'll need to recycle & save everything. We'll need to launch the initial equipment and tools to make tools so most of the needed additional equipment can be manufactured in space. These launches begin in 2030 and each launch from Earth places 50 tons into LEO. The tugship will be refueled and used to transport these components from LEO to the asteroid in high Earth orbit (HEO). The components include:

- Solar Power generator: 1 launch and $200M for 6 megawatts of solar electric power.
- Mining facility (ore movers, grinders, separators): 2 launches, $400M
- Solar smelter, gas collection & refining, metal purification: 5 launches, $1B
- Steel production: 5 launches, $1B
- Rolling mill (girders, rods, sheet metal): 3 launches, $600M
- Finished metal product plant (nuts, bolts, rivets, connectors, pipes, tanks, etc.): 2 launches, $400M
- Silicon refinery & solar panel manufacturing (3 launches, $600M)
- Slag processing, shaping, rock wool production, & slag handling (1 launch, $200M)

The total estimate is $4.4B for equipment and 22 launches (1,100 tons), and this phase begins in 2030, ends in early 2031.

PHASE III: WORKFORCE RAMP-UP & SPS/HABITAT CONSTRUCTION

The workforce & construction shack launches begin in 2030. The initial 36 person worker, housing, and supplies costs is $1.2B ($33M/person). While an initial 36 worker contingent will be sufficient to prove the feasibility of mining, refining, and manufacturing in space, it will be inadequate to achieve sufficient volumes of production for a timely project completion.

A ramp-up to 500 workers by the end of 2031 results in a steel production rate of roughly 100 tons per day, which in turn allows construction of the habitat pressure shell plus containers for the captured volatiles (oxygen, CO2, and H2O). At this point (an interim habitat consisting only of a spinning pressurized shell with partial radiation shielding), many of the workers can work without pressure suits, gravity prevents long-term health problems of zero-G living, and in-space production of food can begin.

Doubling the population and production annually allows the first SPS to be completed by the end of 2032 when steel production is 200 tons per day, comparable to a small mill on Earth. 2033 would see 2 more SPS's completed, and 2034 results in 4 more and completion of the habitat internal structures. By the end of 2034 the habitat capacity is approached, and the associated manufacturing facilities and workforce should be capable of building 8 SPS's per year. It takes all of the slag associated with building the first 12 SPS's to fully shield the habitat, which occurs during 2035. By the end of that year, the first permanent habitat (8,000 person capacity) is complete, along with 15 Solar Power Satellites.

COMPONENTS OF A 5 GIGAWATT SPS

The construction of a Solar Power satellite requires multiple components, most of which will need to be built in orbit. For more details, see my blog post, Solar Power Satellite Design Considerations. The components are:

- Solar Panels (from high-grade silicon, in thin sheets such as commonly manufactured today)
- Steel structures to frame and aim the panels.
- Steel structures and motors to maintain alignment of the panels with the sun, and the antenna with the target Earth station.
- Microwave transmitting antenna
- Microwave transmitter electronics
- Shield mass to protect the electronics from meteorite damage and workers from radiation exposure.

The motors and electronics (including the microwave transmitter) will be launched from Earth ($200M per SPS). While the total mass budget is 5,000 tons per gigawatt, this number is not critical, as using the captured asteroid's ores makes the cost relatively insensitive to the mass. However, there is a significant assembly cost in person-hours, giving an incentive to use efficient solar cells to reduce the needed area as much as possible.

DEPLOYMENT OF SOLAR POWER SATELLITES

Each SPS is built outside the habitat in high Earth orbit and must be deployed into an appropriate geostationary orbit. This requires a considerable amount of fuel.

The total delta-V needed is roughly 2 km/s, the total mass is 25,000 tons, and even using 5,000 ISP ion thrusters, 1,000 tons of fuel is needed. Luckily, that is a small fraction of the 5,000-10,000 tons of oxygen produced as a by-product of the smelting of iron ore into steel for each SPS. Also luckily, a great deal of power is available thanks to the multi-gigawatt solar panel arrays, so the time required for this orbit change is limited largely by the number of ion thrusters (and thus the fuel flow rate) dedicated to this task. Note to ion thruster designers – smelting Apophis into iron produces over a million tons of oxygen, and it may not be a perfect fuel, but it is cheap and plentiful.

Once in GSO, the Earth-launched components are installed, primarily the microwave transmitter electronics and possibly the motors to maintain Earth-station and solar alignments.

Each SPS will require a matching ground receiving station consisting of a large (10+ kilometer) rectenna plus power conversion and distribution. The roughly $1B of ground-side costs are not included in the summary, as this cost would be born by the receiving local electric utility.

KALPANA ONE STYLE HABITAT

Another of my blog posts details the Design of a minimum Kalpana-One style Habitat: a 100-meter radius cylinder, 130 meters wide, spinning at 3rpm for 1G along the outer rim, lined with 3 meters of slag or 5 meters of regolith (a total of 10 t/m^2) which provides excellent shielding against radiation and meteorites. Some fundamental physical constraints of practical orbiting habitats are described by Al Globus, et al., in the 2007 paper, "The Kalpana One Orbital Space Settlement Revised."

This project plan uses a modified Kalpana One style design in which there are multiple floors for living, working, and agricultural space; high-efficiency LEDs are used for farming (the in-habitat power consumption is 6kw/p); and the population capacity is established as the maximum that can be cooled by passive radiation from the shell surface (at 0°C). These changes greatly increase the number of worker/colonists that may be supported.

The outer pressure shell is built using average strength (easily welded) steel plates nearly 1 inch thick, and masses approximately 28,000 tons. Standard engineering formulas for pressure vessel design are used, with the shield mass added to the pressure requirement. Completed first, once spun up and pressurized it provides a shirt-sleeve environment with gravity, boosting the productivity and health of the workers.

Over time, blocks of slag are brought inside to line the exterior walls, and interior structures are built as housing, workspaces, and farmland.

The total internal structures (including the outer 15 meters along the endcaps, 6 levels of rooms lining the cylinder rim, and a 40 meter diameter core structure) masses 126,000 tons (a generous allowance). This is less tonnage than an Oasis Class Cruise Ship (225,000 tons carrying 8,000 passengers and crew) yet is much more spacious.

Power (6 kw/inhabitant or 50 megawatts total) is provided by solar panels. Additional power needed for exterior factories (such as the smelter) is included in their structures and allowances.

It takes considerable fuel and energy to spin up the habitat to 3rpm: about 1150 tons of fuel at an ISP of 5,000. Using 25 megawatts (half of the habitat's available power), the spin up takes nearly 2 years. However, the empty shell (no shield mass) spins up very quickly; the majority of the energy is needed to maintain the spin as roughly a million tons of shield mass is gradually added to the habitat's periphery.

FEATURES OF THE MINIMUM KALPANA ONE HABITAT

Once complete, this habitat houses 8,000 worker / colonists, and provides all life-support needs.

- Agriculture space (primarily for crops) is more than 5.5 million square feet;
- Residential space is over 2.5 million square feet, equivalent to about 300 sf per person;
- There is 1.5 million square feet of offices / retail / light industrial;
- A million square feet of storage and overhead space.
- Most of the volume is left open to eventually become a 12 acre cylindrical park, the ceiling of which is 150 meters overhead.
- A 25-meter-radius core structure will be available as a low-gravity industrial and research space.

All of the 154,000 tons of steel and 1.6 million tons of shield mass are from the asteroid, along with the oxygen, water, and carbon needed for the life support system. The known components to be launched from Earth include the LED's and other light sources for the farms and interior (see another blog post, **Lighting our Space Habitats**), various electronics, seeds, and perhaps 50 kilograms of nitrogen (per inhabitant) needed as fertilizer. We'll continue to depend upon Earth resources for pharmaceuticals and high-tech equipment such as cell phones and computers, of course.

There are no additional launch or equipment costs not included elsewhere (possibly excluding the ion thrusters needed for spin-up or to move the habitat to another orbit).

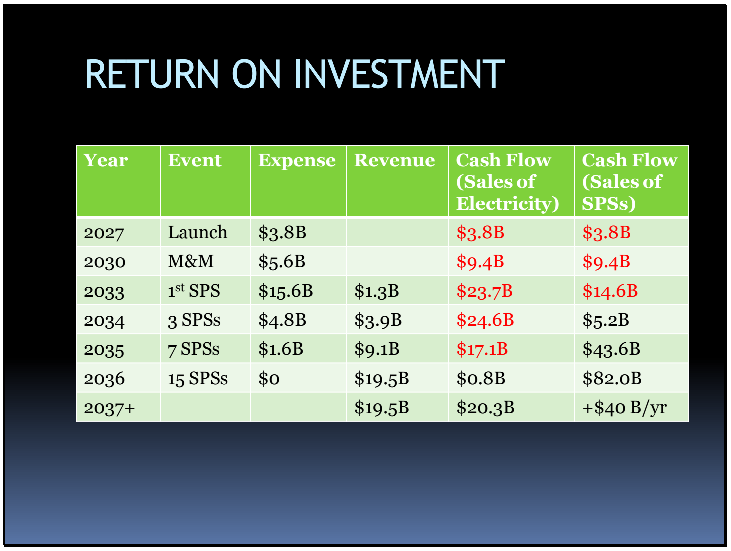
PHASE IV: REPEAT UNTIL RESOURCES EXHAUSTED

This project is an eight-year plan (5 years to the first SPS) culminating in the deployment of a permanent, self-sustaining habitat with a population of 8,000 and fifteen 5-gigawatt Solar Power Satellites in geostationary Earth orbit.

- By completion, the project will have consumed less than 10% of Apophis, leaving the vast majority available to build additional habitats and Solar Power Satellites.
- The capacity will be in place to build additional Solar Power Satellites at the rate of 8 per year, but note that demand is much higher: current global electric demand would need 400 five-gigawatt SPS's to fill.
- Apophis alone has sufficient resources to build up to 150 of these Solar Power Satellites (while building 12 habitats accommodating 8,000 people each), but in the long run additional asteroids will be needed.
- We should build additional habitats, including larger ones, as part of an ongoing project. Note that there is no economy of scale – larger habitats require more steel per person (for the shell), meaning that less steel is left over with which to build solar power satellites. Indeed, a one-kilometer radius habitat (spinning at 1 rpm, and housing nearly 700,000 people) uses all of the steel and slag from a 500 meter diameter stony asteroid, leaving none for SPSs. To build larger habitats, we need iron asteroids or we'll produce more slag than we need for shielding. A side note: while steel is strong enough to build truly huge habitats (100 km radius), the largest practical habitat would have a radius of 8 km and house about 50 million people. The largest known nickel-iron asteroid (16 Psyche) contains enough iron to build over 1.5 million of these, enough to house 75 trillion people – 10,000 times the Earth's current population.

We'll likely need a "mining town" for each asteroid we capture, and an SPS construction & maintenance habitat just outside of geostationary orbit, and even a large habitat in low Earth orbit (or as low as possible without serious atmospheric drag) as an Earth to LEO launch target and tourist destination. Good arguments can be made for additional habitats in various Lagrange points such as L5, and for transition orbits such as LEO to Geostationary, or to the Lagrange points. There may even be a 3:1 Lunar-synchronous stable Earth orbit that visits L3, L4, and L5 in succession, 9.1 days apart – an ideal platform from which to host interplanetary missions, including to Mars.

Speaking of Mars, what safer way is there to travel than in one of these huge, self-contained habitats, accompanied by 8,000 friends? From HEO it takes roughly 5 km/s of delta-V to match orbits with Deimos or Phobos, requiring 175,000 tons of fuel, which is still less than the oxygen produced by the smelting of the ore used to build the habitat and a dozen solar power satellites. And once there, we can begin to mine the moons of Mars which appear to be rich carbonaceous chondrites. The smaller moon, Deimos, contains enough ores to build 9,000 1-km habitats (housing 700,000 each) – a total nearly matching Earth's current population. Phobos is eight times larger.



RETURN ON INVESTMENT

Year	Event	Expense	Revenue	Cash Flow (Sales of Electricity)	Cash Flow (Sales of SPSs)
2027	Launch	$3.8B		$3.8B	$3.8B
2030	M&M	$5.6B		$9.4B	$9.4B
2033	1st SPS	$15.6B	$1.3B	$23.7B	$14.6B
2034	3 SPSs	$4.8B	$3.9B	$24.6B	$5.2B
2035	7 SPSs	$1.6B	$9.1B	$17.1B	$43.6B
2036	15 SPSs	$0	$19.5B	$0.8B	$82.0B
2037+			$19.5B	$20.3B	+$40 B/yr

It all sounds time consuming and expensive: nearly $25 Billion before that first SPS is operational. But in 2033 that first SPS will generate $1.3B in cash flow (at a wholesale price of $0.03/kwh), in 2034 the 3 deployed SPS's generate another $3.9B, in 2035 the 7 deployed SPS's generate $9.1B, and subsequently the 15 SPS's generate nearly $20B/year. The steel production rate is 800 tons per day, allowing 8 or more additional SPS's to be built each year. The peak cash outlay is $25B with all investment repaid in 2036 – and huge net profits after that.

Alternatively, the Solar Power Satellites could be sold outright to the electric utility for perhaps $5B each, reducing the peak cash outflow to $15B, moving breakeven up to 2034, and generating $40B/year after that (assuming an 8 SPS/year build rate), at least until the asteroid is exhausted.

Even considering only that first five-gigawatt SPS, the total cost is comparable to the $5 billion per gigawatt that my local power company plans to spend on a nuclear power plant, without any need for radioactive waste disposal or refueling, and without quite as much local objection to the installation.

RESEARCH & DEVELOPMENT

It may be an unreal oversimplification, but this analysis ignores the fundamental R&D costs for this project although they are large and unknown. NASA, the various governments, and the network of universities should bear this cost as part of their normal operations (supported by taxes and donations), although the more directed research should be borne by the corporations that will profit from the sales of related technologies, equipment, and supplies.

Known areas of research & development include:

- Heavy or super-heavy lift launch vehicles
- Space taxies / trucks (using ion thrusters to cheaply change orbits and to capture the asteroid)
- Long-term life support (recycling & farming in space)
- Zero gravity mining, smelting, refining, and manufacturing (note need to recycle reagents and to capture and utilize byproducts such as CO2).
- Manufacturing solar photovoltaic panels from asteroid materials
- High-efficiency multi-gigawatt microwave transmitters / receivers
- Large-scale in-space construction techniques (of SPS and habitats) with limited resources

CONCLUSIONS

- 2036: Breakeven (after $25B peak investment)
- 2037: $19.5B/year gross profits (8.4% of Apophis)
- 2053: (assuming deployment of 8 SPSs/year)
    - 150 SPSs deployed
    - $195B/year revenue
    - 12 orbital habitats – 100,000 person total capacity
- The asteroid Apophis is only a memory
- *But there are many more asteroids out there!*

This is an optimistic project plan. It is likely to take longer than this project plan, due to unforeseen setbacks. Some additional costs must be considered: the cost of money, the cost of bringing some or all of these workers back to Earth, salaries, ground support costs, resupply costs for items that can't yet be manufactured in space. To be fair, some additional revenues should be included: sales or rentals of habitats or other real estate (condos, retail, office & manufacturing space); life support (food, oxygen, water, recycling); tourism; sales of propellants to third parties; naming rights; tie-ins; possibly product placement; and satellite maintenance services.

But even if it takes another year or two before breakeven, even if the costs might run 20% (or 100%) higher, even if we factor in the up-front R&D costs, even if we add a generous salary for every in-space worker plus free room & board, this is still a wildly profitable venture.

Is there an entrepreneur listening that likes the sound of <u>$200 billion per year</u> of free cash flow for a measly $30 billion investment? And with the bonus of earning a permanent place in the history books for bootstrapping humanity's move into the Solar System?!