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# HUMAN EXPLORATION OF NEAR-EARTH ASTEROIDS VIA SOLAR ELECTRIC PROPULSION

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There have been many proposed technologies and architectures to extend a human presence beyond the Moon. Solar electric propulsion (SEP) provides the capability to implement a wide variety of missions with relatively low injected mass to low-Earth orbit. Because of its broad applicability this technology can enable progressively ambitious steps towards Mars by incrementally increasing power. The benefits of SEP are addressed for cis-lunar excursions, near-Earth asteroid exploration, and missions to Phobos and Deimos, and compared to chemical propulsion and nuclear thermal technologies. In particular, SEP expands the range of near-Earth asteroids accessible with a constrained launch capability (IMLEO).

## INTRODUCTION

In the wake of the monumental achievement of extending our presence to the Moon, there has been much anticipation to further the expansion of destinations for human space exploration. For many, the next desired target is Mars; however, despite decades of proposed missions and comparative analyses there is no definite plan for how we shall go to Mars. Further, any potential mode of Mars exploration only indicates a goal for our space-faring capabilities: it does not provide the (arguably less definite) path to achieving these capabilities. We present a stepping-stone approach [1], [2] from low-Earth orbit to Mars that includes excursions in cis-lunar space, among near-Earth asteroids [3]–[13], and to Phobos and Deimos. The primary goal of this approach is to introduce flexibility into the exploration schedule while minimizing risk to the taxpayers and, more importantly, to the astronauts. Flexibility is infused by incorporating frequent launch opportunities for progressively ambitious missions. Additional flexibility emerges by including multiple technology development paths from Earth-orbital to Mars-orbital missions. The evaluation of multiple steps on multiple paths forms a basis to derive a safe and economical exploration program.

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## EXPLORATION TECHNOLOGIES AND ARCHITECTURES

### Chemical Propulsion

The first architecture for reaching destinations considered is one that uses only chemical propulsion. In this scenario, the Deep Space Vehicle (DSV) is assembled and fueled in LEO and crew rendezvous is in 400 km, circular Low Earth Orbit (LEO). Because of the impulsive nature of high-thrust maneuvers, the $\Delta V$ and propellant required for other staging locations (such as a High Earth Orbit (HEO) or Earth-Moon L1/L2) would be the same or higher. The chemical propulsion system is assumed to be a cryogenic, zero boil-off LOX/LH2 system (450 s Isp). Trajectories are constrained to have a minimum stay time of 30 days at the destination. The crew is returned to Earth via direct-entry in a crew capsule, and the entry speed (at 125 km altitude) is constrained to be 12 km/s or less.

The flight elements are (1) a 22 t transit habitat [14]–[18], (2) a 10 t launch/entry crew capsule [12], [17], [19], and (3) a Cryogenic Propulsion System (CPS) with 20% of the fuel mass as inert mass [17], [20]. Three CPS stages are used: Earth departure burn, arrival rendezvous burn, and Earth return burn. In addition 20 kg/d of consumables are carried for a crew of four [17],[21].

### Nuclear Thermal Rockets

The second architecture modifies the first by replacing the CPS with a Nuclear Thermal Rocket (NTR). The NTR system provides an Isp of 900 s with a 35% inert/propellant mass ratio. The system provides a 0.2 g burn and a thrust to weight ratio of 3.5 for the engine plus shielding [4],[16],[17],[20],[22]. The same staging as the first architecture is used, but only for tanks. The engine and shielding is retained.

### Solar Electric Propulsion

The third architecture used a hybrid of chemical propulsion and Solar Electric Propulsion (SEP) and is distinct compared to the previous two architectures. The DSV is assembled in LEO and spirals with SEP to a 10-day elliptical High Earth Orbit (HEO) with a C3 of -2 $km^2/s^2$. The crew then is launched in the crew capsule for a rendezvous in this orbit. The DSV with crew then performs an escape maneuver at perigee to reach the desired outbound hyperbolic asymptote for the interplanetary trajectory, which is then flown entirely with SEP. This staging and escape sequence is illustrated in Figure 1.

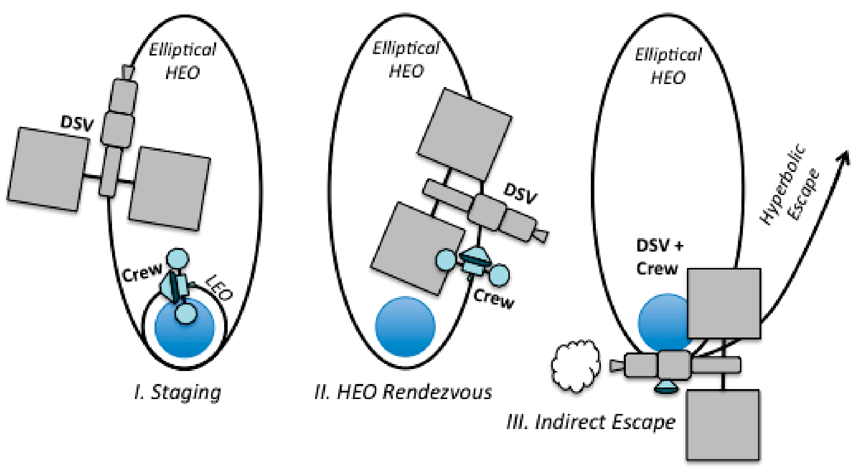


**Figure 1. High Earth Orbit (HEO) Staging and Escape Sequence**

Because this architecture uses low-thrust propulsion the pre-departure staging strategy has a substantial performance impact unlike in the previous two architectures. Staging in the 10-day elliptical HEO with a departure burn at a 400 km perigee can reduce the chemical departure burn by 3.1 km/s. For the DSV, a 2-year SEP LEO to HEO spiral provides this $\Delta V$ much more efficiently than a chemical burn. After the spiral, the DSV can be staged in orbits with perigee above the Van Allen belt and Lunar Gravity-Assists (LGAs) can be used to lower perigee to 400 km and orient the elliptical HEO prior to the departure burn. The crew capsule still uses chemical propulsion for the 3.1 km/s LEO to HEO $\Delta V$, so the crew flight time is not affected by the duration of the SEP spiral and LGA trajectory.

The same flight elements and CPS as Architecture 1 is used with the addition of a SEP stage. The SEP stage has a specific power of 30 kg/kW plus an additional inert mass of 15% of the propellant and operates at power levels of 100s of kW [22]–[28]. The SEP stage would process up to 100 t of propellant [25] with two operational modes: 1) a high-Isp mode with 3000 s Isp and 65% $P_{jet}/P_0$ efficiency for the LEO to HEO spiral and 2) a high-thrust mode with 1600 s Isp and a 50% $P_{jet}/P_0$ efficiency [27].

## TRAJECTORIES TO NEAR-EARTH ASTEROIDS

### Catalog Search

The entire catalog of known near-Earth asteroids (NEAs) in the JPL Small Body Database (http://ssd.jpl.nasa.gov/sbdb_query.cgi) comprising 7650 objects (on January 29, 2011) was used in the near-Earth asteroid trajectory search. The trajectory search parameters included launch between 2015 and 2040, minimum 30-d asteroid stay time, maximum 720-d mission duration, and maximum 12-km/s total mission $\Delta V$. A grid with seven-day intervals was applied to the launch, NEA arrival, NEA departure and Earth return dates and all combinations (within the flight time and $\Delta V$ limits) were examined. Once the mission $\Delta V$ was calculated the trajectories were sorted and filtered to provide the minimum $\Delta V$ for maximum flight times of 90, 180, 270, 360, 450, 540, 630, and 720 days and for launch opportunities in 90-day increments. In this way the minimum $\Delta V$ trajectory in each quarter year for each of the maximum flight times was saved. The end result was ~50,000 filtered trajectories to ~1,400 unique targets.

### Trajectory optimization

The trajectories in the filtered set were used as the seed trajectories (initial guesses) in JPL's impulsive-$\Delta V$ optimizer, MIDAS [29], and low-thrust optimizer, MALTO [30]. The MIDAS trajectories were optimized for minimum $\Delta V$ and deep-space maneuvers were permitted on both the outbound and inbound legs. The MALTO trajectories were optimized for maximum net mass assuming 240 t IMLEO and 300 kW maximum SEP power with the design parameters provided in the "Exploration Technologies and Architectures" section. The mass and power of the resulting trajectories are then scaled to provide the desired payload mass (transit habitat, capsule, and consumables) while maintaining the same $C_3$, $\Delta V$, and flight time of the original trajectories [31].

## EXPLORATION ON A FLEXIBLE PATH

### Mars Surface and Moons

Previous studies have noted that electric propulsion can offer significant reductions in the injected mass to low-Earth orbit (IMLEO) for Mars surface exploration when compared to other promising technologies such as aerocapture, in-situ propellant production, and nuclear thermal rockets [32]–[35]. The key application of this technology to Mars missions is delivery of propulsion stages and cargo to high-Earth orbit and to Mars entry. It was found that scaling the inert mass fractions of current SEP technology to several hundred kW could reduce the IMLEO by 100s of tons compared to all-chemical architectures. Given the combination of high mass efficiency and relative technological maturity, we saw SEP as an ideal investment for sustained deep-space exploration.

However electric propulsion for crew transfers require prohibitively high power levels and unrealistic inert mass fractions to fly on short (150–240 d) interplanetary transfers that permit long (500-600 d) surface stays [35]. The application of SEP appeared to be limited to only cargo transfer for Mars missions. However, if the stay time on the surface is relaxed, then crew transfer with SEP begins to appear feasible. In addition to reduced exploration time, a notable drawback for surface missions is that the crew spends more time in interplanetary space without the natural gravity and radiation shielding of Mars. These concerns are less germane to alternative destinations such as Phobos and Deimos or near-Earth asteroids, where the crew depends on the transit habitat as a safe haven. It was found that a combined stay time of 2–4 months on Phobos and Deimos was possible with trip durations of less than three years (similar to Mars surface missions) and several hundred kW (well less than a MW) of power [36]. An example mission to Phobos and Deimos is presented in Figure 2. The IMLEO values of around 300 t with 600-kW SEP are on par with the IMLEO from NTR, while all-chemical architectures require 700-800 t. The flight time and IMLEO between SEP and NTR are similar, but the impulsive $\Delta V$ trajectories available with NTR provide significantly longer stay times; nevertheless the moons of Mars are accessible with SEP. The moderate IMLEO and power levels required for Phobos and Deimos with SEP help establish these targets as destinations on a flexible path to the surface of Mars. Moreover, the design requirements for these missions provide a target capability to be developed during the NEA exploration missions.

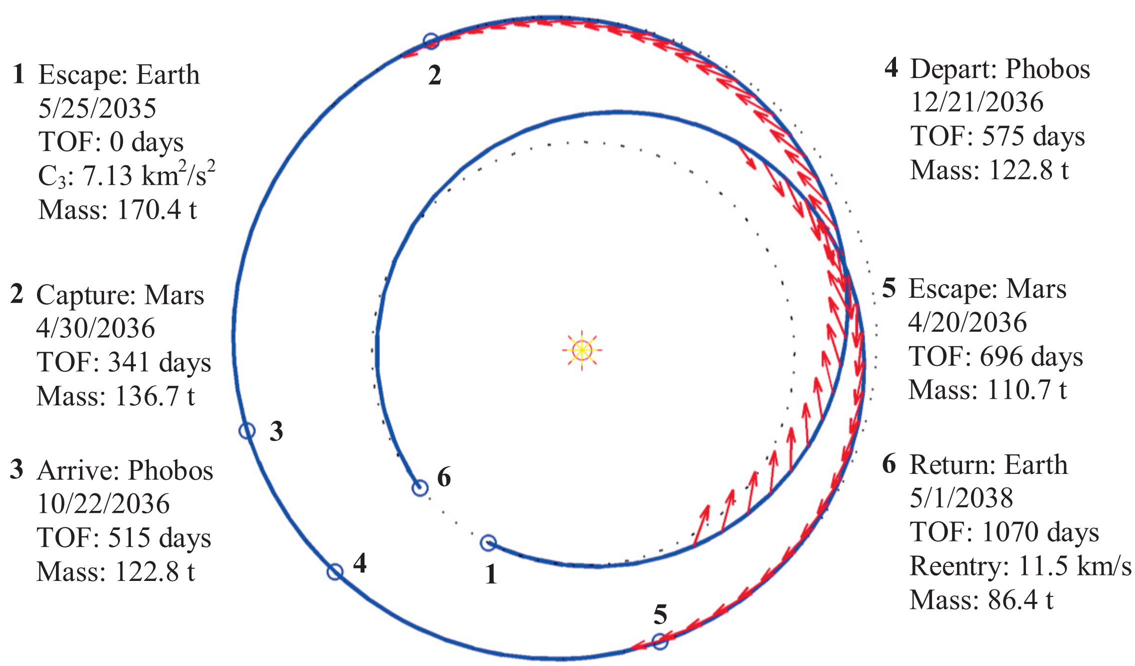


**Figure 2. A two-month stay at Phobos and Deimos is achievable with 600-kW SEP, 270 t IMLEO, and three-year flight time.**

### High-Earth Orbit and Cis-Lunar Space

If missions to Mars represent the ultimate goal for a new era of space exploration, then travel within cis-lunar space would define the starting off point. Further, the technologies that enable the first forays beyond LEO should lead directly to technologies that enable more ambitious missions and introduce additional options on a flexible path to Mars. For example SEP reduces the amount of propellant that must be launched for any mission to depart LEO and is not just applicable to Mars missions. Moreover, SEP is already in common use today (it is ubiquitous on telecommunication satellites), and inherently scales as mission requirements increase [24],[28], making it an ideal technology to bridge the gap in incremental steps from cis-lunar to Mars exploration.

The mass fraction and time to spiral from LEO to high-Earth orbit (to lunar altitude) scales with array power and $I_{sp}$ as given by Figure 3 and Figure 4. These curves do not account for Earth shadowing or radiation effects, which could lengthen trip time if not accounted for [37]. We select a power level (kW) of twice the IMLEO (t) and an $I_{sp}$ of 3000 seconds to provide a balance between efficient mass fraction (71% from Figure 3) and spiral time (2.2 years from Figure 4, or about one Earth-Mars synodic period). The long spiral time precludes the use of SEP to transport crew from LEO to the Moon and thus requires rendezvous in orbit, which presents a trade between mass efficiency with SEP and operational simplicity with heavy lift launchers. For example, a one-year cis-lunar mission can be initiated by pre-placing the habitat (22 t) and SEP stage (15 t, 90 kW) with consumables (7 t) in high-Earth orbit with two 22-t launch vehicles. Two-years later the crew and capsule (10 t) rendezvous with the habitat in high-Earth orbit via a high-thrust upperstage (16 t), thus requiring one or two additional launches. This scenario could be accomplished with four launches and a total of 70 t to LEO. Alternatively, the crew could launch directly to high earth orbit using a 60-t upper stage in a 100-t heavy lift vehicle without the need for existing launch vehicles. If heavy lift technology doesn't mature in time, then SEP can be enabling, or if on-orbit assembly (as demonstrated with the International Space Station) becomes prohibitive, then heavy lift becomes an enabling technology. The investment of on-orbit vehicle assembly buys a mass efficiency with SEP that tends to provide increasingly dramatic reductions in IMLEO as deep-space missions become more ambitious.

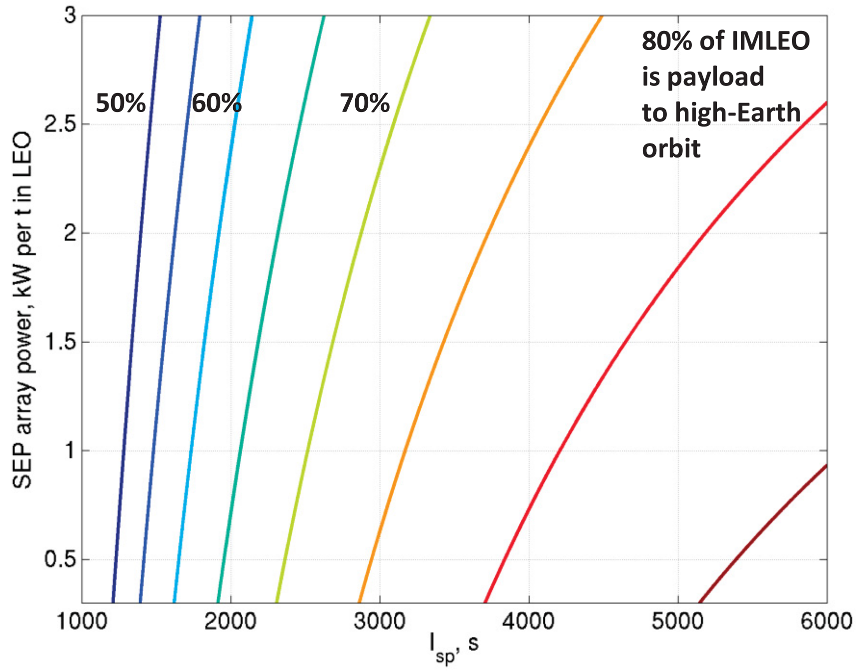


**Figure 3. The payload mass fraction to lunar flyby displays diminishing returns beyond 3,000–4,000 s of specific impulse.**

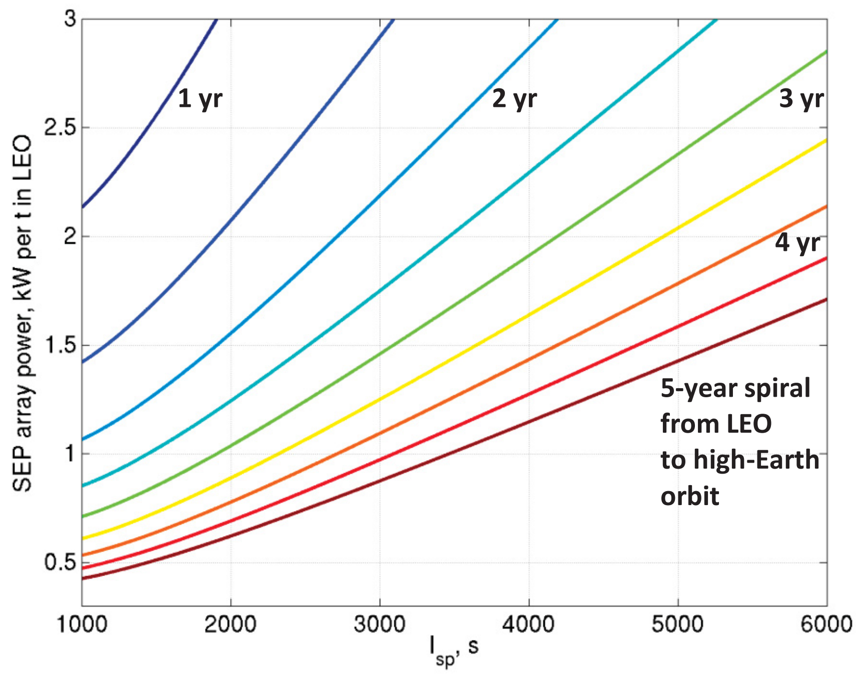


**Figure 4. The flight time to spiral from LEO to lunar flyby increases rapidly for low power and high specific impulse.**

### Near-Earth Asteroids

The NEA trajectory scan resulted in a list of over a thousand potential targets, but not all objects are available in a given launch period or with a maximum IMLEO capability or with a maximum flight time capability. Limiting the NEA exploration capabilities to a few “choice” targets would likely introduce a dead-end on an otherwise flexible path. Conversely, investing in technology that provides sustained access to a desired target population introduces tremendous target and schedule flexibility. For example, in Figure 5 there are several launch opportunities to visit NEAs that are larger than a km in diameter, but these targets are inaccessible with limited launch and habitat capability. (Each dot in Figure 5 represents a unique target and launch year combination.) In this case the desire to explore a choice target could drive capability requirements beyond near-term development and irrevocably delay exploration on a flexible path. On the other end of the spectrum, there are several 10-m objects that are accessible with relatively modest launch and habitat capability (circles in Figure 5), but exploring those targets may not provide a meaningful advancement on a program leading to Mars. In this case the desire to limit mission requirements could drive target availability below a threshold that enables progressively ambitious missions in a flexible exploration program. Between these two extremes lies a mission set that potentially bridges the gap from highly accessible NEAs with cis-lunar capability to highly desirable NEAs with Mars-orbit capability. As deep-space exploration progresses towards Mars, the expanding range of accessible NEAs provides a flexible target set that grows with increasing exploration capability.

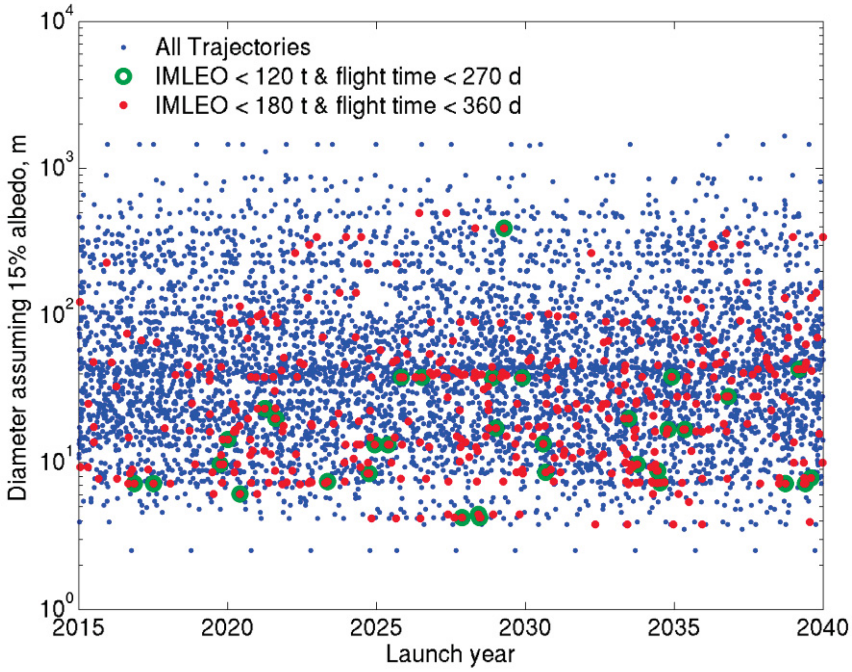


**Figure 5. The number of potential targets depends on IMLEO, flight time, and diameter.**

The ability to match more desirable targets with more capable exploration systems provides flexibility in technology development, and designing frequent launch opportunities to those targets provides schedule flexibility. Instead of expecting innovation to occur on schedule or waiting for an exceptional launch opportunity to a single target, a set of targets could provide regular opportunities over a range of launch years so that a mission is available whenever the technology is. The dependence of mission frequency on target size is illustrated in Figure 6 for different technology architectures. For a desired frequency of opportunities, there is a maximum NEA diameter that is accessible with a given technology set. In the case of once per Earth-Mars synodic period (or 0.47 targets per year) the maximum diameter is about 20 m with chemical propulsion, 100 m with NTR, and about 300 m with SEP. The investment of in-space propulsion technology provides accessibility to a set of targets that are potentially more meaningful on an exploration path to Mars. Moreover, the increasingly ambitious target sets are not tied to a schedule, but instead correspond to technological capability that can grow at whatever pace space policy allows. The mission frequency in Figure 6 is valid for a single combination of IMLEO and flight time, and the number of available missions depends not only on desired target set but also on the launch vehicle and transit habitat capabilities. Conversely, for a desired target size and frequency of launch opportunities, there is a range of IMLEO and flight times that will fulfill the mission requirements.

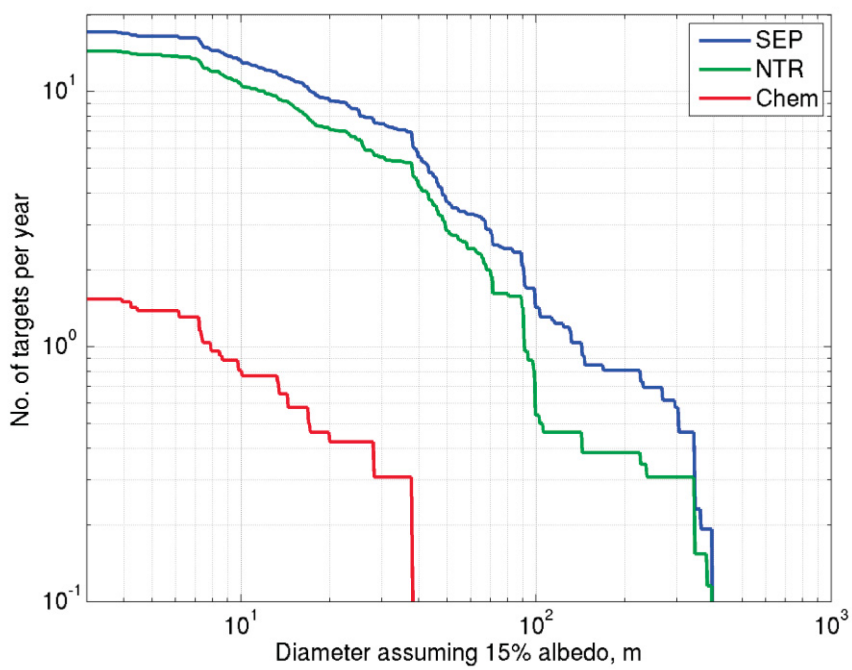


**Figure 6. Number of mission opportunities with IMLEO < 180 t and flight time < 360 days varies with potential target size and exploration architecture.**

In the case of a desired launch frequency of one mission per Earth-Mars synodic period, the range of IMLEO and flight time for various target diameters may be found in Figure 7. The examined NEA diameters (different lines) are 10m, 50m, 100m, 500m, and 1km, and the examined architectures are chemical propulsion (red crosses), nuclear thermal rockets (green x) and SEP (blue circles). This figure encapsulates an entire exploration program beginning with cis-lunar excursions, to various sized NEAs, and eventually to the moons of Mars. Each marker in Figure 7 includes twelve distinct mission opportunities (one mission every 2.14 years from 2015–2040). The missions toward the lower left of the figure would size the capabilities required for the first forays past the Moon, where the development of those capabilities could occur any time between

2015 and 2040. Target sets that include progressively larger objects (used here as a proxy for suitability) can be obtained by sampling the contours from lower left to upper right of Figure 7. NEA missions leading directly to Phobos and Deimos exploration are found towards the upper right, where mission sets comprising twelve opportunities could prove the capability to reach Mars from 2015 to 2040.

The exploration of NEAs supports a variety of potential technology paths from cis-lunar missions to Mars orbit. For example, the development of NTR technology permits a program that begins with low flight times and increasing IMLEO followed by increasing flight times and with a capped IMLEO. Missions with 180-d flight times to 10-m, 50-m and 100-m NEAs are possible with 140-t, 190-t, and 300-t IMLEO, then 500-m NEAs and Phobos/Deimos missions with 300-t IMLEO are possible at 450-day and 950-day flight times. In this case, launch vehicle development would occur first, followed by habitat development. Alternatively, SEP missions with 120-t IMLEO to 10-m, 50-m, and 100-m NEAs are possible with 360-d, 450-d, and 540-d flight times, then 500-m NEAs are accessible with 160-t IMLEO and 720-d flight time leading to a Phobos/Deimos mission with 270-t IMLEO and 1050-d flight time. Here, habitat development would occur first, followed by additional launch vehicle and habitat development. The switch from chemical propulsion to more efficient technology could occur later in the exploration program as well. For example, an increase in IMLEO and flight time capability from 160-t and 360-d to 230-t and 540-d enables chemical missions from 10-m to 50-m NEAs. Then, the development of 300-kW SEP enables missions to 500-m NEAs with the same IMLEO and flight time as the chemical missions to 50-m targets. A doubling of SEP power and flight time could then permit Phobos/Deimos missions with 270-t IMLEO. NEA missions provide the flexibility to progress to Mars via many different technology programs, which facilitates sustained exploration with an uncertain development path and schedule.

In Figure 7 we note that chemical architectures require about twice the IMLEO as NTR or SEP for a given target diameter. NTR technology provides access to more potential targets at short flight times while SEP is more advantageous at longer flight times. For example, periodic SEP opportunities do not exist (where SEP propels the habitat) at flight times of 180-days, while 500-m NEAs can be routinely visited for the same IMLEO that permits only 100-m NEAs with NTR at 720-days flight time. The SEP trajectories require power levels of a few hundred kW as shown in Figure 8. The SEP power level in the remaining figures (Figure 9–Figure 13) never exceeds 500 kW. The power levels are roughly proportional to the corresponding IMLEO.

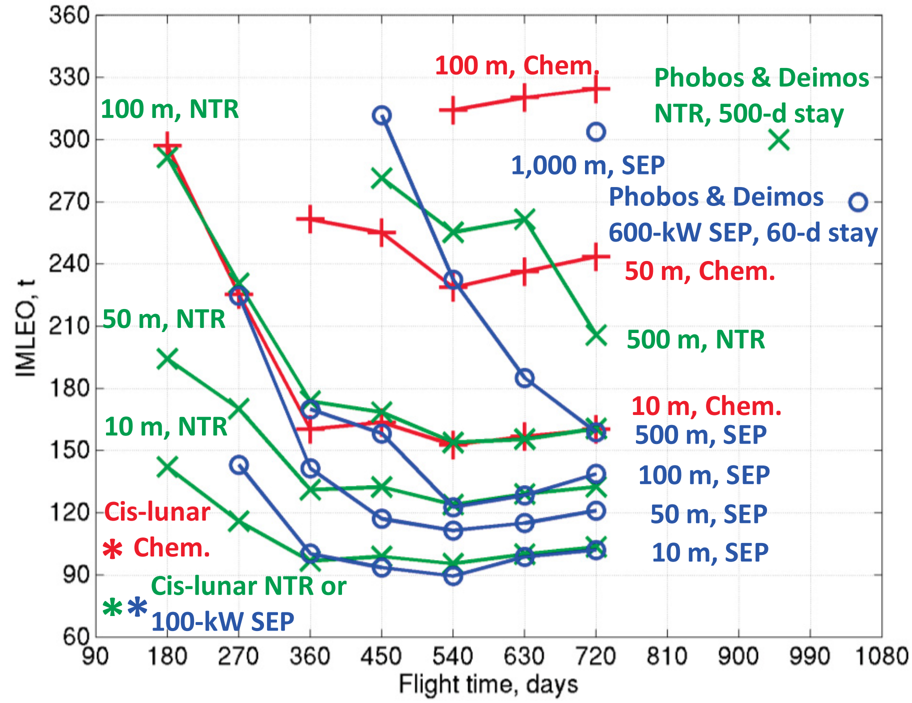


**Figure 7. Target diameter for a potential mission every 2.14 years increases with progressively larger launch mass and flight time.**

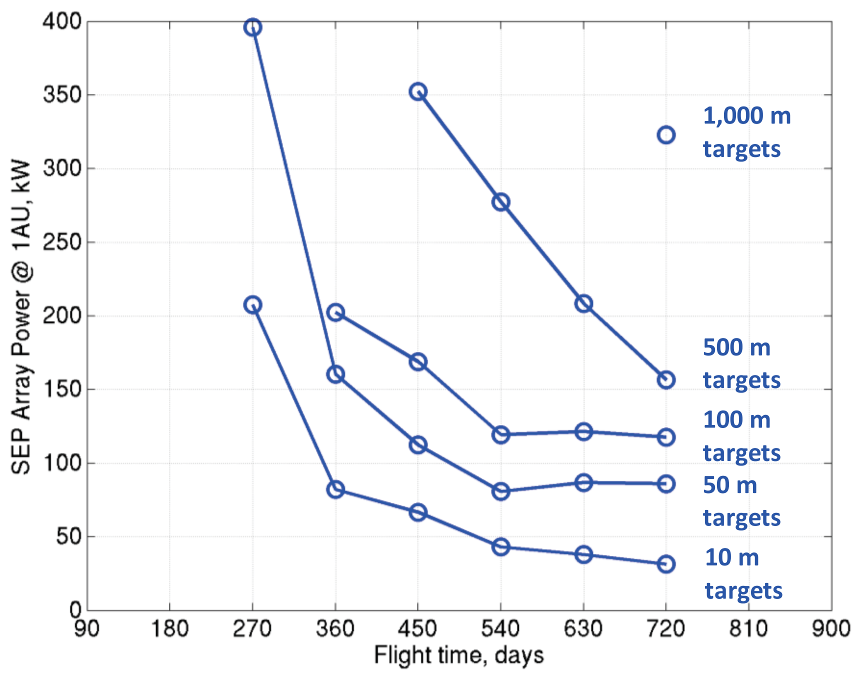


**Figure 8. Interplanetary SEP power levels associated with missions in Figure 7.**

As indicated by the disparate transit habitat designs in [3]–[18], the technology needed to keep astronauts healthy and happy in deep space remains unresolved. In Figure 7, we assume that the habitat mass is constant (22 t) across flight times, which would be appropriate for an exploration program that flies a habitat with excess margin on early (cis-lunar) missions, and later (Mars) missions could fly a more efficient habitat derived from years of development and experience. Alternatively, the habitat mass may be required to increase with longer flight times in order to include additional radiation shielding and habitable space. The IMLEO and flight time required to reach various sized NEAs when the habitat mass varies linearly from 15 t at 90-d flight time to 35 t at 720-d flight time is found in Figure 9. For smaller targets the IMLEO does not vary much for flight times of longer than a year, as the increasing habitat mass is offset by more efficient trajectories. The IMLEO to 100-m objects varies from 180 t to 210 t for trips longer than 360 d with NTR, while a short mission of 180 d would require 260 t. The IMLEO for 100-m objects with SEP remains around 150 t for flight times of greater than a year. Larger, 500-m objects become accessible with 200-t IMLEO and 720-d flight times with SEP. The IMLEO with chemical propulsion is more sensitive to the additional habitat mass due to the relatively low propellant efficiency (Isp) when compared to NTR or SEP.

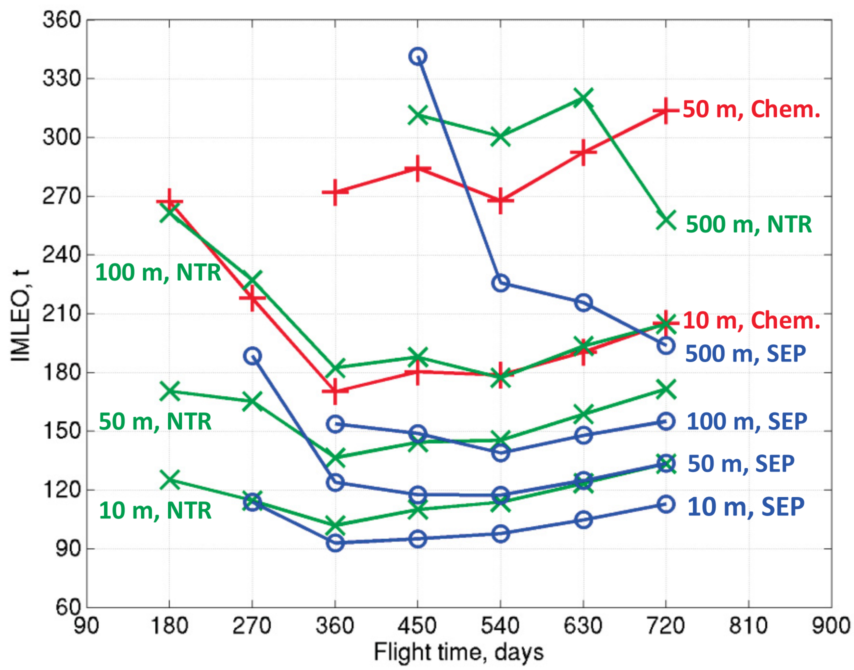


**Figure 9. Potential target diameters for one mission opportunity per 2.14 years where the habitat mass increases from 15 t at 90-d to 35 t at 720 d flight time.**

The contours in Figure 7–Figure 9 assume that all objects in the Small Body Database are suitable targets for human exploration. However, very little is known about most of the targets (typically the absolute magnitude is the only available physical parameter) and certain characteristics (e.g., fast rotation or dangerous terrain) could eliminate targets from the admissible set. If the NEA catalogue is limited to objects with a known diameter, rotation rate, or spectral type, then the target contours shift to those in Figure 10. Large objects are usually better characterized than small ones, thus the contours for 10-m and 50-m objects collapse to the 100-m contour because there are very few 10–100-m objects characterized in the Database. The highly accessible targets that begin to overlap cis-lunar requirements in Figure 7 are essentially eliminated due to lack of knowledge. However, moderate increases in IMLEO or flight time (closer to cis-lunar than Mars) and advanced propulsion could enable a first step to a characterized deep-space target. An IMLEO of 210 t and flight time of 360 d permits access to a 50-m object every 2.14 years with NTR or 10-m objects with SEP, while 100-m objects become accessible at 540 d flight time with an IMLEO of 180 t and NTR or 135 t and SEP.

Another uncertainty in the Database is the knowledge of the NEA's orbit. Many objects have had insufficient tracking to provide a precise estimate of their position at a given time. If only objects with fairly certain ephemerides (as defined by the Minor Planet Center http://www.minorplanetcenter.org/iau/info/UValue.html) are included, then the target contours shift to those in Figure 11. As with the characterized target set (Figure 10) the minimum capability to access smaller targets is affected more than the advanced capability contours to larger targets, which are generally better known. However, the effect is less pronounced in Figure 11, where 10-m objects are accessible at 170-t IMLEO and 180-d flight time with NTR, or at 100-t IMLEO and 360-d flight time with SEP. If larger targets are desirable for a first step beyond the Moon, then an IMLEO of 135 t and flight time of 450 d permits access to 50-m objects with NTR or 100-m objects with SEP.

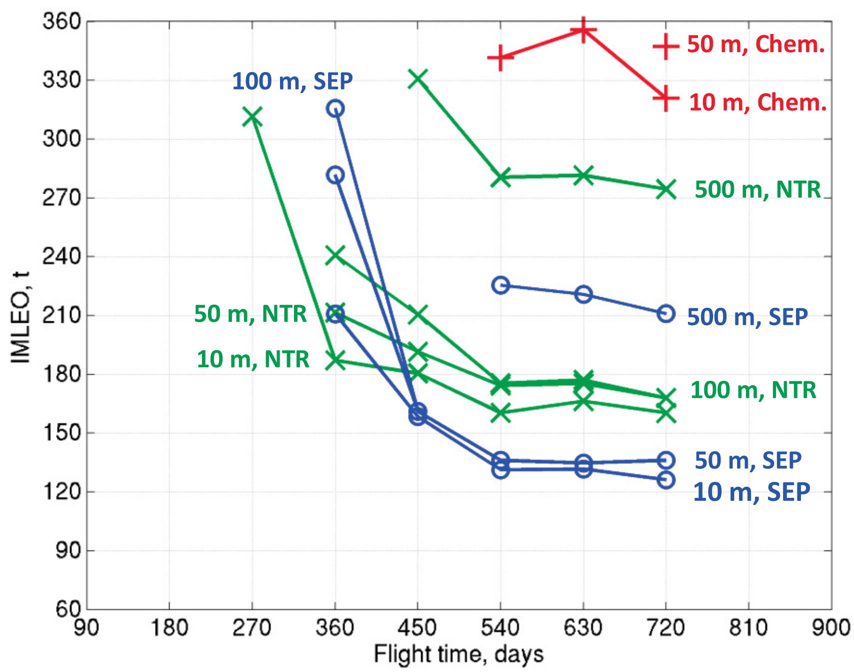


**Figure 10. Potential target diameters for one mission opportunity per 2.14 years where the actual diameter, rotation rate, or spectral type is known.**

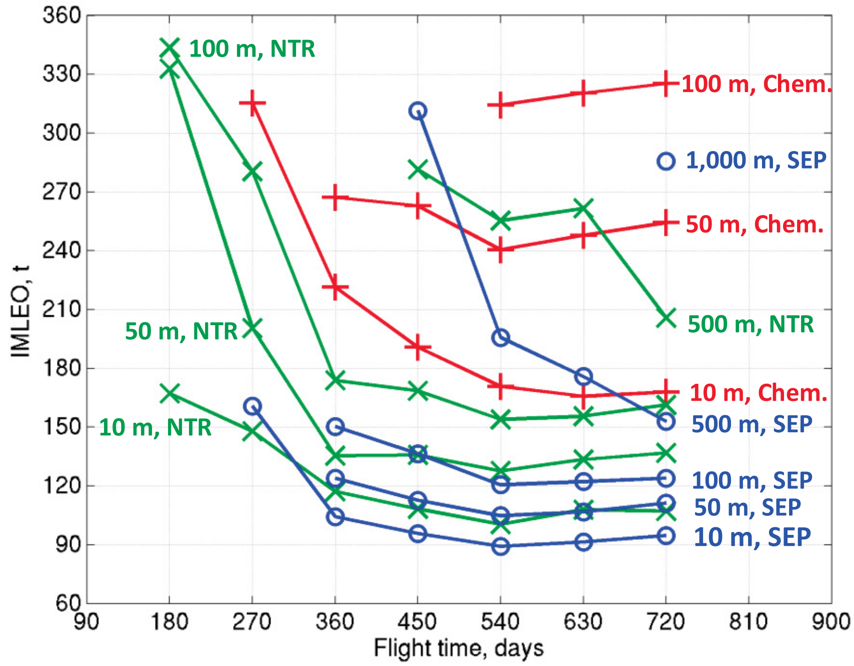


**Figure 11. Potential target diameters for one mission opportunity per 2.14 years with orbit condition code < =3 (low ephemeris uncertainty).**

If the ephemeris, diameter, rotation rate, and spectral type were known for all the objects in the Small Body Database then the contours in Figure 10 and Figure 11 would match those in Figure 7. These characteristics are all attainable via remote observations (telescopes) and a survey mission could determine the characteristics for these objects. Moreover, a NEA survey mission would likely add many new objects to the database (albeit preferentially to smaller ones, as a larger percentage of large objects have been observed), and the number of launch opportunities would increase for a given target diameter, IMLEO and flight time (i.e., the curves in Figure 6 would shift up). Conversely, missions with a low frequency of launch opportunities in the current set could be used as a proxy for missions with frequent opportunities in the "complete" data set. That is, if there is currently only a single feasible mission with a given capability, then there could be many opportunities if several similar objects are discovered. In this case, the NEA contours in Figure 7 would more closely match those in Figure 12, where only one potential mission per decade exists with the current Database. This figure also portrays the mission requirements if schedule flexibility was eliminated from the exploration program and progressive steps to Mars were only available intermittently. In this case 10-m objects come into play at 160-t IMLEO and 180-d flight time with chemical technology, which is a moderate increase in IMLEO from cis-lunar requirements. However, there is a large performance gap from 10-m objects to 50-m objects with chemical architectures, where the next capability step would likely be 330-t IMLEO and 180-d flight time or 220-t IMLEO and 360-d flight time (depending on whether technology investment went to launching mass to LEO or to deep-space habitation). From there, 100-m objects become attainable at 270-t IMLEO and 360-d flight time. Thus, even the most accessible known targets require relatively large IMLEOs to venture into deep-space with chemical propulsion. With NTR or SEP, 10-m objects become accessible at 100-t IMLEO and 180-d flight time, which is on par with the requirements for cis-lunar chemical missions. A modest increase in capability to 120-t IMLEO and 360-d flight time could enable missions to 50-m objects with NTR or 100-m objects with SEP, then 100-m NEAs with NTR or 500-m NEAs with SEP become available with 120-t IMLEO and flight time of 540 days. Large, 1-km NEAs also become accessible at moderate IMLEO, but the timing of the mission to known targets within a given decade is unlikely to match a capability development schedule. Since most targets of this size have already been catalogued, it is unlikely that an undiscovered population would fill in the gaps.

While a NEA survey program could uncover many new objects, the set of potential targets could actually decrease if most of the objects are unsuitable for human exploration. For instance, the characterization of surface features to scout a landing site requires in situ observations that are not available from a broad survey, and multiple targets may need to be assessed before a suitable one is found. In this case, multiple potential targets per year would be required to sustain an exploration program, and the capability contours may match those in Figure 13, where two objects are considered per year. This figure also portrays the situation where backup opportunities are desired each year (though Mars missions are generally available only once every 2.14 years). When compared to a program that includes only one opportunity per Earth-Mars synodic period (Figure 7) the gap from cis-lunar exploration to the most accessible NEOs becomes wider, where 10-m objects become accessible with 120-t IMLEO and 360-d flight times with NTR or SEP, and 240-t IMLEO is required for chemical architectures. An increase in habitat capability to 540 days enables access to 50-m objects with NTR or 100-m objects with SEP with an IMLEO of 150 t. On the other end of the spectrum, objects larger than 500 m can be reached with exploration capabilities commensurate with Mars orbital missions.

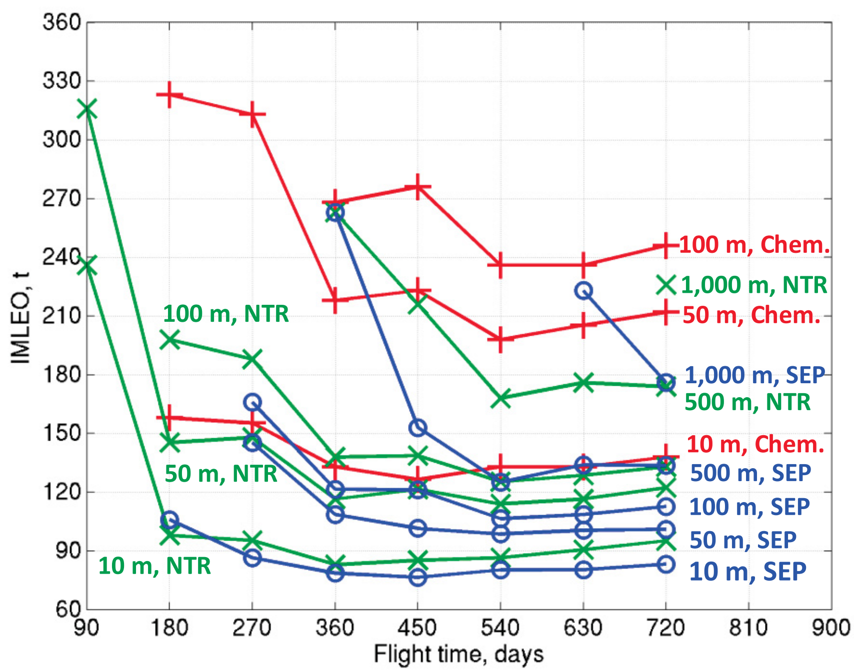


**Figure 12. Potential target diameters for one mission opportunity per decade.**

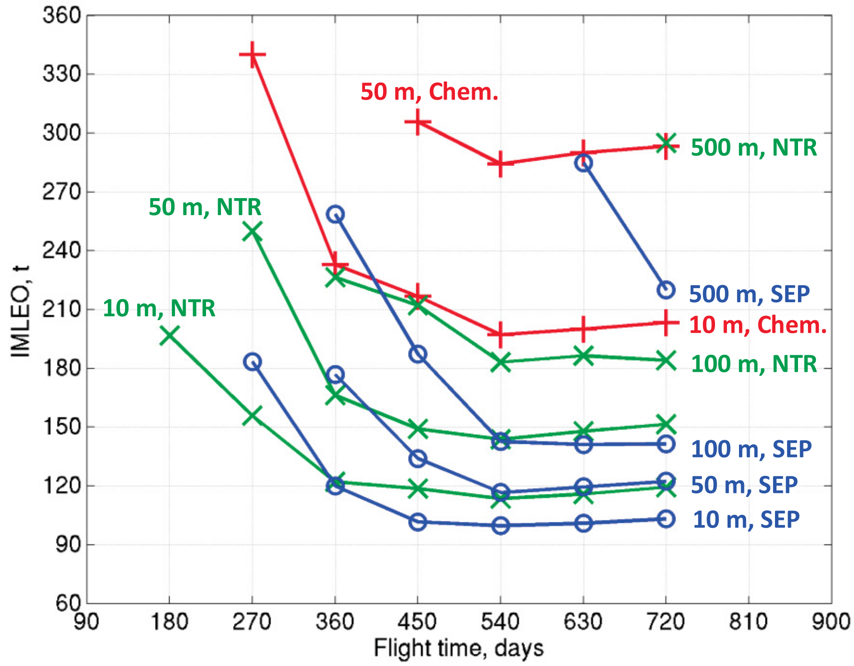


**Figure 13. Potential target diameters for two mission opportunities per year.**

## CONCLUSIONS

Incremental improvements in both mass to LEO and flight time capability provide access to increasingly attractive targets. With the set of currently known NEAs, exploration of small, 10-m objects is intermittently available with cis-lunar capability, while recurring access to 1-km sized objects becomes possible with capability required for Phobos/Deimos missions. Schedule flexibility emerges when systems are designed to sustain a desired launch frequency to a set of targets. Technology flexibility arises from the many development paths from cis-lunar missions to Mars through the NEA mission design space.

Solar electric propulsion has potential to significantly reduce the IMLEO of a variety of human exploration missions from cis-lunar space and near-Earth asteroids to Phobos and Deimos and ultimately to the surface of Mars. For power levels of 100-600 kW the IMLEO with SEP is comparable to mass required with nuclear thermal technology. SEP provides routine access to a wider variety of near-Earth asteroids than NTR or chemical propulsion for flight times of longer than a year, making it an ideal technology to introduce flexibility on an exploration path to Mars.

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