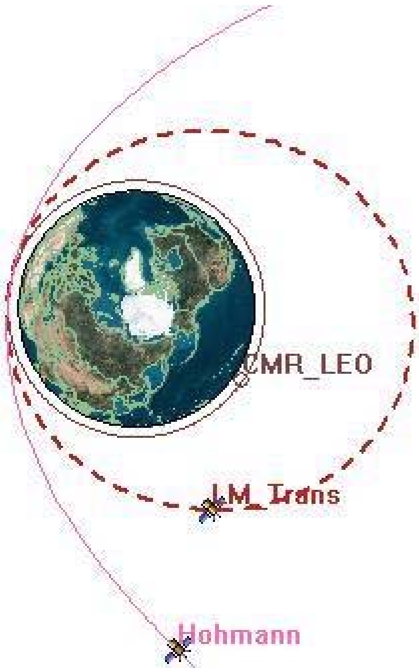
Propellantless Space Travel Using Recycled Kinetic Energy



Puzzler: The image at left shows two satellites simultaneously launched from a circular low Earth orbit (LEO). Satellite Hohmann is following a conventional Hohmann transfer orbit to L5. How can spacecraft LM_Trans launched from LEO at half the velocity required for a Hohmann transfer orbit beat conventional satellite Hohmann from LEO to L5 while expending only one tenth the fuel of a conventional rocket?

Conventional space travel is governed by the rocket equation, demanding an ever larger fraction of a vehicle's total mass be devoted to the fuel required to effect changes in velocity. What new combination of technology might allow a spacecraft to free itself of most of the fuel required for conventional space travel? In this paper a form of propellantless space travel is investigated. The two main factors needed are high round trip energy conversion efficiencies and synchronized transfer orbits. The necessary technology and architecture are formulated. Once understood, answers can be obtained to questions such as, "What new lower delta vee is obtainable for trips from Earth to Mars?" and "Why can round trip travel from the surface of the Earth to the lunar surface be economically and efficiently executed at a maximum acceleration of three gees?"

1. The concept of Recycling

Everyone has a basic understanding of the concept of kinetic energy from everyday experience. When you drop a ceramic dinner plate onto a tile floor, it shatters into numerous pieces. In 2005 NASA's Deep Impact spacecraft struck within 50 m of an aim point on a comet it encountered at a closing speed of 10.2 km/s, delivering 19 GJ of kinetic energy (KE) to the comet. The U.S. military demonstrated a similar technology level of readiness in 1984 by striking a simulated incoming missile warhead at a closing speed of 6.1 km/s during the Homing Overlay Experiment. Hit-to-deliver guidance accuracies measured in meters at closing speeds from 100 m/s to a modest 1.5 km/s is the first necessary condition for kinetic energy recycling to be viable.

What happens when a spacecraft runs into a kinetic energy Recycler? In this case, the arriving spacecraft exerts a net force and possibly a net torque on the Recycler. If the kinetic energy is not properly managed, severe and catastrophic damage can occur to both the spacecraft and the

Recycler. When properly managed, the kinetic energy extracted from the arriving spacecraft is immediately transferred to a departing partner spacecraft, nulling out the net forces acting on the Recycler by the arriving spacecraft. **If the departing partner spacecraft has the same mass and delta vee as the arriving spacecraft, then the net force acting on the Recycler is zero and its orbit remains unchanged.** That is, if the departing partner spacecraft replaces the arriving spacecraft on its transfer orbit, the entire space transportation system remains stable. When such a transfer occurs it is called a normal engagement. Torques are managed by design.

Directly transferring KE from one spacecraft to another by purely mechanical means is impractical. Instead, the KE of an arriving spacecraft is converted into electrical energy using a highly efficient process commonly used in the electric automobile industry named regenerative braking. Motor/Generators mechanically couple to an arriving spacecraft as it passes through a portal (or portals). **The inertia of the arriving spacecraft draws magnets through coils of wire, producing electricity at the expense of KE.** High temperature superconducting electrical conduits transfer the generated electricity to a launch portal (or portals) where motor/generators immediately launch a departing partner spacecraft. Commercially available motor/generators are 80 % efficient. Large scale (up to 50 m radius) motor/generators with a round trip efficiency of at least 25 % is the second necessary condition for viable KE recycling of spacecraft.

Superconducting Magnetic Energy Storage (SMES) rings have entered service on the U.S. electrical grid demonstrating the maturity of this energy storage technology. Emerging manufacturing techniques for carbon nanotubes following their discovery in 1991 hold the promise of carbon nanotube cables in 100 km lengths becoming commercially available within the next 10 years with tensile strengths significantly higher than other known materials. These technologies and materials are blended into an orbiting space platform named a CataMitt Recycler (CMR). The braking or launching distance for a given spacecraft engaging a Recycler can extend over 100 km, making it impractical to launch a partner spacecraft in line with an arriving spacecraft. To prevent a net torque from being applied to the Recycler, one of the two spacecraft arrives or is launched in a split configuration that later reconnects into a single spacecraft before arriving at the next Recycler. Figure 1 schematically illustrates the KE recycling process at the heart of this concept.

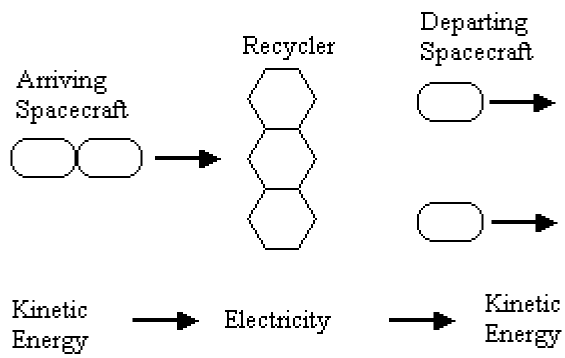


Figure 1. Spacecraft energy recycling schematic includes two highly efficient energy conversions managed at an orbiting CataMitt Recycler.

These disparate elements – hit-to-deliver guidance accuracies, regenerative braking, high temperature superconductors, carbon nanotube tethers, low temperature SMES rings, and large flywheels (for backup housekeeping energy storage) – form the basis of CMRs. Together they provide a given spacecraft most of the benefits of employing an upper stage at a destination orbit without the mass penalty normally associated with bringing along fuel or engines to use that upper stage. Hence, the propellant required for a series of orbit transfers can drop by an order of magnitude, operations costs can drop by a factor of five or more, and transit times can potentially beat Hohmann transfer times, all while enjoying accelerations no greater than one Earth gee.

2. Newton's Laws and Recycling

Before developing a long distance space transportation architecture, consider the following simple scenario. Suppose NASA wishes to exchange crews at the International Space Station (ISS) using the new Crew Exploration Vehicle (CEV). NASA's baseline scenario calls for a CEV Block 1A configuration to launch from Kennedy Space Center (KSC) into an orbital inclination of 51.65 degrees. The Crew Launch Vehicle (CLV) injects the CEV into a 55 km x 296 km delivery orbit. The CEV Service Module (SM) pushes the CEV the rest of the way into a circular 400 km orbit for an eventual ISS rendezvous. (All data is drawn from NASA's Exploration Systems Architecture Study [ESAS] final report, ignoring later changes.)

Employing a CMR304 Recycler (3 portals, 400 m/s maximum engagement speed) significantly affects the scenario outcome. Consider a Recycler stationed in the ISS orbit. The CLV lobs the CEV onto a suborbital trajectory that engages the Recycler at apogee. This requires less launch energy than reaching NASA's delivery orbit (Specific Energy = -30.4 km^2/s^2 for NASA's orbit versus –32.4 km^2/s^2 for the suborbital trajectory). At 12 minutes after launch from KSC the CEV is overtaken from behind by the Recycler at a closing speed of 394 m/s. An interface plate deployed from the Recycler cradles the CEV as both the plate and CEV coast through the Recycler's center portal **at essentially the same relative speed**. That is, they dock below 1m/s.

Regenerative braking begins after Spectra 2000 tethers deployed from the Recycler subsequently attach to the interface plate. A one gee braking acceleration acting over 8 km generates 32 MW average power for 40 s. This electrical energy is immediately expended launching a departing CEV to Earth. The descending Crew Module (CM_d) mass of 9,062 kg in one Recycler outer portal mismatches the deorbiting SM (SM_d) mass of 6,496 kg in the Recycler's other outer portal. The SM_d is launched with a relative velocity of –230 m/s while the CM_d is launched at –170 m/s to apply zero net torque to the Recycler. Both SM_d and CM_d fall below 60 km within 25 minutes off the coast of Yemen. Figure 2 illustrates the Recycler initial and end states.

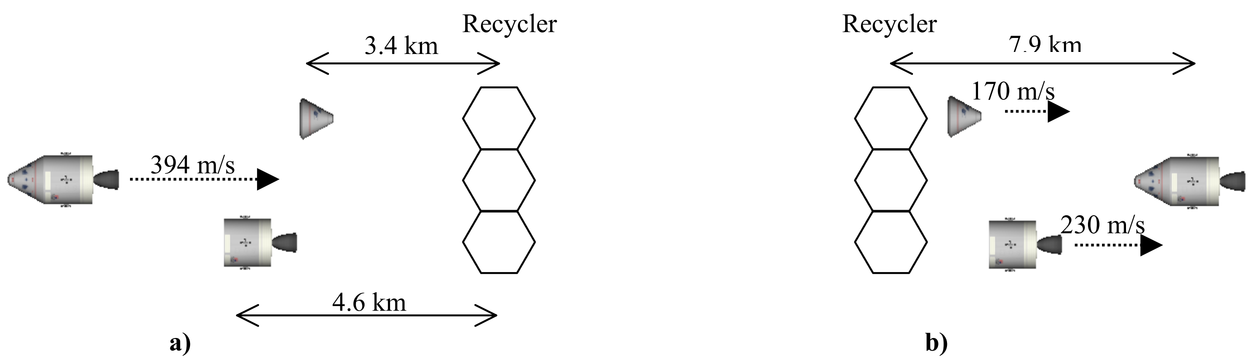


Figure 2. Arriving CEV is overtaken by Recycler at 394 m/s in a) as a split partner CEV awaits launch from the Recycler. In b) the kinetic energy of the arriving CEV has been transferred to the departing split partner CEV.

The kinetic energy coupling efficiency of the Recycler has been reduced to 25 % in this example to illustrate the advantage of recycling even when energy losses are high. Only 25 % of the arriving CEV's KE is carried away by the departing partner CEV. The difference in energy is wasted heat. A 7 m targeting error by the arriving CEV would result in 1 % of KE diverting to torque management ballast on the CMR. The difference in momentum requires a CMR reboost.

For 35 days following this normal engagement a bank of 120 Ion engines (with a combined thrust of 11 N) fire for up to 10 minutes at every apogee to restore the Recycler to its original circular orbit. These engines are clones of the flight proven NSTARS engine used on NASA's Deep Space 1 spacecraft (92.4 mN of thrust with an Isp of 3,120 s). (Theoretical Ion engines promise much greater performance.) Sixty percent of the output of a full set of 8 ISS class solar arrays (generating 78 kW of usable power) mounted on the Recycler is channeled into the reboost operation. A total mass of 102 kg of Xenon propellant is expended. The Recycler laps the ISS once to return to its operational station offset from the ISS by 23 km – the minimum distance to ensure spacecraft engaging the Recycler never pass closer than 2 km to the ISS.

The baseline SM main engine runs on Methane/Oxygen with an Isp of 353 s. Transferring the CEV from NASA's baseline injection orbit to an ISS orbit requires 577 kg of propellant using the SM main engine. Presuming the descending CEV leaving the ISS is loaded up with down mass so it once again has a total mass of 15,558 kg coupled with a deorbit burn of –104 m/s (to drop perigee to 46 km) leads to an additional propellant expenditure of 460 kg. Now compare.

NASA's CEV expends 1,037 kg of propellant going to a 400 km circular orbit from the initial delivery orbit and in deorbiting from the 400 km orbit. The Recycler expends 102 kg of propellant reboosting its own orbit after exchanging CEVs between a suborbital trajectory and the ISS orbit—a net gain of 935 kg for the Recycler method. For safety, let the ascending CEV retain the 577 kg of propellant required to reach the ISS in the event a Recycler engagement is aborted following a CEV's commitment to launch from Earth. A fair claim is **the Recycler doubles the cargo capacity of a Block 1A CEV** (400 kg in the ESAS report) **even as it delivers at least 500 kg more Methane/Oxygen to the ISS orbit** in a nominal engagement. Note the trip from Earth is **shortened from 2-3 days to less than 4 hours** (12 minutes from Earth to the Recycler plus 15 minutes for release from the Recycler plus 3 hours 10 minutes to complete two phasing orbits for final docking at the ISS). Exchanging ISS crews do not meet when Recycling.

While much of the analysis presented in this paper centers around the ESAS final report, the preferred hardware concept for Recycler payloads consists of two separable components of equal mass as suggested in figure 3. Kinetic energy and momentum transfer losses are minimized when the departing partner spacecraft exactly replaces the arriving spacecraft with respect to arrival mass and arrival velocity vector. The CEV is compatible with Recycling because it is separable.

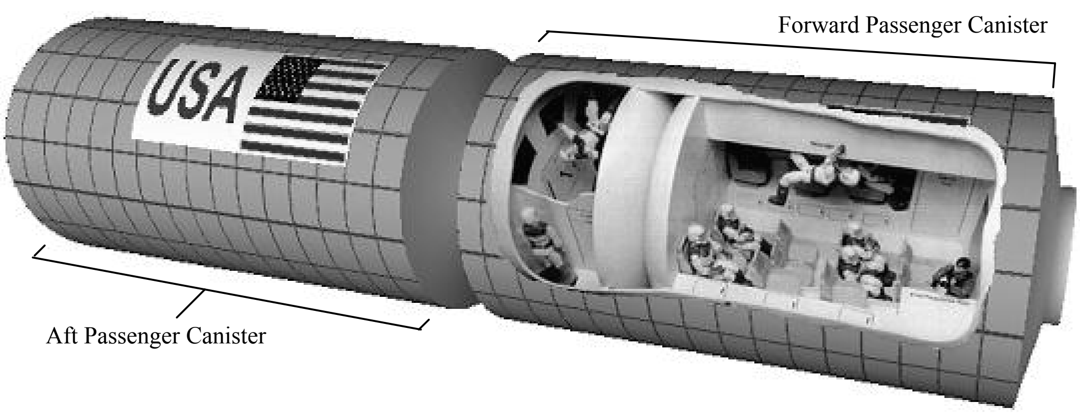


Figure 3. A single spacecraft preferably consists of two separable components of equal mass such as these two passenger canisters. Canister interior image courtesy Claremont McKenna College.

Recycler portals are six sided structures, with the inner length of each side set to 22 m. The clear radius of each portal is 17.6 m to permit positional errors up to +/- 9.5 m for External Tank (ET) sized spacecraft engaging the portal. The distance from the center of one portal to the center of an adjacent portal is 136 m. Multiple pairs of CLV 2^{nd} stages berthed at rotating sub-assemblies mounted about the Recycler's y and z axes compensate for torques induced by positional errors of arriving spacecraft. The 2^{nd} stages can be jettisoned as a means of shedding excess angular momentum. Minimizing guidance errors minimizes wasted KE and maximizes KE coupling.

An arriving or departing spacecraft might be equipped with the nominally six eyelets required to connect with the grappling hooks located at the ends of the tethers deployed from a Recycler. For all other spacecraft, an interface plate is required. A center portal interface plate sized for an arriving spacecraft mass of 26,330 kg has an estimated mass of 1,500 kg. In addition, tethers as well as the spools holding the tethers must also be brought up to the engagement speed of an arriving spacecraft before it arrives. An estimated 6,400 kg of mass must be put into motion at speeds up to 1.5 km/s by a Recycler prior to each engagement, amounting to 7.2 GJ of KE from onboard systems. If a Recycler pulls an empty center portal interface plate at 5 gees up to an engagement speed of 1.5 km/s an onboard power output level of 81 MW is required. These mechanical energy and power requirements constrain the choices for an electrical energy storage system for use on a Recycler. SMES rings form the primary energy storage system. Flywheels collocated with the tether spools are used as an independent backup energy storage system.

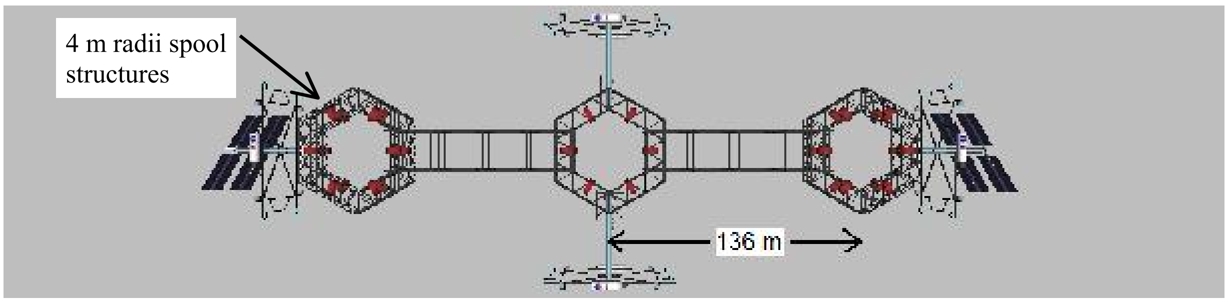
A Recycler lacks an onboard power supply capable of independently launching anything significantly larger than a microsatellite. **The kinetic energy of an arriving spacecraft *is* the power supply for launching a departing partner spacecraft.** A partner spacecraft is therefore stranded near a Recycler in a Recycler orbit until an arriving spacecraft engages that Recycler.

Recyclers are three axis stabilized platforms able to slew in yaw and pitch to engage arriving spacecraft at significant angles off axis from the Recycler's velocity vector. While this broadens the window of opportunity for engaging a Recycler, preparation time is required to position a partner spacecraft properly for a given engagement geometry. The requirement of physically intercepting a Recycler in its circular LEO at less than some maximum engagement speed severely constrains the width of the launch window for a rocket launching from Earth to engage a Recycler. **A launch window 20. s long is feasible** due to the pitch capabilitiy on a Recycler.

Imagine a world in which the only known form of air travel is the helicopter. Affordable commercial air travel between Tokyo and Los Angeles would not exist, for no single helicopter would be economically capable of making such a long trip while carrying along all the fuel needed in addition to the desired passengers and cargo. Instead, flying might well be strictly in the province of only the wealthiest governments of the world, much as conventional space travel is today. In a development analogous to the multistage rocket, staged helicopters might have been invented to extend the capabilities of helicopters, doing little to increase their affordability.

The contrast between Recycler based space travel and conventional rocket travel is as great as the contrast between helicopter travel and jet travel. Helicopters and conventional rockets carry with them everything they need to hover, land and relaunch themselves; Jets and spacecraft using Recyclers require an airport type infrastructure at their destination. Helicopter and rocket flights are individual events; jet and Recycler flights are community activities – ships are restocked, refurbished, and reused on a cyclic basis, delivering high volume traffic to popular destinations and then returning the traffic (tourists) to their starting point. **Recycling is a new paradigm.**

Figure 4a shows a CMR304 Recycler. Each portal clear aperture is 35 m, the center to center portal spacing is 136 m, and it employs Spectra 2000 tethers to ensure it can be built with existing technology and materials. The estimated mass is 220,000 kg (excluding CLV 2[nd] stages). An attainable objective is to package at least one entire portal for unfolding deployment from a single Cargo Launch Vehicle (CaLV). At least 16 inert CLV 2[nd] stages can be mounted on the pitch and yaw axes as reaction mass for attitude control and engagement torque management. A Recycler is similar to an airport. It isn't replaced; it is upgraded. Figure 4b shows a (same scale) Recycler upgraded to a CMR315 (3 portals, 1.5 km/s maximum engagement speed). Its 50 m radii spool structures (containing carbon nanotube tethers, tether spools, flywheels, motor/ generators, cooling infrastructure, and superconducting conduits) lead to its distinctive shape.



a) CataMitt Recycler CMR304 is rated to 400 m/s delta vee.

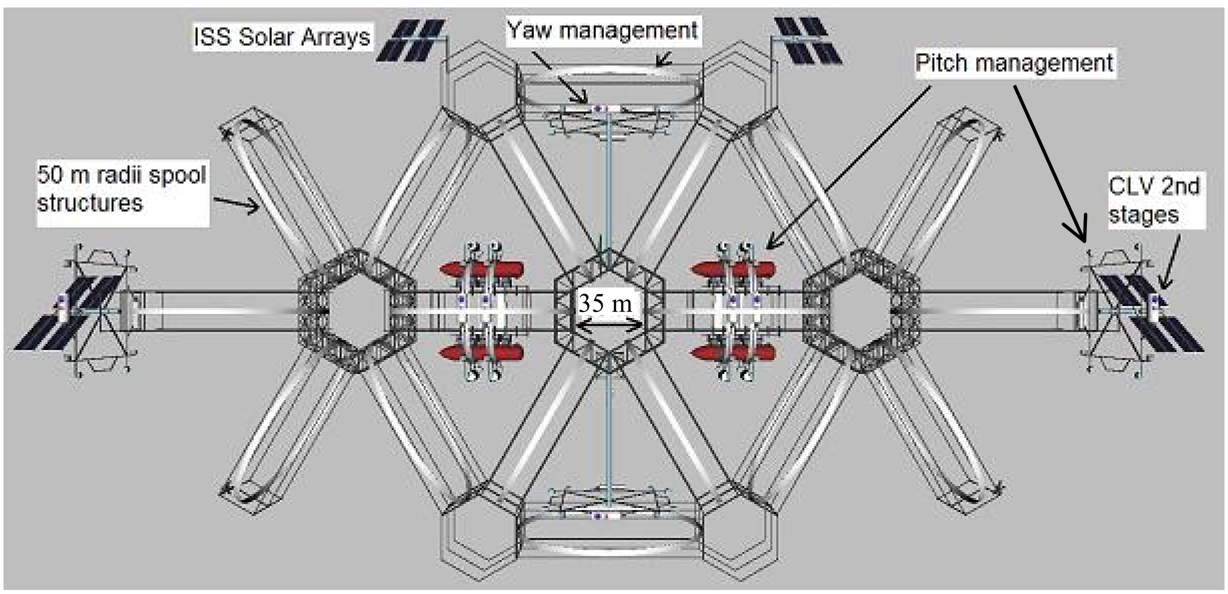


Figure 4. b) A CataMitt Recycler upgraded to a CMR315 is uprated to 1500 m/s engagement delta vee.

3. Orbit Synchronization

The flexibility of Recycler operations can initially seem overwhelming. Consider the ESAS design reference mission to exchange crews at a lunar outpost. A baseline scenario was created using Satellite ToolKit (STK) software. The nominal ESAS mission modeled arrives into a 100 km circular low lunar orbit (LLO) on 24 Dec 2034 with a Lunar Orbit Insertion (LOI) ΔV of 1.066 km/s established to pass over the Aitken Basin landing site at 162 W, 54 S on the lunar farside. The net injected mass toward the Moon is 66,763 kg, split between a 22.2 metric ton (mT) CEV and a 44.6 mT Lunar Surface Access Module (LSAM). A crew of 4 descends to the outpost with a ΔV of 1.9 km/s, abandoning the LSAM Descent Stage (DS) on arrival. The departing crew ascends in their own LSAM Ascent Stage (AS) to rendezvous with the CEV waiting to return them to Earth. The Trans Earth Injection (TEI) ΔV is nominally 896 m/s.

Add to this baseline scenario a single CMR315 Recycler rated to a maximum 50 % energy coupling efficiency (λ) and observe the numerous possibilities this enables. The Recycler is deployed in a circular lunar orbit at a 662 km altitude matching the ESAS orbit inclination.

Option 1: CEV/LSAM engage the CMR to arrive into lunar orbit. Unused LOI fuel is offloaded from the DS at the Recycler, then the CEV/LSAM undergo a Hohmann transfer of 203 m/s to enter LLO and proceed with the ESAS mission. No further interactions with the Recycler occur. This option has a net gain of 11.9 mT of H_2/O_2 at the Recycler. It also transfers up to 36 GJ of KE into KE storage orbits. There is flexibility in the mass and velocity assigned to the launched partner spacecraft. Generally, the launched partner should be targeted to miss the Moon, remain gravitationally bound to the Moon, transport away as much of the arriving spacecraft's momentum as practical, and enter a storage orbit where it can be nudged into a future engagement with the Recycler with a minimum expenditure of maneuvering fuel. This option is also probably the easiest to accept: the engagement occurs 12 minutes before the CEV/LSAM reach perilune. If the CMR engagement is missed, the baseline ESAS mission continues. The raised Recycler orbit can be adjusted using propellants or cleverly designed future engagements.

The AS is abandoned in LLO at the end of the ESAS baseline mission. It is just 308 kg of CH_4/O_2 away from rendezvousing with the Recycler on its own, but has nominally only 266 kg in its tanks. It can exhaust its fuel bringing itself as close to the Recycler as it can, or it can expend 157 kg of propellant to engage the Recycler at a ΔV of 98 m/s, bringing 25 MJ of KE to the Recycler as it slightly lowers the Recycler's orbit. Either way, the AS can easily be recovered (the Recycler's interface plates are mini-space tugs) for use as reaction or partner mass in future engagements. The AS is recovered in all options presented due to its value for transporting KE.

Option 2: CEV/LSAM engage CMR on arrival into lunar orbit. DS expends unused LOI fuel to enter orbit and dock with the CMR after delivering the AS to the lunar surface. This has a net gain of 2.9 mT of H_2/O_2, stores up to 36 GJ of KE, and recovers a complete LSAM at the CMR.

Option 3: CEV/LSAM engage CMR on arrival into lunar orbit. DS ascends straight up after the end of the ESAS mission to engage the CMR while momentarily stationary 662 km above the lunar surface. This has a net gain of 5.6 mT of H_2/O_2, stores 36 GJ of KE at LOI, but also delivers 9.7 GJ of KE to the CMR during its engagement with the empty DS. The CMR orbit is lowered in this 2nd engagement. Note if an objective is to substantially lower the Recycler's orbit, the partner in this second engagement could be forward launched off the Recycler instead of aft launched, sending the partner into a storage orbit even as the Recycler undergoes a double negative impulse – one from engaging the stationary DS, one from launching the partner.

Option 4: CEV/LSAM engage CMR on arrival into lunar orbit. Ascending DS and crewed AS from the surface come straight up to engage the Recycler while momentarily stationary 662 km above the outpost. This engagement powers the launch of the descending LSAM with the new crew onto a direct vertical descent to the outpost. This option has a net gain of 4.4 mT of H_2/O_2 plus 5.6 mT of CH_4/O_2. Note a fueled DS at the outpost can be on standby as a rescue vehicle to recover the crewed AS if it becomes disabled or otherwise misses an engagement after leaving the outpost. The DS would ascend straight up, turn over, dive to match velocities with the AS in freefall, turn upright, berth the AS, then descend to a landing. A DS in the Recycler orbit can similarly stop its motion, match velocities with the disabled AS, berth it, and reenter orbit.

Option 5: CEV/LSAM engage CMR on arrival into lunar orbit. The CEV/LSAM descend to LLO, crews are exchanged per the ESAS baseline, followed by the CEV returning to the CMR for Recycler launch to Earth. The partner launched at LOI is maneuvered to engage the CMR 3.5 days later. This second engagement powers the TEI for the CEV returning to Earth. The partner launched in this option is named Rocky starboard and Rocky port. Each Rocky has a launch mass of 26.5 mT; λ is 39 %. Nearly 1.0 km/s of maneuvers are required to set up each Rocky to engage the Recycler for TEI. Only one of the Rockys is used – the other Rocky is a backup. The 2 Rockys consume a total of 12.6 mT of CH_4/O_2 in this option. The net effect is a loss of 5.8 mT of CH_4/O_2 and a gain of 5.6 mT of H_2/O_2 relative to the ESAS baseline. It reuses LOI KE .

Option 6: CEV/LSAM engage CMR on arrival into lunar orbit. Crews exchange via CMR (as per option 4). The partner launched at the LOI engagement is maneuvered to engage the CMR 6 days later to power the TEI launch of the CEV. This partner is named Sandy port and Sandy starboard. Each Sandy has an initial mass of 28.4 mT and needs 0.6 km/s of ΔV to set up for the TEI engagement. As with Rocky, only one Sandy is used (splitting to enter both outer CMR portals) while the other is a backup. This has a net gain of 4.4 mT of H_2/O_2, 0.5 mT of CH_4/O_2.

This bewildering list of options merely suggests the possibilities. The essential point is Recyclers enable previously unstudied options for conducting lunar missions. Not yet analyzed are missions exploiting KE transferred into storage orbits during previous lunar missions. Most likely, a variation of Sandy could be set up over 6 months to support a TEI engagement for a subsequent lunar outpost mission for perhaps 2 mT of CH_4/O_2, yielding a net gain of 11 mT of propellant even as a complete LSAM is recovered into lunar orbit. Separately, profitable commercial activity could feed off the KE, fuel, and hardware recovered from these missions. Figure 5 shows the orbits for LLO, the CMR, Rocky, Sandy, and the vertical trajectory analyzed.

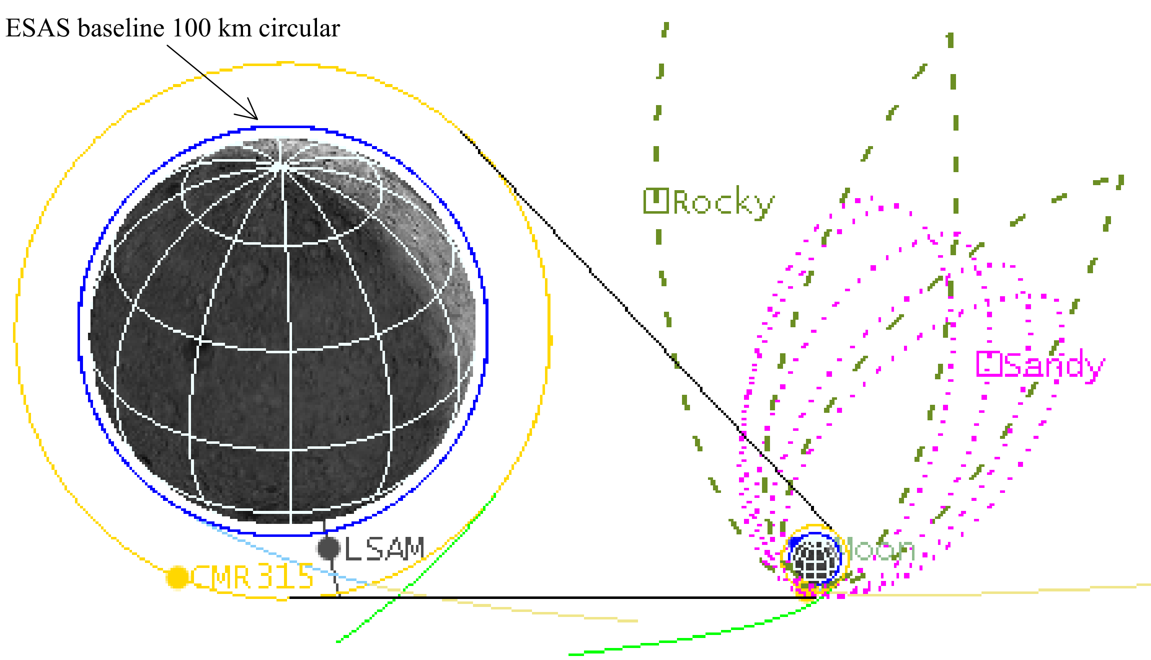


Figure 5. Lunar outpost mission orbits ESAS LLO (NASA baseline), CMR315 (Recycler), Rocky (KE storage), Sandy (KE storage), and LSAM (662 km vertical ascent and descent) analyzed in this paper.

Table 1 ΔVs along transfer orbits from LEO to L5

Between	And	ΔV (km/s)	Fig. 6
LEO	LM_Transfer	1.293	Δv_1
LM_Transfer	MEO	1.356	Δv_2
MEO	MG_Transfer	1.223	Δv_3
MG_Transfer	GEO	1.201	Δv_4
GEO	G5_Transfer	1.154	Δv_5
G5_Transfer	L5	1.068	Δv_6

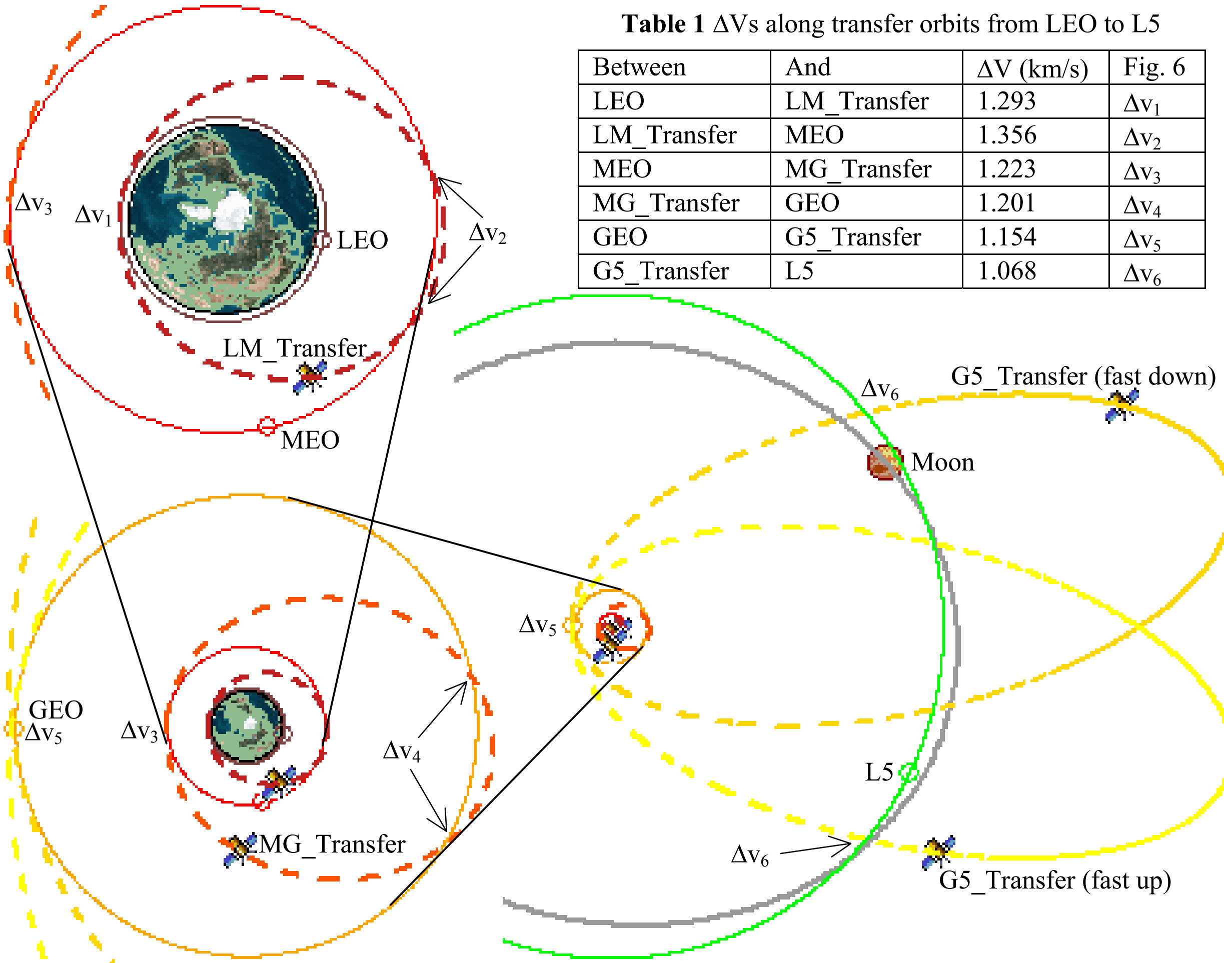


Figure 6. Transfer (dashed) and Recycler (solid) orbits from LEO to L5 shown to three scales.

Recyclers come into their own when they work together to form a space transportation network. **Favorable performance is predicated on a judicious choice of Recycler and transfer orbits.** Table 1 lists the ΔVs to transfer along a set of synchronized orbits spanning a LEO altitude of 554 km to L5. The data in table 2 is sufficient to construct an animation of transfer spacecraft and Recyclers undergoing multiple encounters. The epoch is set to 1 Jul 2006 12:00:00 UTC.

Table 2 Representative transfer and Recycler orbit phasing parameters at Epoch 1 Jul 2006 12:00 UTC.

Label	Perigee r (km)	Apogee r (km)	Period	RAAN (deg)	ν (deg)
LEO	6,932.38	6,932.38	1.6 hrs	0	0
LM_Transfer	6,932.38	15,076.57	3.2 hrs	0	0
MEO	14,419.94	14,419.94	4.8 hrs	0	53.017958
MG_Transfer	14,419.94	45,569.44	14.4 hrs	0	57.858
GEO	42,164.17	42,164.17	24.0 hrs	0	70.592082
G5_Transfer_up	42,164.17	735,416.67	28 days	356.489252	236.4
G5_Transfer_down	42,164.17	735,416.67	28 days	21.995677	181.87
L5	384,400	384,400	28 days	0	100

A satellite on any transfer orbit (dashed lines in fig. 6) repeatedly encounters a Recycler (solid lines) at perigee. It also repeatedly encounters a second Recycler at one higher point in its orbit. Synchronized orbits are a critical requirement for efficient Recycler operations. (Note the LEO to GEO set repeats on a 6 day cycle.) Encountering a Recycler does not compel an engagement (i.e., a transfer of KE), as arriving spacecraft can pass near or through a Recycler without engaging it. In general, each Recycler should maintain two separable ballast satellites (1 at the Recycler, 1 nominally in the higher intersecting transfer orbit) available for duty as a partner spacecraft in Recycler engagements. The essential feature is **the transfer orbits are kept continuously occupied** – either by spacecraft or ballast transiting between Recyclers. **The KE that runs the system is stored in the transfer orbits** in the form of spacecraft in those orbits.

The kinetic energy formula (KE equals one half times mass times the square of the velocity) explains what happens to a departing spacecraft when it is launched from a Recycler. Consider a partner spacecraft awaiting launch from the LEO Recycler to enter onto the LM_Transfer orbit linking LEO to Middle Earth Orbit (MEO). By table 1, the required Δv is 1.293 km/s. If the LEO CMR has a λ of 25 %, then only 25 % of the KE of a spacecraft arriving at the LEO CMR from the LM_Transfer orbit is transferred over to the departing partner spacecraft. However, because the velocity varies as the square root of the KE, 50 % of the required velocity is imparted to the departing partner spacecraft. Thus, the shortfall in launch velocity for the departing partner spacecraft is only 646 m/s. If λ = 50 %, then the shortfall in launch velocity is 379 m/s. For λ = 80. % (an obtainable value), the shortfall in launch velocity is 1.293 km/s *(1 – √(.8)) = 137 m/s.

No energy conversion process is 100 % efficient. A fraction of a system's initial energy is unavoidably converted into heat in any energy conversion process due to friction. With every engagement at a Recycler, a fraction of the arriving spacecraft's KE is unavoidably diverted to heat or unwanted rotational KE of torque ballast. Hence, the energy coupling efficiency λ can never be 100 % -- unless KE lost to engagement inefficiencies is replenished. The strategy for efficient Recycler operations is to replenish KE lost during each engagement by boosting the launch velocity of the departing partner spacecraft as it departs a given Recycler. Rather than place a rocket engine on the departing spacecraft, the rocket engine is mounted on the spacecraft interface plate that mechanically couples the departing spacecraft to the Recycler's tether spools. With this arrangement the departing spacecraft is freed from carrying its own rocket engine or fuel, while the employed rocket engine (or cluster of engines) is reliably maintained and reused at a given Recycler. The fuel and engines of space travel become concentrated at the Recyclers.

The calculated Δv of engaging a Recycler depends on economics as well as physics. Recall two classes of spacecraft occupy Recycler transfer orbits – active users and ballast. Partners who are active users can be expected to pay their own way, that is, they are financially responsible for replenishing their own shortfall in Δv when departing a Recycler. When the partner is ballast, the (financial) responsibility for replenishing the shortfall in Δv of the ballast falls on the active user. The analysis is summarized by defining three classes of users of Recycler based space travel:

1. A first class user values time as more important than money. They will pay the cost of launching ballast at every engagement so they may transit the Recycler system in the least time.

2. A second class user is intermediate between a first class user and a third class user.

3. A third class user values money as more important than time. They will linger at a Recycler or in a transfer orbit until an active user engages with them as a partner, however long it takes.

Example 1 A First Class Round Trip Between LEO and GEO

A first class user wishes to complete a round trip between LEO and GEO, including a 3 day stop in GEO. Determine the Δv required for the trip. Presume λ = 80. % for all Recyclers.

Solution Consulting table 1, the Δv to launch from LEO onto LM_Transfer is 1.293 km/s *(1 – √(.8)) = 137 m/s. The Δv to arrive from LM_Transfer at MEO is 1.356 km/s *(1 – √(.8)) = 143 m/s. The Δv to launch from MEO onto MG_Transfer is 1.223 km/s *(1 – √(.8)) = 129 m/s. The Δv to arrive from MG_Transfer at GEO is 1.201 km/s *(1 – √(.8)) = 127 m/s. The Δv to launch from GEO onto MG_Transfer is 1.201 km/s *(1 – √(.8)) = 127 m/s. The Δv to arrive from MG_Transfer at MEO is 1.223 km/s *(1 – √(.8)) = 129 m/s. The Δv to launch from MEO onto LM_Transfer is 1.356 km/s *(1 – √(.8)) = 143 m/s. The Δv to arrive from LM_Transfer at LEO is 1.293 km/s *(1 – √(.8)) = 137 m/s. The total Δv for the round trip sums to (137 + 143 + 129 + 127) m/s * 2 = 1.072 km/s. In comparison, the total Δv to complete the same round trip using a single Hohmann transfer orbit is 7.592 km/s.

Example 2 A Third Class Round Trip Between LEO and GEO

A third class user wishes to complete a round trip between LEO and GEO, including a minimum 3 day stop in GEO. Determine the Δv required for the trip. Presume λ = 80. % for all Recyclers.

Solution Consulting table 1, the Δv to launch from LEO onto LM_Transfer is 1.293 km/s *(1 – √(.8)) = 137 m/s. The Δv to arrive from LM_Transfer at MEO is zero m/s as the partner departing MEO is an active user. The Δv to launch from MEO onto MG_Transfer is 1.223 km/s *(1 – √(.8)) = 129 m/s. The Δv to arrive from MG_Transfer at GEO is zero m/s as the partner departing GEO is an active user. The Δv to launch from GEO onto MG_Transfer is 1.201 km/s *(1 – √(.8)) = 127 m/s. The Δv to arrive from MG_Transfer at MEO is zero m/s. The Δv to launch from MEO onto LM_Transfer is 1.356 km/s *(1 – √(.8)) = 143 m/s. The Δv to arrive from LM_Transfer at LEO is zero m/s. The total Δv for the round trip sums to (137 + 0 + 129 + 0 + 127 + 0 + 143 + 0) m/s = 0.536 km/s. This is a reduction in Δv of one order of magnitude relative to conventional rocket travel. The trip requires 8 engagements with four active partners. Each active partner is responsible for their own launch Δv shortfall, avoiding double billing.

The MEO Recycler is stationed in the Van Allen belts – a high radiation environment. While the reset time for a typical Recycler is expected to be roughly 12 hours, technology enhancements can be applied to the MEO Recycler to shorten the reset time there to approximately one hour. Care must be taken to ensure radiation sensitive cargo (including people) are not stranded at the MEO Recycler for long periods of time awaiting the arrival of a partner spacecraft.

AIAA paper 2003-6934 provides an empirically derived formula for estimating the cost of engaging a Recycler. The relevant formula is Cost ($) = 2.73 * $(kW)^{1.091}$, where kW represents the thrust power of the engine. A Recycler's thrust level is just one Gee, leading to an engagement cost of $ 1 million (FY 2000) for a typical Hughes HS 702 communications satellite.

Example 3 A Race From LEO to L5

A first class user wishes to race a conventional rocket from LEO to L5. Calculate the time and Δv required for trip, and compare the results with a Hohmann transfer orbit. Presume λ = 80. % for all Recyclers.

Solution The Δvs to travel from LEO to GEO were calculated in example 1. Transferring those results here, Δv = (137 + 143 + 129 + 127) m/s = 0.536 km/s from LEO to GEO. The Δv to launch from GEO onto G5_Transfer_up is 1.154 km/s *(1 – √(.8)) = 122 m/s. The Δv to arrive from G5_Transfer_up at L5 is 1.068 km/s *(1 – √(.8)) = 113 m/s. Thus, the total Δv from LEO to L5 is (536 + 122 + 113) m/s = 0.771 km/s.

Consulting table 2 and animating the orbits, the transit time from LEO to MEO is 2 hrs. The reset time at the MEO CMR is 1 hr. The transit time from MEO to GEO is 10 hrs. The reset time at GEO is presumed to be 12 hrs. The transit time from GEO to L5 is 3.1 days. The total travel time from LEO to L5 using Recyclers is (2 + 1 + 10 + 12) hrs + 3.1 days = 4.2 days.

In comparison, the Δv for a Hohmann transfer from a 554 km LEO to L5 is (Δv_1 = 3.045 km/s) + (Δv_2 = 0.826 km/s) = 3.871 km/s. The transit time on a Hohmann orbit is 5.0 days. The first class Recycler user beats the conventional rocket to L5 by a day expending one fifth the Δv needed for the Hohmann route.

4. Advanced Applications

Desirable operating features emerge when Recyclers are considered as a system. Although designed to efficiently recycle kinetic energy, Recyclers can be employed in recovering space debris both to mitigate the orbital debris hazard as well as for training and educational purposes. Small spacecraft can engage Recyclers to both land and launch without involving partner spacecraft – at the expense of the Recycler's momentum and onboard energy. This can be used to advantage to maneuver a Recycler without expending conventional rocket propellant. A Recycler can be deployed on the lunar surface or any other airless body, providing the advantage of using the Moon as a stabilizing anchor for the system – an infinite source or sink of momentum, much as the Earth is used as an infinite source or sink of charge (ground) for electrical systems. The KE liberated by an arriving spacecraft engaging a Recycler is converted in electricity. Any source of electricity (such as solar arrays) can be employed to replenish lost electrical energy – **effectively using sunlight to maintain a nearly propellantless space transportation system.** Recyclers can also effect orbit inclination changes for spacecraft.

The holy grail of tether systems is the space elevator, spanning from Earth's surface to GEO. Presume such a space elevator exists and pose the question, what delta vee would be required to place a spacecraft in LEO? The space elevator orbits the Earth in 24 hours. At an orbital height of 554 km a point on the elevator is moving at 0.50 km/s. Orbital velocity at this height is 7.58 km/s. A spacecraft stepping off the space elevator here would therefore require a delta vee of 7.08 km/s to enter into LEO. Alternatively, stepping off the space elevator in GEO and using a Hohmann transfer orbit to LEO would require a delta vee of 3.80 km/s. In comparison, the delta vee to transfer from GEO to LEO using 3 Recyclers as listed in table 1 is 0.270 km/s for a third class user. Thus, even if a space elevator did exist today, **Recyclers would still be built and used** to travel to destinations below and above GEO, and be used to change inclinations at GEO.

A CataMitt Recycler on the lunar surface adds the Moon to the Recycler transportation network. The conventional delta vee to land on the Moon from low lunar orbit is 1.9 km/s. A Recycler portal tangent to the lunar surface can take out the last 1.5 km/s but conventional rockets are still required to take out the difference just before engaging the surface portal. The launch portal of a surface Recycler can be oriented independently of the landing portal and at a considerable distance away. (With two portals instead of three, a lunar surface Recycler is designated a CMR215.) The delta vee for a conventional round trip between LEO and the lunar surface is 11.8 km/s. The same round trip executed using Recyclers (λ = 80 %) is 1.9 km/s for a third class user.

What are the accelerations associated with space travel to the Moon? A conventional rocket might impart 3 gees to a CEV launching from Earth. The trip to the lunar surface and back toward Earth would involve lower accelerations. However, reentry to Earth entails higher accelerations – above 4 gees, ruling much of the general population unfit for space travel to the Moon. In comparison, engagements at Recyclers are designed to involve 1 gee of acceleration. While launch from Earth would entail the same 3 gee acceleration experienced by a conventional rocket, the rest of the trip starting with arrival into LEO and ending with the return to LEO from the Moon would involve accelerations no greater than one gee. Reentry to Earth would begin from LEO, not from a high orbit, resulting in more benign reentry accelerations for more people.

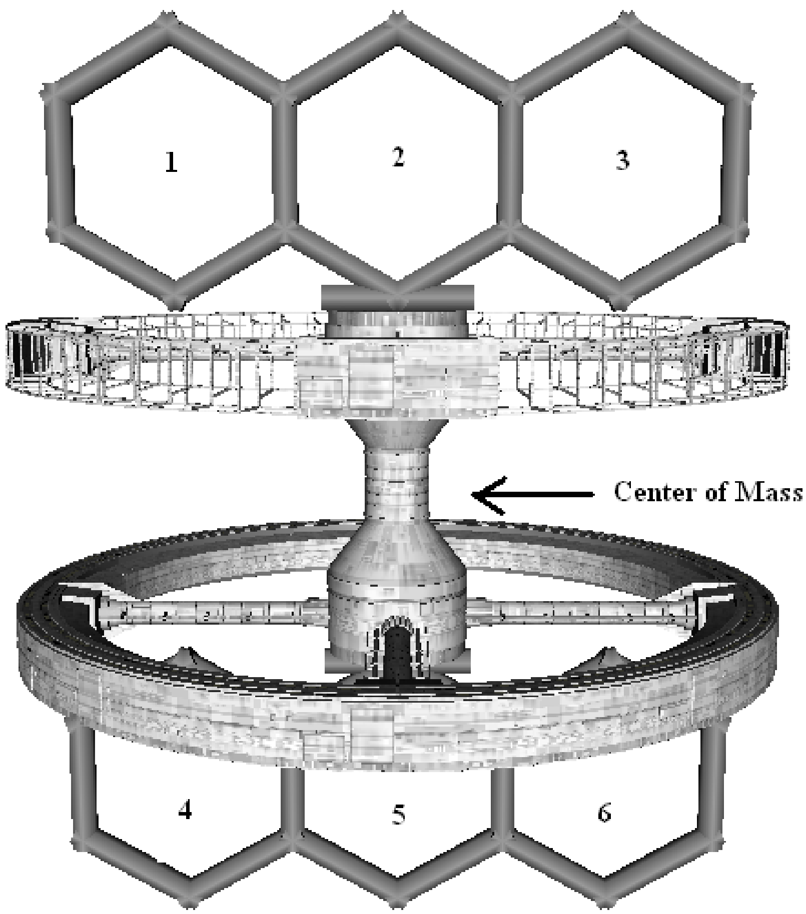


Figure 7. A pair of CataMitt Recyclers straddling a space colony construction site brings numerous benefits to the endeavor.

Consider an upper Recycler with portals labeled 1, 2, 3 and a lower Recycler with portals labeled 4, 5, 6 straddling a space colony construction site as shown in Figure 7. Spacecraft arriving in portals 3 and 6 (or launching into the picture from 1 and 4) would apply positive torque to the bracketed colony. Spacecraft arriving in portals 1 and 4 would apply negative torque. Spacecraft arriving in portals 1 and 6, or 2 and 5, or 3 and 4 would apply zero net torque to the colony. Launching less mass than arrives results in a net gain of electrical energy at the colony at the expense of imparting a net impulse (orbit adjusting maneuver) to the colony. **All of these benefits accrue to the colony regardless of the contents of the arriving payloads** and without expending rocket fuel.

Textbook Δvs to leave LEO for Mars are 3.59 km/s plus 2.10 km/s to arrive from Earth into a low Mars parking orbit (LMO). Launching to Mars from GEO reduces the TMI Δv by 1.42 km/s – an attractive option enabled by Recyclers. The Δv to enter a circular orbit around Mars is minimized for arrivals from Earth at an orbital radius of 12,500 km. With an orbital radius of 9,378 km Phobos is well placed for Recycler operations linking Mars to Earth. The currently favored Recycler deployment scenario envisions **dispatching two single portal Recyclers from Earth to simultaneously encounter Phobos**, one passing above Phobos as the other passes below it. As the minimum encounter speed between the Recycler portals and Phobos is 1.88 km/s, measures are required to reduce the encounter speed by 0.38+ km/s prior to the encounter.

Recycler tether ends are not inert grappling hooks, they are nanosatellites equipped with seekers and thrusters to maximize the probability of a successful tether end attachment in every engagement. The Recycler arrival at Phobos calls for each portal to aft deploy its six tethers at 1.5 km/s to hook to the other portal's tethers as 20 km diameter Phobos passes between the portals, lassoing Phobos. If this technique can be executed without requiring a precursor mission to prepare the surface of Phobos for the encounter the implication is profound as there are a speculated 10^9 bodies at least 5 km in diameter in the Kuiper Belt region of the solar system. If Phobos can be lassoed by a passing pair of Recycler portals, then there must be at least a million suitable similar bodies spanning the solar system useable for Recycler space travel operations.

A Recycler portal may be 4 or more times the reference mass of a spacecraft, rendering a CMR315's set of standard 115 km long tethers inadequate for braking a portal to rest at Phobos. A custom braking tether is required for this task, coupled to disk brakes mounted on each portal that are required to dissipate (not recycle!) at least 10^{11} J of kinetic energy through friction. Fig. 8 shows the situation just after the two portals come to rest.

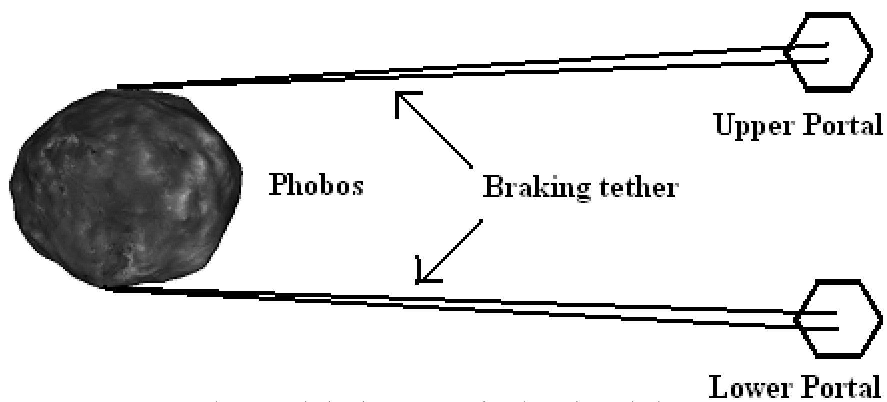


Figure 8. Two Recycler portals brake to rest after lassoing Phobos.

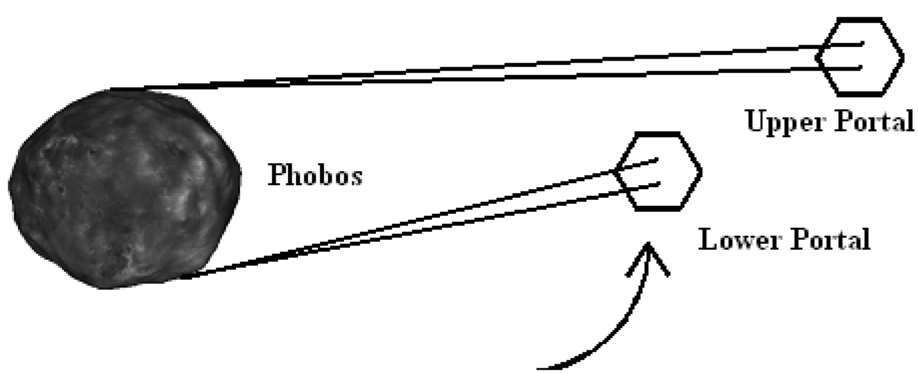


Figure 9. Recycler portals wrap the braking tether around Phobos.

Next, the portals wrap the braking tether around Phobos, firmly securing both portals to Phobos (fig. 9). Solar arrays deploy, the SMES rings recharge, the disk brakes are dismounted, the braking tethers are repositioned to keep each portal's engagement axis clear, standard engagement tethers are brought online and the two portals electrically connect to each other (if not already done through the braking tether). Sacks of Phobos dust are collected and positioned to await catapult launch from a portal. With that, **Phobos is rapidly transformed into a Recycler** (fig. 10). Due to its inertial mass of 10^{16} kg a launch portal on Phobos is free to point in any direction independent of the velocity vector of an arriving spacecraft. Nor are spacecraft split apart at Phobos. As each early new arrival from Earth engages the Phobos Recycler sacks of Phobos dust are launched onto synchronized elliptical orbits – perhaps more properly renamed as kinetic energy storage rings – for future use. Propellant boil off is not a problem when sacks of Phobos dust are used. The propulsive delta vee to arrive at the Phobos Recycler from Earth is 0.38 km/s. The delta vee to arrive at a Deimos Recycler from Earth is 0.42 km/s (for a third class user).

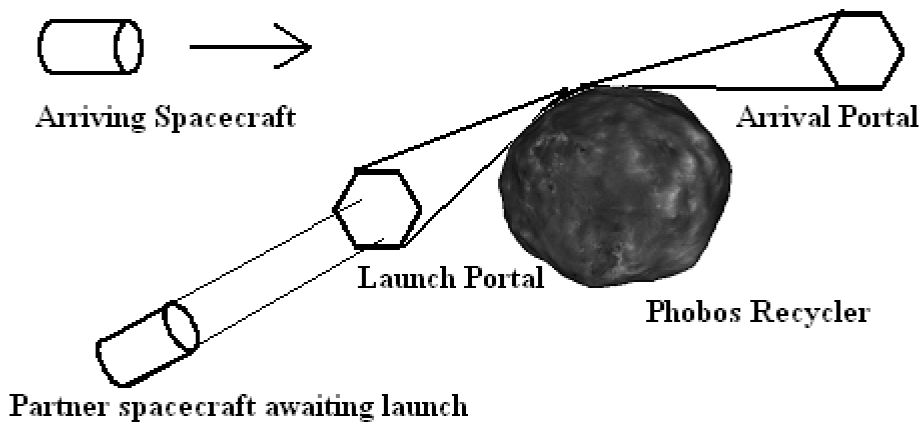


Figure 10. Phobos can be rapidly transformed into a CataMitt Recycler.

Limiting the maximum engagement delta vee of a Recycler to 1.5 km/s, the Phobos Recycler can access a 323 km low Mars orbit (LMO) inclined up to 43 degrees. A CMR315 deployed to this LMO results in a propellant delta vee of 0.54 km/s for a spacecraft to arrive from Earth at Phobos and then transfer to a Recycler at 323 km inclined 43 degrees (80% energy coupling efficiency, third class user). A Deimos Recycler can access a 297 km low Mars orbit inclined up to 80. degrees. A CMR315 deployed to this LMO leads to a propellant delta vee of 0.58 km/s for a spacecraft to arrive from Earth at Deimos and then transfer to a 297 km altitude Recycler inclined 80 degrees (80% efficiency, third class user). **Adding CMR315s in low Mars orbit drops the total Δv from LEO to low Mars orbit to 2.98 km/s** (using 5 Recyclers at 80 % λ).

Available partner spacecraft enable domino engagements. Imagine a Mars habitat arriving at Phobos from Earth powering the launch of a fresh lunch, a Harry Potter book, plus Phobos dust ballast directly from Phobos to Deimos. When they arrive at Deimos two hours later their kinetic energy powers the launch of a resource satellite into a high inclination Mars orbit. Spacecraft pass kinetic energy and momentum along the Recycler network much as one falling domino passes kinetic energy and momentum to the next domino. After all, all moving mass has KE.

A single portal Recycler passing within range and relative speed limits of 10 m to 10 km radius asteroids can exploit them to significantly alter its own velocity vector by using an asteroid belt. An asteroid belt consists of an impact absorbing sheath on the side facing the asteroid and an

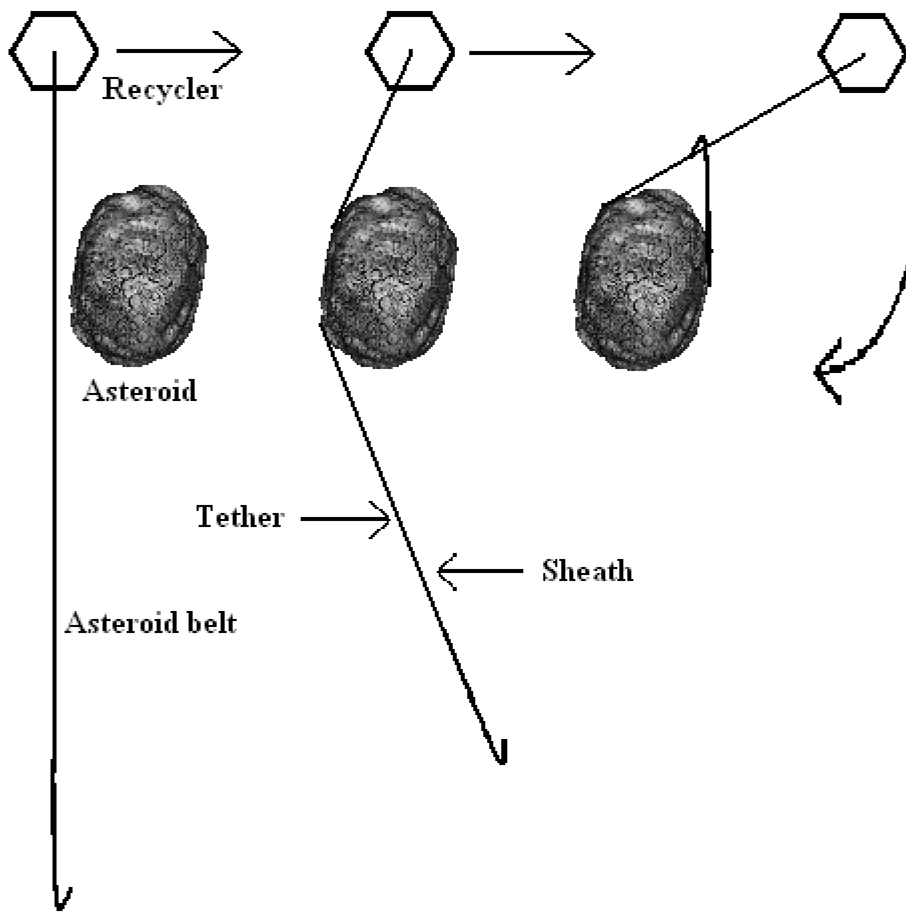


Figure 11. A single portal Recycler can enjoy artificial gravity and propellantless velocity changes by lassoing a passing asteroid.

engagement tether generally free to slide along on the side facing outward from the asteroid. As a passing asteroid bumps into the deployed belt the end of the belt whips around the asteroid to hook onto itself, capturing the Recycler to the asteroid (fig. 11). Conservation of angular momentum dictates the Recycler will swing around the asteroid undergoing centripetal acceleration. This artificial gravity coupled with the radiation shielding potential of the dc magnetic fields generated by the SMES rings provide hypothetical passengers on a Recycler with a relatively healthy environment during their stay around the asteroid. Recyclers posses a means of propulsion, a means for providing artificial gravity, and a means of radiation shielding. These impulse engines are well suited to serve as true vessels of exploration by a space faring nation.

A Recycler can potentially swing itself across vast distances of space at great speeds reminiscent of Spiderman swinging from web to web he self deploys as he goes. Later, as infrastructure becomes emplaced onto asteroids providing asteroid belts, motors, electricity and engagement tethers to hook onto approaching spacecraft, operations reminiscent of Tarzan swinging from existing vine to existing vine are possible. At this point the number of unique routes linking the planets become so great it is a real challenge to calculate the fastest or the cheapest possible route from planet to planet. Perhaps university teams will some day be sponsored in Recycler races between Earth and Mars to inspire students to study physics on their way to the stars.

End Note and Supplementary Material

This paper was released on October 18, 2006. As of this date analysis of Recyclers is ongoing. Scenario CEV_ISS is tentatively scheduled for release in December 2006. This scenario will show the exchange of Crew Exploration Vehicles at the International Space Station using a CMR304 CataMitt Recycler. The scenario will be released as a .vdf file, viewable using AGI Viewer (available at www.stk.com and on this DVD). Stay tuned.

This paper is bundled on a DVD containing several files. This paper – Propellantless Space Travel – is a .pdf file describing the concept in a physics textbook format.

CMR104_r1a is an .avi file showing a care package launched from Keenedy Space Center and engaging a Recycler in LEO at a closing speed of 104.5 m/s. This animation was released in 2004. Hence, some details on the Recycler model are outdated. The care package shown is launched on a Delta 2, and uses built in eyelets to engage the Recycler's tethers.

CMR304_progress_r1a is an .avi file showing unmanned Progress vehicles exchanging via Recycler near the ISS. This animation was released in July 2005. The corresponding .vdf file (playable using AGI Viewer) shows the same scenario.

CMR304_progress_r2 shows unmanned Progress vehicles exchanging via Recycler near the ISS. This 3D animation was released in July 2005. Study it with the corresponding .avi file.

energy schematic_0001 is a .wvmv file schematically showing an unsplit spacecraft engaging a Recycler.

energy schematic 2 is a .wvmv file schematically showing a split spacecraft engaging a Recycler.

LEO_L5_r1 is an avi file showing synchronized Recycler orbits from LEO to L5. A second pass is annotated with calculated delta vees using 80 % energy coupling efficiencies at each Recycler. A first class user uses ballast satellites as partners in engagements.

Man22614 is AIAA paper 2004-6053: "CataMitt Recycler Concept for the Reuse of Orbital Kinetic Energy" presented at the Space 2004 conference and exhibit in September 2004.

AGI Viewer is an installable set of 3D viewer files for use with scenario CMR304_progress_r2.

Enjoy!
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Oct 18, 2006

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