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AFFORDABLE DEBRIS REMOVAL AND COLLECTION IN LEO

J. Pearson, E. Levin, J. Carroll*

Star Technology and Research, Inc., USA
*Tether Applications, Inc., USA

The ElectroDynamic Debris Eliminator (EDDE) is a LEO vehicle of a new class. It is solar-powered and uses electric current in a long conductor to thrust against the Earth's magnetic field. Operating without propellant, EDDE can repeatedly change its altitude by hundreds of kilometers per day and its orbital plane by several degrees per day. EDDE weighs about 100 kg, but it can move multi-ton payloads. We consider three options for debris removal campaigns in low Earth orbit using EDDE. A dozen EDDE vehicles could remove all large debris from LEO in 7 years. They could all be launched on one ESPA ring (two per slot), but phased deployment has advantages. Two EDDE vehicles can be launched each year and retired 5 years later. In 9 years of operation, 2,000 tons of large legacy debris and 97% of the collision-generated debris potential in LEO can be removed, at an average cost of less than $400/kg and an average annual cost of less than $90M. We also consider a campaign that removes only upper stages from LEO. This eliminates any need to capture satellites with large appendages. In 7 years of operation, 1,000 tons of upper stages and 79% of the collision-generated debris potential can be removed, at an average cost of less than $500/kg and an average annual cost of about $70M. In these campaigns, debris objects are dragged to altitudes below ISS and released into short-lived orbits. But 3/4 of the LEO debris mass is in objects over 1 ton, and they may not burn up completely. In the third campaign, old upper stages between 650 km and 1200 km in the 71-74°, 81-83°, and the Sun-sync clusters are captured and delivered to slightly maneuverable "orbiting scrapyards" near 650 km. Objects are collected as they pass through nodal coincidence with the scrapyard. Within 7 years 400 tons can be collected. This will reduce collision-generated debris potential by 40%. Each scrapyard can be propelled electrodynamically without fuel expenditure for collision avoidance and orbit maintenance. This allows time to develop recycling technologies. Even selective recycling can serve to ventilate stages, to encourage more complete burnup of the remainder.

I. INTRODUCTION

The NASA Orbital Debris Program Office at the Johnson Space Center in Houston studies space debris and formulates rules to limit debris creation. These rules include eliminating loose bolts and bands when spacecraft are released, venting fluid tanks to prevent later explosions, and requiring that satellites re-enter within 25 years after mission completion. These practices are now widespread but they are also known to be insufficient. Unless we begin removing existing debris from orbit, inevitable collisions involving objects like 8-ton rocket bodies and 5-ton satellites will eventually create millions of pieces of dangerous small shrapnel. This may make LEO unusable for centuries[1].

The direct threat to satellites is mostly due to small "shrapnel" that is not tracked but has enough mass (of order 1 gram) to do serious damage in hypervelocity impact. Most future shrapnel is likely to result from collisions between two massive objects, as in the Cosmos/Iridium collision in 2009. Most of that collision risk in turn involves spent stages and satellites in discrete congested bands between 750 and 1000 km altitude. It makes sense to remove most of those objects before tackling the debris populations above 1000 km.

NASA JSC has analyzed the debris population growth. Their simulations indicate that the debris population over 10 cm could be stabilized by removing 5-10 of the most threatening large objects in LEO each year[2] and achieving 90% post-mission disposal compliance. To remove large debris with rockets would be very costly[3]. There is a way to eliminate this high cost and make LEO debris removal affordable by using the "ElectroDynamic Debris Eliminator" (EDDE) spacecraft. EDDE is described on the next two pages. The remainder of the paper describes three different EDDE debris removal campaign concepts.

Corresponding author: jp@star-tech-inc.com

II. THE EDDE SPACE VEHICLE

The ElectroDynamic Debris Eliminator (EDDE) is a vehicle of a new class that was presented at the 61st IAC in Prague, CZ, in October, 2010[4]. It grew out of an earlier concept first described at the AIAA Joint Propulsion Conference in 2003. It is a solar-powered space vehicle that "sails" in the ionosphere by using electric current in a long conductor to develop thrust by reacting against the Earth's magnetic field. Electrons are collected from the plasma near one end of the conductor, and are ejected at the other end by an electron emitter. The current loop is closed through the plasma. The principle of operation is shown in Figure 1.

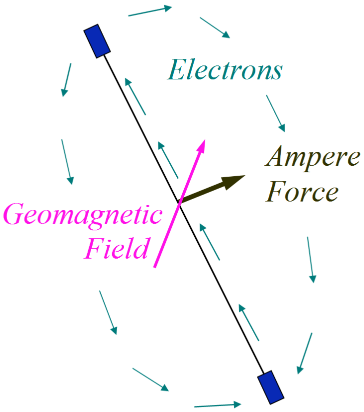

Figure 1. EDDE Propellantless Propulsion

This concept was tested by NASA JSC on the 1993 Plasma Motor-Generator (PMG) flight test. It flowed 0.3A through a 500m wire, with external current closure. In 1996, NASA MSFC's TSS-1R test achieved 1A through a 20 km wire.

The Ampere force on the conductor induced by the magnetic field scales with its length, the current, and the magnetic field strength normal to the conductor. Average thrust when EDDE is descending can be far higher than when moving up, because energy to drive the current loop can be extracted from orbital motion.

EDDE is a high performance upper stage and autonomous roving space vehicle that is propellantless, with virtually unlimited delta-V. EDDE uses flexible lightweight solar arrays for power, and rotates slowly to improve stability and performance, thrusting to change all elements of the orbit.

Rotation is the key feature that enables high performance, by both stiffening the tether against the transverse thrust forces, and allowing a wider range of average thrust directions.

Providing adequate tension and control requires a rotation rate of 6 to 8 turns per orbit. The rotation rate and plane can be controlled by periodically varying the current level and direction along the conductor length. The EDDE design is covered by three US utility patents, one for the spinning operations[5]. and two for the method[6] and apparatus[7] for active control of EDDE.

EDDE consists of a long, segmented conductor incorporating electron collectors, solar arrays, current controllers and electron emitters. It can be equipped with net managers at each end to deploy large, lightweight nets to capture objects, or payload managers to support and release payloads. A schematic of EDDE is shown in Figure 2.

This unique, patented design sets EDDE apart from previous electrodynamic tether system concepts. Conventional hanging tethers depend on the gravity gradient force to provide tension and stability; this limits the allowable tether current and the thrust, because this force is relatively small.

Too much electrodynamic thrust causes a hanging tether to librate excessively, causing loss of control. By contrast, because it is stabilized by rotation, EDDE can operate with currents and thrust levels much higher than those that would destabilize hanging tethers. Rotation also widens the range of available thrust angles to the magnetic field and further improves EDDE agility compared to hanging tethers.

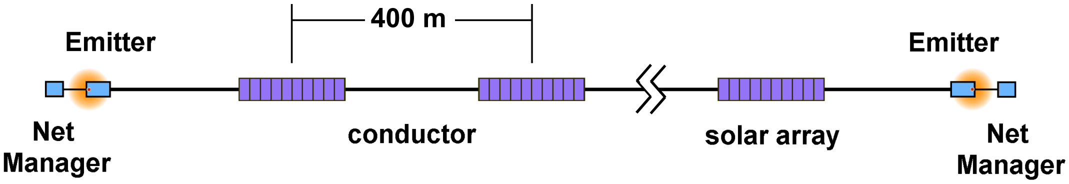

Figure 2: EDDE Vehicle Schematic, Showing Arrays, Conductor, Emitters, and Net Managers

The EDDE tape design also radically reduces the risks of cut by hypervelocity impact. Electrodymanic tethers that use small diameter wires can be cut by impactors down to 1/3 the wire diameter. To overcome this, some electrodynamic tethers use multiple strands with cross-members, like a ladder.

But the small wires and many connections pose fabrication and deployment challenges, such as keeping the strands apart. The EDDE approach is simple but effective—a broad ribbon of aluminum 30 mm wide, reinforced with quartz fiber composite strips for strength and tear resistance. This greatly reduces vulnerability to small micrometeoroids and debris. EDDE actively avoids all tracked objects to eliminate the danger from them. The danger from untracked debris less than 10 cm is much smaller, because the threat to EDDE scales with debris width, and most of the cumulative debris width is due to large tracked objects.

Finally, EDDE design addresses the arcing problem seen on the Tethered Satellite System in 1996. Any long bare conductor in LEO can see a high enough EMF to drive a sustained arc, and may also have enough exposed electron collection area to allow large and hence damaging arc currents. Arcs on multi-km tethers can be self-sustaining, burning through and severing the conductor as happened to TSS. EDDE plans solar array spacing of 400 m, and each 400-m deployed tape length has a winding core at the middle. Putting arc-control circuits at each solar array and each winding core lets us isolate each 200-m tape length when an arc is detected. This reduces both EMF and electron collection area.

Segmentation also allows better control of current and hence force along the length. This improves EDDE control of spin plane, rate, and bending dynamics. It also allows control after component failures, including tape severance by hypervelocity impact. Segmented design lets EDDE become a highly redundant vehicle controllable from either end. The segments provide redundant electron collection, emission, power, command and control. In the unlikely event that EDDE were to be cut by a meteoroid or debris object, each part would still be able to thrust and control itself, and could either continue the mission at a lower rate, or deorbit itself to prevent danger to other spacecraft.

Challenges imposed by EDDE's segmented design include the need to properly sequence the deployment of a large number of tape segments and solar arrays that are stowed separately but near each other, and to properly coordinate operation even after component failures. EDDE can be packaged into one of the secondary payload slots of the ESPA ring on an Atlas V or Delta IV, for example, and deploys autonomously after the primary payload is released, as shown in Figure 3. (This artist's rendition shows just one of each of the many solar arrays and tape segments.)

EDDE deployment requires a slow spin. This is started by small thrusters and then continued electrodynamically, once enough bare conducting tape area has paid out. A very slow spin is enough to gently unfold the solar arrays. Then the spin is increased to deploy the tape windings.

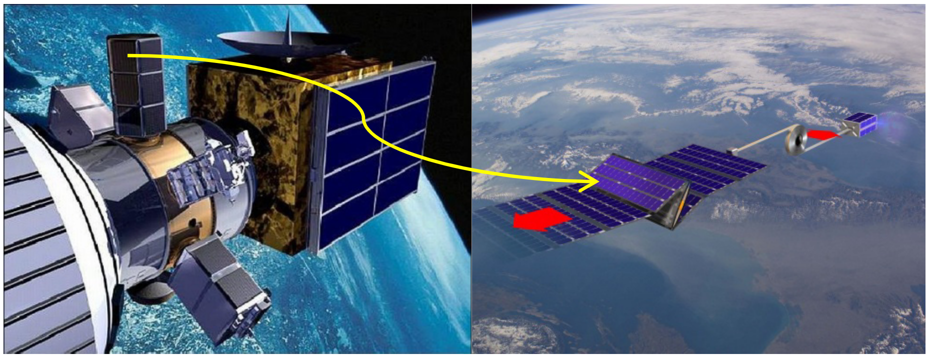

Figure 3. EDDE Component Deployment Concept from ESPA Payload Slot

III. WHOLESALE DEBRIS REMOVAL CAMPAIGN

There are two distinct types of collisions that we really should distinguish: collisions between large objects that create lots of shrapnel but may not involve immediate asset losses, if both objects are debris, and expensive lethal collisions of mostly untracked shrapnel with high-value assets years to decades later. EDDE protects future assets by greatly reducing future production of shrapnel.

We considered three different options for LEO debris removal campaigns. The goal of the first campaign is the wholesale removal of all large debris in LEO. Our recent analysis in Acta Astronautica[8] concluded that a dozen EDDE vehicles can remove all large debris from LEO in about 7 years. They can all be launched on one ESPA ring (two per slot), but our analysis shows that phased deployment has advantages. Two EDDE vehicles can be launched every year and retired after 5 years of service. In 9 years of operation, 2,000 tons of large legacy debris and 97% of the collision-generated debris potential in LEO can be removed at an average cost of less than $400 per kg and an average annual cost of less than $90M. The progression of this campaign is illustrated in Figure 4.

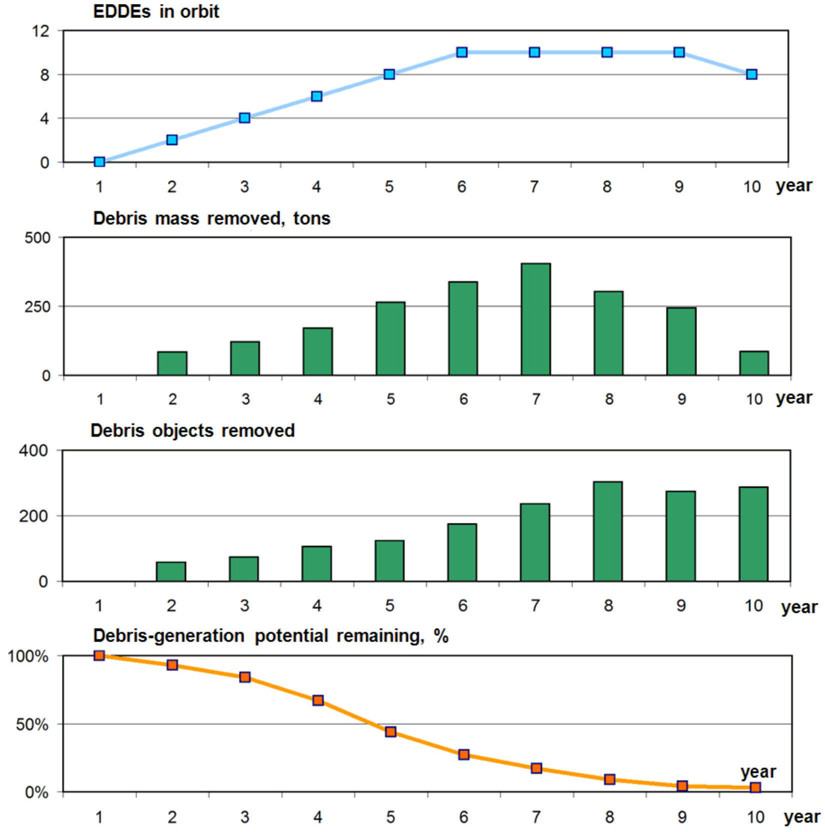

Figure 4. Debris Removal Campaign 1

In years 1-8, we build 2 EDDE vehicles per year and launch them the year after they are built. We reach a peak of 10 EDDEs in orbit in year 6. In year 7, we start retiring 2 vehicles per year after 5 years of service, as they finish removing the bulk of the existing large debris.

We do not plan to go after the largest debris objects in the beginning, because we need to gain experience and perfect the removal operations. We will gradually increase the limit on the size of the debris objects from 1.5 tons in year 2 to 3 tons in year 4, with no limit after that. In years 2-6, we work on removing the upper stages from the high-inclination clusters. We start removing defunct satellites in year 7. Smaller debris objects are removed mostly in the second half of the campaign. To estimate throughput, we add 20% time margins on all operations. On top of that, we assume 80% capacity utilization in the first year, increasing 5% each year until it reaches 95%.

This debris removal campaign results in a major reduction of the debris-generation potential within 10 years. After that, EDDE debris removal efforts would scale down to an equilibrium level, in which EDDE mostly removes new spent stages and failed satellites.

The price structure that supports this debris removal schedule and minimizes the overall average price per kilogram removed is as follows. The average price per object removed starts at $1.5M in year 2 and drops by 23% every year to $185K in year 10. The campaign requires an initial investment of $30M, which is repaid through dividends and capital redemption in 5 years.

Figure 5 illustrates the cash flow during the campaign, and Table 1 gives the overall averages.

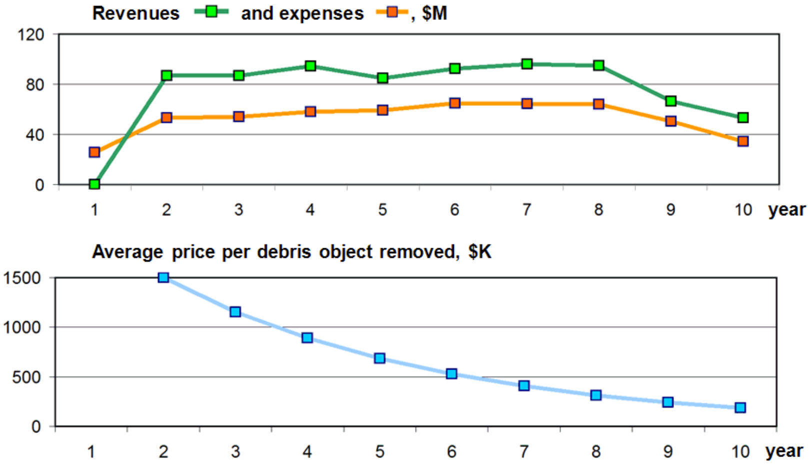

Figure 5. Financial Results for Campaign 1

Table 1. Overall Characteristics of Campaign 1

Debris mass removed	2,017 tons
Debris objects removed	1639
Average object mass	1,231 kg
Average cost per kg	$374
Average cost per object	$461K
Average annual cost for the customer*	$84M

*starting from the second year

Figure 6 shows the comparative cost per kg of wholesale removal using EDDE propellantless propulsion vehicles, compared with chemical and ion rockets. It also shows the reduction in potential of debris generation from collisions between the large debris objects as the debris is removed.

It is groundbreaking that the unit cost of debris removal can be a small fraction of the typical launch costs. For rockets, the unit cost of debris removal is comparable with the launch costs which is prohibitive. It is hard to justify debris removal if it costs as much per kg as launch. The service must be much cheaper than launch to make economic sense to satellite operators.

Participation of the 12 members of the Inter-Agency Space Debris Coordination Committee can create an international regime supporting wholesale debris removal by EDDE vehicles at a reasonable annual cost to the members. The regime put in place as a result of this effort should set rules of prompt removal of spent stages and failed satellites in the future.

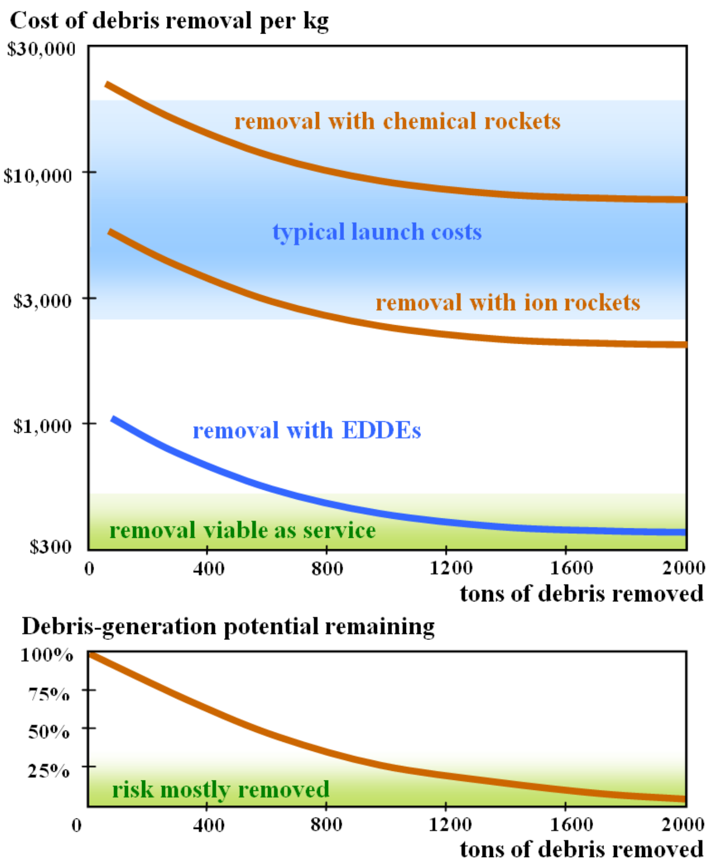

Figure 6. Wholesale Debris Removal Costs

IV. UPPER STAGE REMOVAL CAMPAIGN

We also considered a second campaign that removes only upper stages from LEO. In 7 years of operation, 1,000 tons of upper stages and 79% of the collision-generated debris potential can be removed at an average cost of less than $500 per kg and an average annual cost of about $70M. The progression of this campaign is illustrated in Figure 7.

In years 1-4, we build 2 EDDE vehicles per year and launch them the year after they are built. We reach a peak of 8 EDDEs in orbit in year 5. In year 7, we start retiring 2 vehicles per year after 5 years of service, as they are finishing the job. By that time, we expect to see accumulation of at least another 100-200 tons of the newly-launched upper stages that we will need to remove. In year 10, the last 2 EDDE vehicles would need to be replaced to continue removal of the upper stages from the new launches.

As in campaign 1, we gradually increase the limit on the size of the debris objects from 1.5 tons in year 2 to 3 tons in year 4, with no limit after that. When calculating the throughput, we add 20% time margins on all operations. On top of that, we assume 80% capacity utilization in the first year, growing by 5% per year until it reaches a 95% capacity.

Through year 5, campaign 2 develops similar to campaign 1, but starting from year 5, no additional EDDE vehicles are built and launched because the population of targeted debris objects is smaller. Consequently, campaign 2 is shorter and the residual debris-generation potential at the end of the campaign is higher compared to campaign 1. In a sense, campaign 2 can be considered as a subset of campaign 1 focused entirely on the upper stages in LEO.

The price structure that supports this debris removal schedule and minimizes the overall average price per kilogram removed is as follows. The average price per object removed starts at $1.5M in year 2 and drops by 25% every year to $267K in year 8. The campaign requires an initial investment of $30M, which is repaid through dividends and capital redemption in 5 years.

Figure 8 illustrates the cash flow during the campaign, and Table 2 gives the overall averages.

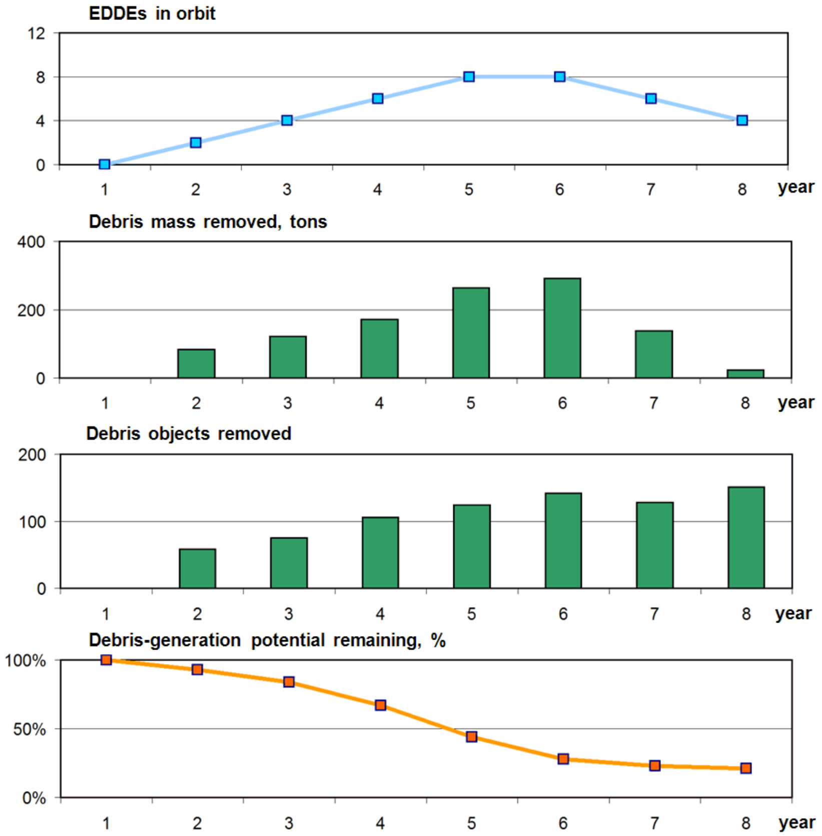

Figure 7. Debris Removal Campaign 2

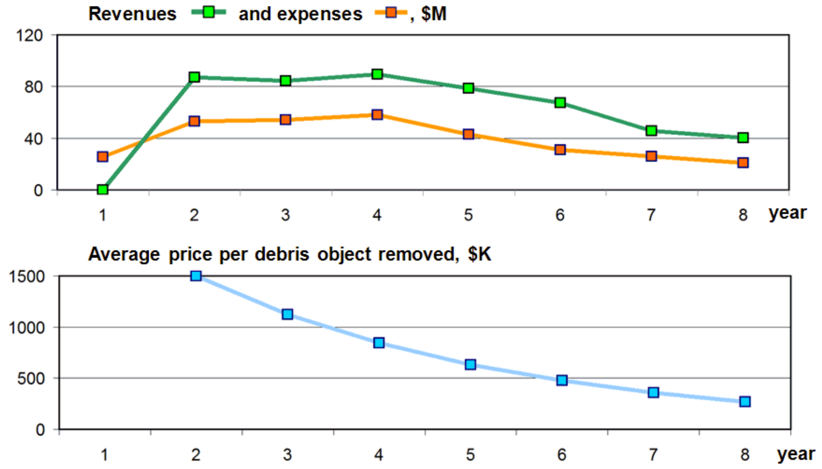

Figure 8. Financial Results for Campaign 2

Table 2. Overall Characteristics of Campaign 2

Debris mass removed	1,090 tons
Debris objects removed	784
Average object mass	1,390 kg
Average cost per kg	$452
Average cost per object	$628K
Average annual cost for the customer*	$70M

*starting from the second year

Both of the above campaign concepts require an initial investment of $30M. Substantial amounts are allocated for liability insurance. It is not required now but may become part of future government regulations. We included rough estimates to show its potential impact.

V. UPPER STAGE COLLECTION CAMPAIGN

In the first two campaigns, debris objects are dragged to altitudes below ISS and released into short-lived orbits that end with an uncontrolled reentry. But uncontrolled reentry is not desirable for objects that are not expected to burn up completely. EDDE debris removal campaigns would greatly increase the annual rates of uncontrolled reentry of ton-plus objects.

To avoid reentry liabilities, consider a third campaign that collects upper stages rather than letting them re-enter. In this campaign, old upper stages orbiting between 650 km and 1200 km in the 71-74°, 81-83°, and the Sun-sync clusters are moved to 650 km and attached to several maneuverable “tethered scrapyards.” Collection is constrained by differential nodal regression, and will slow down once most of the stages have been collected.

Each scrapyard is at a different altitude near 650 km. Only rocket bodies heavier than 200 kg with perigee above 650 km and apogee below 1200 km are targeted. In this altitude range, there are 87 stages totaling 248 tons at 71-74°, 188 stages totaling 267 tons at 81-83°, and 42 stages totaling 80 tons in the sun-synchronous cluster. Overall, there are 317 spent stages totaling 595 tons in the altitude range of interest, just in these three inclination clusters.

We cannot go into detail on how EDDE can hand stages off to a tethered scrapyard. But each scrapyard uses electrodynamic propulsion to allow collision avoidance and orbit maintenance without propellant. Once suitable technologies are developed, some fraction of the collected mass could be reprocessed into MMOD or radiation shielding, and eventually new structures could be fabricated. Recycling of spent stages could become the starting point for large-scale space manufacturing.

Overall collection throughput can be impressive. If one collection facility served by one EDDE vehicle is placed in each cluster, then within 7 years, about 400 tons of the target rocket bodies can be captured and removed from the most dangerous altitudes, reducing the statistically expected future generation of collision fragments in LEO by more than 40%. That mass will be gathered in a much less crowded altitude band.

Collected stages can be stored as long as needed, until a decision is made and acted on, to recycle or deorbit the collection. Even very selective recycling may be able to “ventilate” stages enough that they will burn up thoroughly in reentry. This may make targeted deorbit unnecessary.

Several EDDE vehicles operating between the scrapyard/recyclers and “marketplace orbits” such as ISS could provide ~100 tons/year deliverable to ISS or other orbits on demand. Such “barely extraterrestrial” materials could be the starting point for large-scale space manufacturing. This may also help pay for debris removal.

VI. EDDE TECHNOLOGY MATURATION

EDDE's technologies, components, and control strategies are now being matured under contract with the NASA OCT Game Changing Technology Division at NASA Langley Research Center. At the end of this contract we plan to start flight hardware construction.

In parallel with this NASA effort, the US Naval Research Laboratory has developed "TEPCE": the Tether Electrodynamic Propulsion CubeSat Experiment. TEPCE is shown below. The end cubes are connected by a 1-km conducting tether stowed around a stacer spring in the center. The tether design and stacer-driven deployment were proposed by Joe Carroll.

TEPCE will test emission, collection, and electrodynamic propulsion[9], using electron collectors and emitters relevant to EDDE. The first flight is scheduled for mid-2013. The altitude and tether area limit the orbit life but allow good tests of hardware and software. A follow-on flight to higher altitude with the same hardware will allow testing of reboost, active avoidance, and other key EDDE functions.

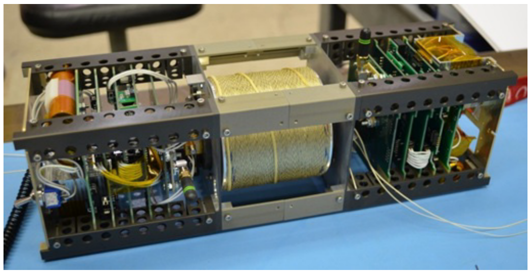

Figure 9. TEPCE Flight Hardware

Following TEPCE, our plans are to test a "Mini-EDDE" vehicle using full-scale EDDE components. It will weigh less than 50 kg and could be 3 km long. It will be designed to allow large orbit changes and rendezvous. This can be followed by a full-mission-capable EDDE that can fly as a secondary payload on any flight with ~100-kg payload margin. It can test net-based capture and de-orbit of US debris objects.

VI. CONCLUSIONS AND RECOMMENDATIONS

The likelihood of collisions that generate large amounts of lethal but untracked shrapnel will continue to grow until debris removal rates exceed launch rates, and will remain high until wholesale removal is achieved. Electrodynamic propulsion technology appears to be the most affordable credible option for wholesale removal. EDDE, for the first time, makes it feasible to remove all LEO debris over 2 kg at reasonable cost. And there is a substantial cost associated with catastrophic collisions in LEO[10] that will continue if the large debris is not removed.

EDDE makes it possible to shift from reducing the rate of growth (the current policy and near-term plans involving selective removal) to wholesale cleanup. This has many implications that are not appreciated. EDDE is low cost, versatile, robust, and able to actively avoid all tracked objects. It is the logical solution to LEO debris removal, so a successful maturation effort should be followed by a flight test.

Sixteen EDDE vehicles launched as secondary payloads on ESPA can affordably remove 2,000 tons of large debris from LEO in about 9 years. That would remove more than 97% of the collision-generated debris potential in LEO. It would take only 10 vehicles and 7 years to remove 1,000 tons of upper stages, reducing collision-generated debris potential by 79%. Or in 7 years, 400 tons of upper stages from the 71-74°, 81-83°, and the sun-sync clusters can be removed from the congested altitudes and collected near 650 km in 3 "tethered scrapyards", each served by one EDDE, for later recycling or deorbit. This will reduce the collision-generated debris potential by 40%.

There is no other vehicle that can match or even remotely approach this performance today. It is important to understand that collisions involving large debris objects create lots of shrapnel, but may not involve immediate asset losses, while this mostly untracked shrapnel could disable high-value assets years to decades later[10]. EDDE protects future assets by greatly reducing future production of shrapnel.

The estimated cost per kilogram of debris removed by the EDDE vehicles is a small fraction of typical launch costs per kg, making it possible to shift from debris mitigation to wholesale active removal of all large debris objects from LEO. Debris removal by ion engines is likely to be 5 times as expensive as EDDE, and chemical rockets 20 times as expensive as EDDE, for the same amount of debris removed.

US-based EDDE operations will initially have to be limited to the 1/6 of the LEO debris mass (and much less than 1/6 of the threat) that is US-owned. As soon as it is clear that wholesale debris removal or collection are technically and economically viable (by whatever means), it will be timely to start discussing removal with other countries. This seems likely to require agreements between the launching state and the removing state on liability implications. Such agreements may be not just necessary, but possibly even adequate as a basis for wholesale LEO cleanup.

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