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# LOW-COST LAUNCH SYSTEMS FOR THE DUAL-LAUNCH CONCEPT

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## ABSTRACT

Current launch costs into low Earth orbit (LEO) are extremely high. This study identified cost reductions possible using a dual launch strategy—using high-reliability/high-cost launch vehicles for high-value payloads, and lower cost launch vehicles for low-value payloads. The approach was to assess existing expendable launch vehicles for development, production, and operations cost using a parametric mass-based cost model, TRANSCOST 6.2. Performing fewer engine tests, designing structures with lower structural margins, parallel processing, eliminating payload clean-room requirements and extensive testing before launch, horizontal integration, lower-cost labor, and reduced insurance costs were examined to lower costs. Nearly an order of magnitude reduction can be achieved from current launch costs to LEO for low-value payloads. The use of conventional expendable rocket vehicles, however, keeps costs above $2,000 per kilogram to LEO. Revolutionary methods, such as first-stage lasers, electromagnetic and ram accelerators, and upper-stage orbiting tethers, were examined to achieve even lower launch costs. The best combination examined uses the ram accelerator and orbiting tether, with an estimated cost of $250-$350 per kilogram into LEO. That might be further optimized to achieve $100/kg. No launch techniques were discovered that show launch costs below $100 per kilogram.

## INTRODUCTION

The Defense Advanced Research Projects Agency (DARPA) has a program to demonstrate on-orbit repairing and refueling of satellites by an autonomous, space-based robotic spacecraft. The Orbital Express[1] would replenish low-value payload such as spacecraft fuel, cryogenics and batteries and upgrade or repair satellites. ASTRO, the Autonomous Space Transporter and Robotic Orbiter, is a "micro-Shuttle" with a mass of 100 to 500 kg. It would have propulsion to change orbits and to service multiple satellites. ASTRO could also place microsatellites into their intended orbits.

The Orbital Express concept calls for 50-500-kg packages of fuel and electronics to be launched into space, which are then grabbed by ASTRO and taken to operating satellites. Because these packages will be small and relatively cheap, the booster to launch them would not require high reliability. Furthermore, because ASTRO can rendezvous with and pick up the payloads, they can be launched into imprecise orbits, allowing for the use of less accurate launchers. The payloads might even be gun-launched.

### Dual Launch Concept

The Orbital Express concept is made affordable if the payloads of fuel and supplies are launched into orbit on a low-cost launch system. This led DARPA to the Dual Launch concept, in which high-value cargo such as fragile instruments, humans, and satellites are launched on reliable, higher-cost vehicles, whereas low-cost cargo such as fuel, water, and other bulk supplies are launched on less reliable, lower-cost vehicles.

This study, by Ball Aerospace and the Air Force Research Laboratory, addressed the low-value cargo of the dual-launch concept, with the focus on expendable launch vehicles[2]. A major goal was to quantify the predominant cost drivers and to find means to reduce their cost effects. A conservative, top-down cost analysis method was selected that could be applied to current, evolutionary advanced, and even revolutionary launch systems. Thus a single cost analysis was used to evaluate all systems with the same consistent method.

## COST METHOD SELECTION AND CALIBRATION

After screening several candidates, the TRANSCOST[3] (TCS) model, version 6.2, was chosen for cost analysis of the Dual Launch system. TRANSCOST is a parametric method based on component mass and regression equations based on a large database extending over virtually every launch system of the past 40 years. The model's equations are available to the user, and the regression equations have been checked against the known costs of existing systems. The mass-based equations provide simple means by which to extend the cost analysis to advanced and revolutionary systems. The model is used extensively by the international launch community, and is available without the payment of fees or licenses.

The TCS model was applied to current launch systems for calibration. A launch vehicle database was prepared using the International Reference Guide to Space Launch Systems[4] and Mark Wade's *Encyclopedia Astronautica*[5], as well as information from Ball Aerospace proprietary sources. About two dozen different launch systems were analyzed. The data was entered into Excel spreadsheets so that the cost equations could be automated easily for calculation of system costs.

The TCS results are consistent, following the relative costs of small, medium, and large launch vehicles. However, the results averaged 20-50% higher than advertised prices. This discrepancy was resolved by the observation that current market prices do not include development cost amortization.

### Cost Drivers

The total number of flights, or the number of launches per annum, is a key parameter in overall costs. If development costs are to be amortized over sufficient numbers of flights to make them reasonable, there must be a large number of flights. A medium launch system with the capacity to launch 5,000 kg into orbit, that costs $1 billion to develop and has 100 flights, must charge $2000 for each kilogram of payload just to amortize the system development costs. And very few launch vehicles systems have flown more than 100 times. To make a cheaper launch vehicle, development costs must be drastically reduced, or the number of flights must be greatly increased.

The effect of the number of flights on the total cost in dollars per kilogram is shown in Figure 1 for a typical launch vehicle. The total number of flights is spread over 10 years. Development costs are amortized over the total number of flights, so the share of the development cost per flight drops directly with the number of flights. The cost of the vehicle is much more constant, but the higher number of flights implies greater production rates, yielding some savings due to the learning effect for serial production. Operations costs decline with the number of flights, reflecting more efficient use of the launch crews.

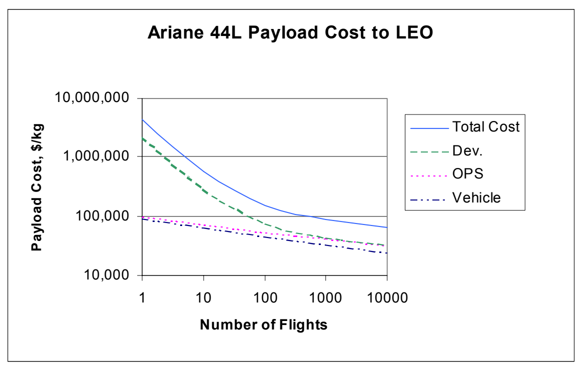


**Figure 1. Effect of Number of Launches on Cost**

### Mission Requirements

Because of the requirement to amortize the large development costs, a low-cost launcher must be flown many times, at a high annual rate. With just 100 flights, the amortization of the development cost is as high as the production cost of the vehicle. However, the number of flights is related to the size of the vehicle and to customer demand. The effect of mission requirements is shown in Figure 2. The cost in dollars per kilogram is calculated, based on the size of the vehicle and the mission demand. The curves have a minimum cost, with both the small payload and the large payload cases costing more. Vehicles with smaller payloads cost more per kilogram because smaller vehicles require more structure per kilogram of payload. Vehicles with larger payloads cost more per kilogram because they fly fewer times, and their development costs are amortized over fewer flights.

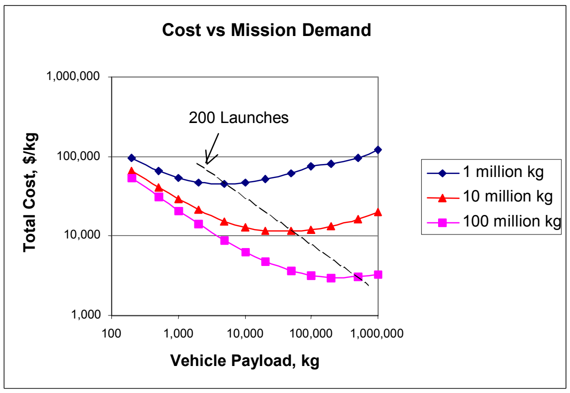


**Figure 2. Effect of Mission Demand on Cost**

Each mission requirement shows a minimum cost at a different size vehicle. Interestingly, the minimum cost occurs for about 200 flights, regardless of the size of the vehicle. This means that the 1-million-kg mission is best served by 200 launches of a 5,000-kg-payload vehicle, and the 10-million-kg mission is best served by 200 launches of a 50,000-kg-payload vehicle. (The largest, 100-million-kg, mission favors 500 flights.) Of all the launch vehicles in the world, only the Soyuz, Kosmos, and Proton have flown more than 200 times.

## LAUNCH COST REDUCTION SCENARIOS

Four major cost reduction scenarios were examined. These were engine reliability, structural reliability, operations and processing, and manufacturing.

### Engine Reliability Scenario

The conventional method for improving engine reliability is to conduct a large number of test firings. Typically, an expendable rocket engine will undergo 1000 development firings to achieve a reliability of 0.995. This translates directly into development costs for rocket engines, and therefore the reliability of engines can be directly related to cost.

TRANSCOST 6.2 relates the number of test firings, the reliability, and a quality cost factor, $\mathbf{f_2}$, which is used in developing the engine development cost estimating relationship (CER). This relationship can be used to quantify the cost of engine reliability in terms of man-years (MYr). The TRANSCOST regression lines for engine development and vehicle stage development in terms of reference mass are:

$$\mathbf{H_E = 228\ M^{0.59}} \qquad \text{MYr}$$

$$\mathbf{H_V = 80.1\ M^{0.583}} \qquad \text{MYr}$$

Because both engines and stages must go through similar design, manufacturing, and basic testing processes, the difference must lie mainly in the repetitive testing required to make rocket engines more reliable. The average test cost, $\mathbf{C_T}$, can then be approximated by the difference between these costs, divided by 1000 firings:

$$\mathbf{C_T = 0.148\ M^{0.59}} \qquad \text{MYr}$$

Here the higher exponent has been used to be more conservative. The overall engine development cost can be divided into the normal development plus the additional testing required:

$$\mathbf{H_E = (80.1 + 0.148\ n)\ M^{0.59}} \qquad \text{MYr,}$$

where **n** is the number of test firings required. Since Koelle developed a relationship between the number of test firings and engine reliability, a price can be put on the added engine reliability. The Koelle relationship for reliability **R** and test firings **n** in TRANSCOST 6.2 can be described as:

$$\mathbf{\log (1-R) = -\ 1.125 \log n + 1.043}$$

Solving this equation for n gives:

$$n = 10^{0.9271 - 0.8889 \log(1-R)}$$

Substituting this into the equation for $H_E$ gives:

$$H_E = (80.1 + 0.148 \times 10^{0.9271 - 0.8889 \log(1-R)})M^{0.59}$$

This equation can now be used to calculate the cost of increasing reliability for liquid propellant rocket engines. The results are that if cost is normalized to 1.0 for 1000 test firings (reliability of 0.9953), then for a reliability of 0.9 (corresponding to 62 test firings), the relative cost is 0.39, and for a reliability of 0.999, the relative cost is 2.91. This means that by performing just 62 development firings instead of 1000, and accepting the resulting reliability of 0.9, 61% of the engine development cost can be saved. The results are shown in Figure 3 in terms of 1 minus reliability, showing little gain below an engine reliability of 0.9.

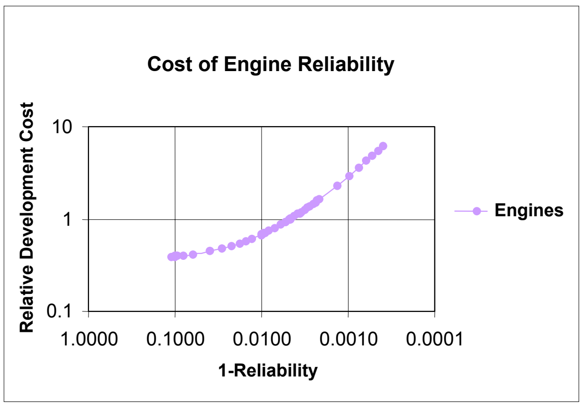


**Figure 3. Engine Development Cost vs. Reliability**

Figure 4 shows the results for engine reliabilities from 0.995 down to 0.4. The minimum cost occurs for an engine reliability of about 0.9. Lower engine reliabilities than 0.9 cause higher overall costs, because the expense of replacing the entire launch vehicle after each failure overcomes the savings from lower engine development costs. The absolute minimum cost for this mission of 1 million kg to LEO calls for an engine reliability of 0.89 and a payload of 5000 kg. The overall vehicle reliability is less than the engine reliability, depending on the total number of engines on the entire multi-stage vehicle. Two-stage vehicles with large single engines can benefit more from reduced engine reliability and cost than one such as the Ariane 44L, which has ten separate engines on three stages and four strap-on boosters. The effects of non-catastrophic engine failure were not considered; each failure was assumed to cause loss of the vehicle. This is a conservative approach that does not over-estimate the savings from reduced reliability.

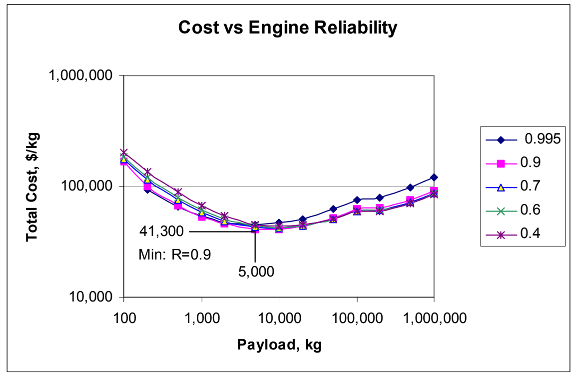


**Figure 4. Launch Costs vs. Engine Reliability**

### Structural Reliability Scenario

Some low-cost vehicle approaches have emphasized higher structural margins, for wider error tolerances and reduced touch labor[6]. The assumption behind these approaches is that reliability will be maintained or even increased, and a robust vehicle would be cheaper than a high performance system. However, this study shows that if reliability is considered as an independent variable, the results are quite different.

TRANSCOST 6.2 represents the development cost in man-years for expendable stages, either cryogenic or storable propellants, in the following form:

$$\mathbf{C_d = 80.1\ f_2\ M_s^{0.583}} \quad \text{(MYr)},$$

where $\mathbf{C_d}$ is the development cost of the vehicle stage, $\mathbf{f_2}$ is the technical quality factor, and $\mathbf{M_s}$ is the structural mass of the stage without engines. The value of the technical quality factor is a function of the net mass fraction of the specific vehicle stage compared with a reference value:

$$f_2 = k_{ref}/k,$$

$$k = M_s/M_p,$$

where **k** is the ratio of the structural mass of the vehicle stage to the usable propellant mass, $\mathbf{k_{ref}}$ is the reference value of **k**, $\mathbf{M_s}$ is the structural mass of the stage (the empty mass less the engine mass), and $\mathbf{M_p}$ is the propellant mass.

The value of $\mathbf{k_{ref}}$ is determined from a regression curve fitted through values for representative storable-propellant vehicles, as shown in Figure 5. The values of $\mathbf{k_{ref}}$ developed from these charts can be represented by the following equations, simplified from the regression formula:

$$k_{ref} = 0.12(\log M)^{-0.75}$$

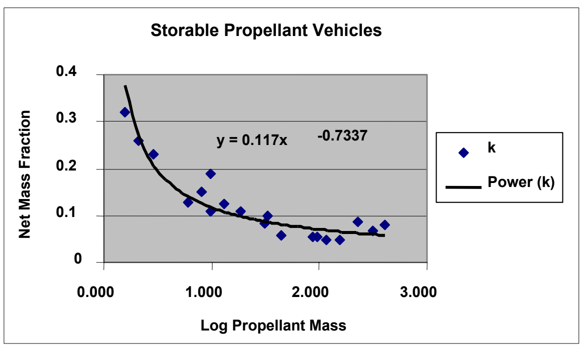


**Figure 5. Net Mass Fraction for Storable Propellant Vehicles**

This relation can be used to evaluate the effects of designing a higher net mass fraction for a liquid-propellant vehicle, accepting a lower payload fraction in return for lower development cost. From Sackheim and Dergarabedian[7], the payload fraction of a launch vehicle can be given by:

$$M_{pl} / M_0 = [(1-\gamma) / (e^{-V/nIg} - \gamma)]^n$$

where $\mathbf{M_{pl}}$ is the payload mass, $\mathbf{M_0}$ is the takeoff gross mass, $\gamma$ is the mass fraction, **V** is the required ΔV for LEO, **n** is the number of stages, **I** is the specific impulse, and **g** is the acceleration of gravity. The mass fraction $\gamma$ is defined as:

$$\gamma = M_n / (M_n + M_p) = (M_s + M_e) / (M_s + M_e + M_p)$$

where $\mathbf{M_n}$ is the net mass, $\mathbf{M_p}$ is the propellant mass, $\mathbf{M_s}$ is the structural mass, and $\mathbf{M_e}$ is the engine mass. The value of **k** used by Koelle and the value of $\gamma$ used by Sackheim and Dergarabedian are related by:

$$\gamma = (k + M_e/M_p) / (k + M_e/M_p + 1)$$

Similarly, the production costs in man-years for the theoretical first unit for storable propellant vehicles can be put into the form:

$$C_p = 0.83\, f_2\, M_s^{0.65} \qquad \text{(MYr)}$$

A spreadsheet was used to investigate the effect of net mass fraction on cost. Stage masses and mass fractions were calculated for various vehicles. Then, holding escape velocity constant, payload and stage mass fractions were varied to calculate the net mass fraction that minimizes cost, using the "solver" routine in Excel, which uses the Generalized Reduced Gradient (GRG2) nonlinear optimization code.

The assumption was made that the vehicle production cost is proportional to the same Koelle **f2** as vehicle development cost. This is reasonable, because as the net mass fraction declines, the vehicle is more fragile, and greater care must be taken in manufacturing and assembly. For a cylindrical propellant tank, the achievable **k** for a given material is proportional to $\mathbf{s}^{-1/3}$, where **s** is the specific strength of the material compared with the baseline 2219 aluminum. The cost of stronger materials, like aluminum/lithium 2195, is much higher than conventional 2219 aluminum. Typical figures are that 2195 is 5% lighter, 30% stronger, and saves 10% of the mass in a tank compared with 2219, but the cost[7] is 4-8 times as high. Allowing for future reductions in cost, a figure of 88% more expensive was used, which gives a cost proportional to $\mathbf{s}^2$.

The results for the Kosmos 3M stages are shown in Figure 6. Depending on the relative cost of higher strength materials, there is a particular value of net mass fraction that results in minimum cost.

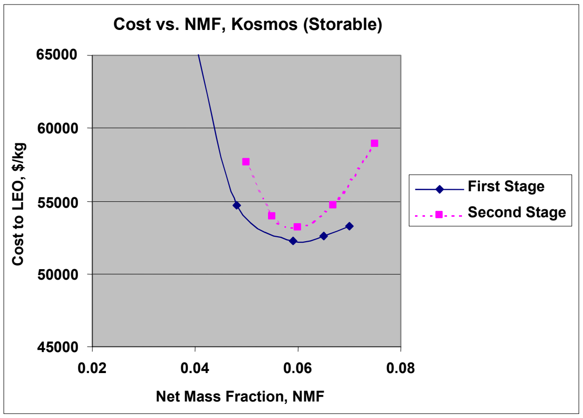


**Figure 6. Cost vs. Net Mass Fraction for Kosmos 3M**

The next step is to relate structural mass fraction to reliability. Propellant tanks typically have safety factors of about 1.2. Assuming that the propellant tank will fail under a load that is higher than the safe stress and that the safety factor of 1.2 represents the 3σ level on the Gaussian failure distribution, then the tank reliability can be calculated based on a change in mass. This change in mass can be related to a corresponding change in net mass fraction of the tank, and thus to its cost. The results are summarized in Figure 7. The structural reliability scenario was applied to all tanks in each stage for four vehicles, and the results from the individual stages were combined to produce an average in terms of payload cost to LEO versus propellant tank reliability. The vehicles examined were the Kosmos 3M, the Ariane 44L, the Zenit 2, and the TRW low-cost expendable vehicle concept (LCELV).

The minimum cost typically occurs at an overall vehicle structural reliability of about 0.67. This corresponds to a propellant tank reliability of about 0.9 for a two-stage vehicle with 4 tanks. (The overall vehicle structural reliability is taken as $R^n$, where R is the individual tank structural reliability and n is the number of tanks.) The Ariane 44L has three stages and four strap-on liquid propellant boosters, and a total of 14 tanks. The Ariane curve shows a minimum cost at a propellant tank structural reliability of about 0.97, which again corresponds to an overall vehicle structural reliability of about 0.67.

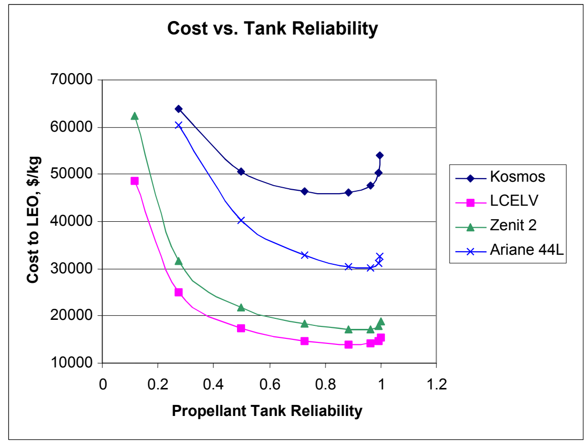


**Figure 7. Cost Reduction vs. Propellant Tank Reliability**

### Operations and Processing Scenario

This cost reduction scenario provides major reductions in launch operations, flight controls, and range operations. Savings are also achieved through elimination of payload insurance costs for the low-value cargo. The total reductions are 8-9% through pre-launch ground costs, including horizontal vehicle integration, reduced testing, and elimination of expensive payload integration processing. The elimination of subsystem tests, and not repeating tests as the vehicle is integrated stage by stage, result in some savings. Other savings result from encapsulation of the payload on the ground rather than on the pad, and changing the labor mix to emphasize lower-cost personnel for integration, checkout, and testing.

### Manufacturing Scenario

The manufacturing cost reduction scenario was more fruitful. This scenario directly addresses the high cost of conventional launch vehicle production. The analysis was initiated using baseline manufacturing information found in Bachtel and Lyles[8], and in Andrews[9] et al. Additionally, the reduced cost engine and vehicle described in the TRW work by Sackheim[10] and Gavitt, and by Gavitt[11] et al, were incorporated, and the SSTO and TSTO cost data from Koelle[12]. This data was fed into the cost scenario worksheet to get the final numbers.

The reduced manufacturing costs include simplified engines with much lower part counts and simplified operations in manufacturing. They also include simplified tank structures with higher structural margins and cheaper monocoque construction instead of chem-milled isogrid structures. These changes also reflect back into the development costs. This approach is being taken in the design of the Kistler reusable launch vehicle, using a large vehicle with more room for structural margin. At the expense of some additional, mass, the tankage is designed for thicker welds that are easier to fabricate and can be subjected to reduced inspections and testing. The result is simpler engines and structures that are cheaper to fabricate and handle, at the cost of reduced payload.

The results of the four cost reduction scenarios are summarized in Figure 8 for three launch vehicles. The reliability and manufacturing scenarios provide the most cost reduction.

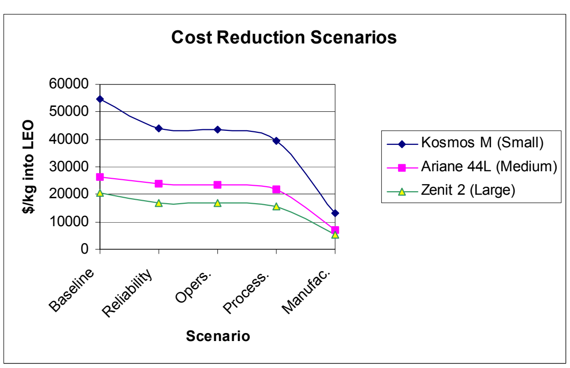


**Figure 8. Cost Reduction Scenario Results**

## REVOLUTIONARY LAUNCH TECHNIQUES

Various schemes other than conventional rocket vehicles have been proposed for low-cost launch. There are revolutionary concepts for the boost stage, using conventional rockets for orbit insertion; revolutionary concepts for orbit insertion, using conventional rockets for the boost stage; and one or more revolutionary techniques that perform both boost and orbit insertion. Representative systems from each type were examined.

Aircraft or balloons can lift a vehicle to high altitude, but provide little or no velocity change, or $\Delta V$, and therefore they provide very little of the total energy required to reach LEO. The conventional rocket system must still provide the bulk of the launch energy, resulting in costs that are in the same range as conventional rockets.

Remote beamed power, from ground-based or space-based lasers or microwave sources, has the advantage that the power source does not have to be carried with the vehicle into orbit. This concept requires extremely high power lasers, a dual-mode engine aboard, plus the fuel for the rocket portion. There is no clear cost advantage over conventional rockets.

The direct launching of orbital payloads by electromagnetic guns[13] has been proposed, but such launcher concepts require an upper stage propulsion system, leading to larger projectiles or smaller payloads. Gas pressure accelerators, including guns and ramjet accelerators, can launch smaller, g-tolerant payloads. The 16-inch guns on the battleship USS Missouri could launch 20-kg payloads into low Earth orbit from an equatorial location, firing projectiles with solid-rocket boosters for orbit injection.

Payloads launched from ground-based accelerators or guns produce trajectories that return to the surface, unless they receive velocity changes after leaving the launcher. An upper stage rocket is expensive, but a rotating tether[14] in orbit could catch payloads and release them in other directions to provide the orbit insertion $\Delta V$. Rotating tethers are simple and cheap, but the rendezvous of a payload with the end of a rotating tether has not been demonstrated, nor has the capture of a payload by a net on a rotating tether. These demonstrations will be required before the concept can be applied.

Most of the revolutionary techniques require great improvements in materials or lasers, or enormous masses in orbit. The development costs would be so large that these could not be considered low-cost launch systems. A compromise system is needed that imparts most of the energy requirements on the ground and requires minimum mass in orbit. The most promising is the combination of ram accelerator or light gas gun and orbiting tether. Bruckner and Hertzberg proposed the ram accelerator[15] for direct launching of space cargo. Pearson proposed a rotating tether to replace the upper stage rocket, and performed a preliminary concept definition study[16].

The baseline system is shown conceptually in Figure 10. The ground-based ram accelerator is fed by a light gas gun, and fires its payloads at a fixed muzzle angle. The payloads are slender projectiles with protective nose cones that are fired several times a day to reach the orbit of the rotating tether. The rotating tether has a tip velocity that matches the velocity difference, $\Delta V$, between the projectile and the rotating tether orbit. The tether end attachment captures the payload and drops it into orbit, where it can be retrieved as needed.

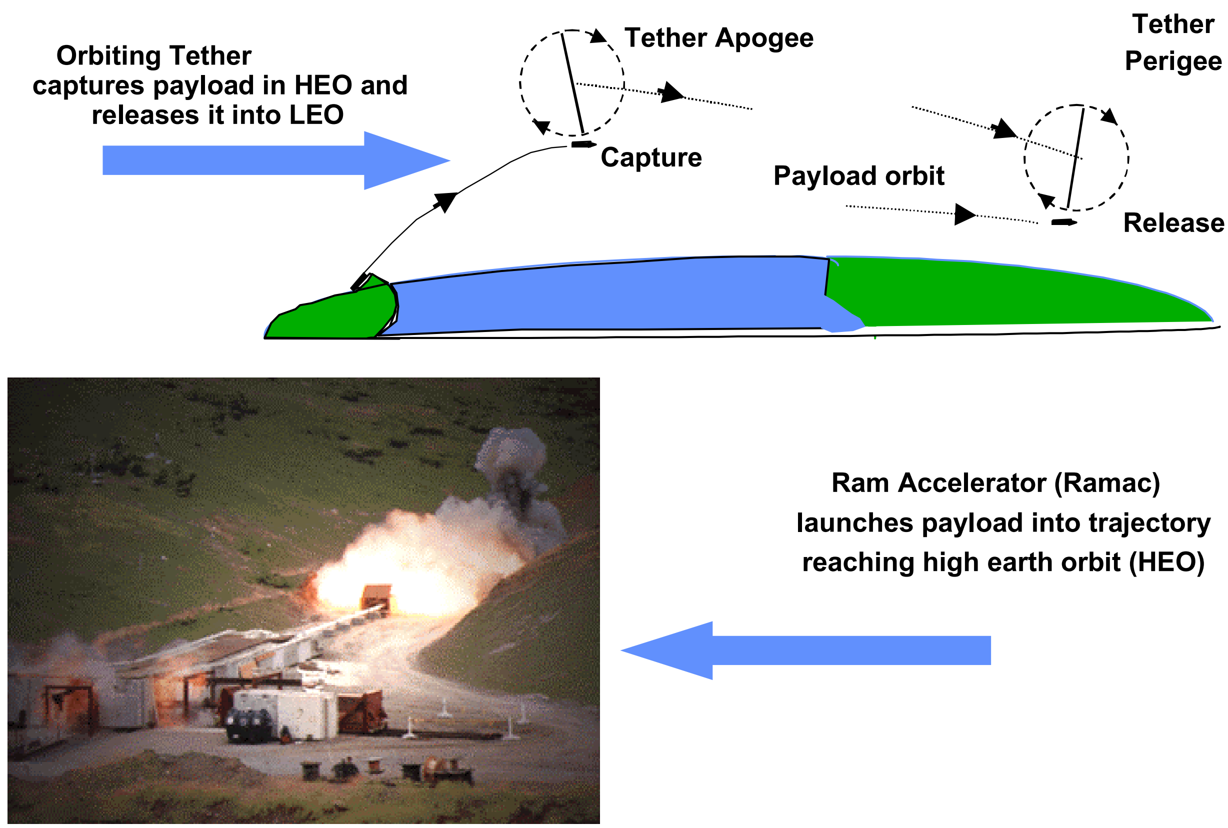


**Figure 10. The Ram Acceleration/Rotating Tether Concept**

The overall launch costs for the ram accelerator/rotating tether were analyzed using the calibrated TCS cost analysis. Regression factors for the ram accelerator were developed based on costs of development of small research installations of ram accelerators, and scaled up. The costs of the rotating tether were based on NASA experience with past and current tether flight experiments. The use of the rotating tether eliminates the need for an upper stage on the projectile. The small payload mass requires only a small ram accelerator, with low development cost, and is well suited to supply the DARPA Orbital Express.

Figure 11 shows the cost components for a 500-metric-ton mission. The minimum cost is about \$250/kg at a 50 kg payload, and \$260/kg at 100 kg payload. A higher mission requirement lowers the overall cost and drives the system to higher payload capacities.

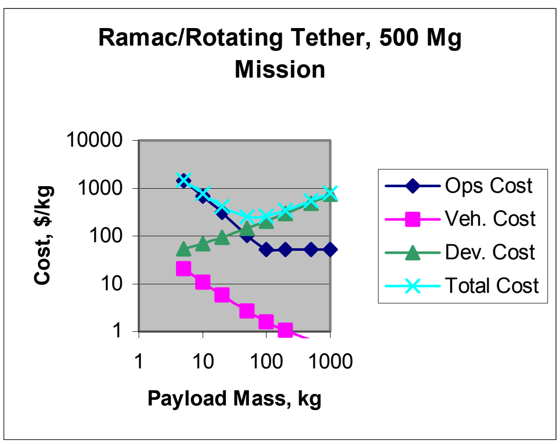


**Figure 11. Launch Costs for 500-Mg Ram Accelerator/Rotating Tether Mission**

## SUMMARY OF RESULTS

Potential methods were examined to make possible the DARPA dual launch concept by reducing the cost of launching into low Earth orbit. A parametric cost analysis method, TRANSCOST 6.2, was selected and calibrated against existing launch systems. It was then modified to apply to new vehicles and revolutionary launch schemes. The limits of cost reduction in conventional systems were assessed, along with the promise of some revolutionary schemes, using this consistent and verifiable cost estimation method. This is apparently the first time that both conventional and revolutionary launch systems have been analyzed for comparative cost under a uniform, credible cost analysis.

The calibrated cost analysis method was applied to evaluate the cost impacts of four cost reduction scenarios—engine reliability, structural reliability, operations and processing, and manufacturing. The total reduction in cost per kilogram in LEO was 74-78%, less than an order of magnitude. Low-cost manufacturing and reduced reliability produced the greatest cost reductions.

The original DARPA hypothesis that lower reliability vehicles could reduce launch costs was shown to be correct to a certain extent. The minimum cost reliability corresponds to an overall vehicle reliability of about 0.67, with individual component reliabilities of about 0.89-0.97.

The overall results of the study are summarized in Figure 12, which plots the cost of launching payloads into low Earth orbit in dollars per kilogram versus payload. Conventional rocket launch vehicles appear in the band across the upper part of the chart, trending downward to the right. The general slope shows the advantage of larger vehicles over smaller ones. Vertical lines in this portion of the chart show the effects of the cost-reduction scenarios on individual vehicles. None of these vehicles reaches as low as \$2000/kg into LEO.

In contrast to the rockets, launch costs for the revolutionary launch methods trends downward to the left, becoming cheaper with smaller payloads. Closest to the pure rocket case is the rocket/tether combination, a first-stage rocket vehicle and a rotating tether. Because the rocket is relatively large and provides most of the total

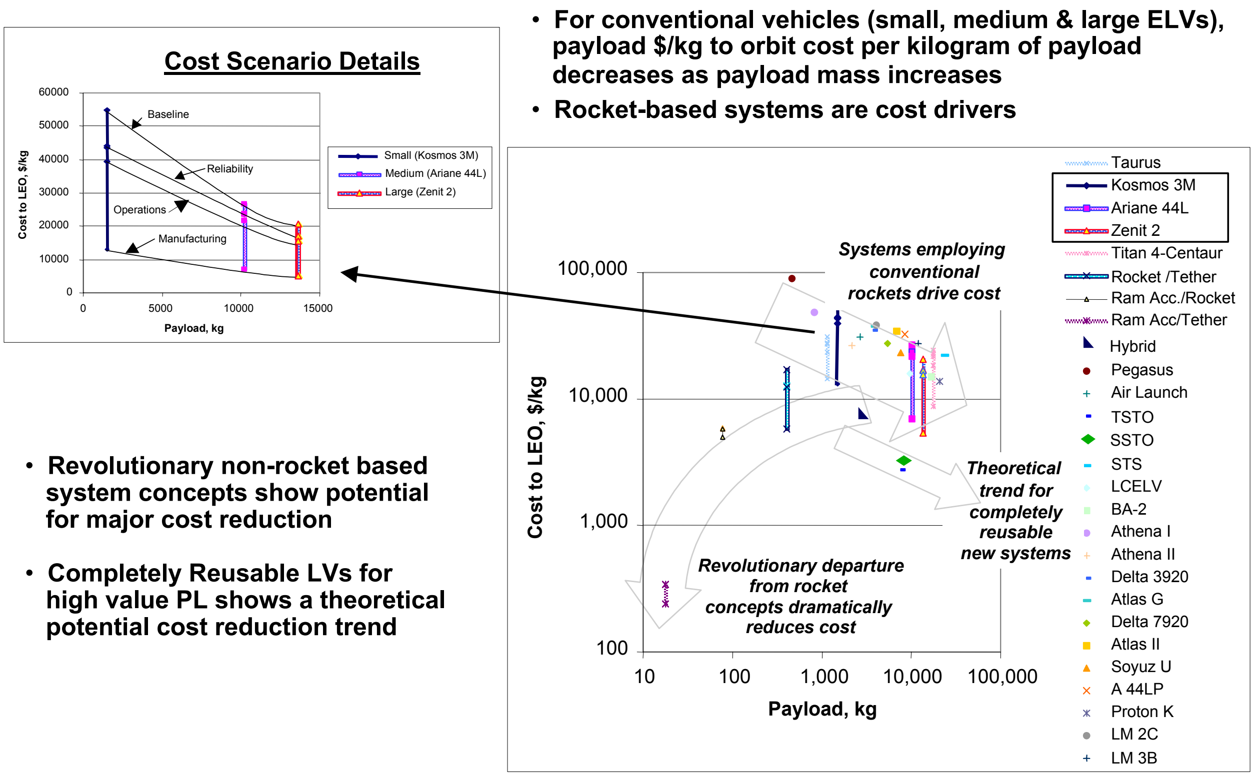


**Figure 12. Launch Costs to LEO vs. Payload**

ΔV, the cost of this combination is close to that of the pure rocket vehicle. Applying the four cost scenarios reduces the cost to about the same as pure rocket vehicles with payloads 40 times as great, roughly $5,000-$15,000/kg.

Further along the revolutionary launch system band is the ram accelerator/rocket combination. This method combines a first-stage booster of a ram accelerator launch tube combined with an upper-stage rocket. Because the rocket provides less ΔV, this system is cheaper than the rocket/tether combination. However, there is still a cost to be paid for the rocket stage, given that more than half the projectile mass consists of solid fuel for the rocket. This combination provides a cost of about $5000/kg to LEO.

Finally, the lowest costs (and smallest payloads) on the revolutionary concept band are for the combination of the ram accelerator and orbiting tether. This combination consists of two revolutionary techniques working together, and dispenses with the rocket vehicle entirely. The payload carrier is simply a fuel tank or commodity container designed to withstand the loads.

## CONCLUSIONS

A parametric cost estimation method, TRANSCOST 6.2, was used to evaluate current, advanced, and revolutionary launch techniques with a common basis. The method yielded consistent and reliable cost analysis of various concepts and scenarios. The results showed that launch costs can be reduced by lowering reliability of engines and structures; the minimum cost for commodity payloads occurs at an overall vehicle reliability of about 0.67. Rockets can be optimized for nearly an order of magnitude payload-to-orbit cost reduction, but reasonable extrapolations still show costs of $2500/kg of payload into LEO. One promising revolutionary technique, the combination of the ram accelerator and orbiting tether, promises payload-to-orbit costs of $250-350/kg, and with refinement, might achieve $100/kg. No revolutionary launch concepts were discovered that would yield payload to orbit cost less than $100/kg.

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