JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 43, No. 3, May–June 2006

# Engineering Notes

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## Low-Cost Launch of Payloads to Low Earth Orbit

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### Introduction

A CRITICAL factor for the viability of a sustained human presence in space is launch cost. The exploration vision brings a heavy lift requirement for thousands of metric tons of propellant and hardware to establish, resupply, and expand moon and Mars bases. Because the basis for the exploration effort is guided by budget limitations, it is expected that the development of off-planet infrastructure will be chiefly driven by launch dollars per kilogram.

High launch costs have a multiple budgetary impact. With present heavy lift technology, launch costs are in the range of $6000–$20,000/kg. Because high launch costs severely constrain system mass, ultralightweight reliable structures and payloads must be developed at high cost. Consequently, budget limits and high launch cost determine the scale of the entire exploration effort.

### Cost Model

An empirical cost model described here predicts that launch costs can be sharply reduced by employing existing aerospace technology. The genesis of the cost model is the observation that the operating cost of high-power systems is not dictated by delivered energy but by peak system power. Electric utilities, for example, charge residential customers in energy units of kilowatt hours, but charge high-peak-power customers for the transmission lines and switching costs dictated by maximum-peak-power load. We have applied this paradigm to aerospace vehicles for which operating cost and performance data are available,[1] as plotted in Fig. 1. The plotted cost for fixed-wing aircraft is based on the operating cost for maximum load carried to maximum range. For boosters, operating cost is based on launch cost to low Earth orbit. The operating power for aircraft is taken for cruise conditions, where power is equal to drag multipled by cruise velocity. Operating power for boosters is taken as peak power for vacuum conditions, where power in terms of vacuum thrust and exhaust velocity is $P = (1/2)(TU_e)_{\text{vac}}$.

The data in Fig. 1 are adjusted to calender year 2004 (CY04) dollars. It is evident from the linearity of the curve fit in this log–log plot that a power law curve fit gives a reasonable prediction of operating cost for aerospace vehicles over many orders of magnitude in peak power, of the form

$$\text{cost (CY04 \$)} = 0.00157(P_{\text{watts}})^{1.09} \qquad (1a)$$

In terms of millions of dollars and power in megawatts,

$$\text{cost (CY04 \$millions)} = 0.0055 \cdot (P_{\text{MW}})^{1.09} \qquad (1b)$$

All data fit between the dashed lines, a factor of 1.5 above and below the curve fit. This range is narrow considering that the plot represents both aircraft and booster technologies, reusable and expendable systems, high and low flight rates, and a range of technology maturity, over six orders of magnitude in thrust power.

Data points are predicted in Fig. 1 for the operating costs of the Magnum and Saturn V boosters and a supersonic business jet. Also shown is the air-launched Orbital Sciences Pegasus. The systems cover a power range of 60 kW to 60 GW (six orders of magnitude) and an operating cost range of $200–$800,000,000. Figure 1 also shows published data for two systems currently under development: the Space X Falcon one and the Kistler K-1, with the latter falling below the curve fit.

The heavy lift problem is restricted to the upper range of power shown in Fig. 1. This range can be represented by a linear fit, resulting in Eq. (2) for launch cost to low Earth orbit in terms of peak power:

$$\text{launch cost (CY04 \$millions)} \cong \text{peak power (MW)}/100 \qquad (2)$$

Using this linear cost relation results in a simple analytic model that compares launch costs of various proposed systems to allow evaluation of attractive low-cost launch architectures.

Equation (2) implies that peak power must be minimized to minimize launch cost. The analytic model assumes that the propulsion system, whether liquid, solid, or a combination, is represented by a single trajectory-dependent system specific impulse, as shown for some typical cases in Table 1.

For booster systems, system $I_{\text{sp}}$ is calculated from $\langle I_{\text{sp}} \rangle = (V_{\text{LEO}}/g) \cdot \ln(m_{\text{LEO}}/m_0)$, where $m_{\text{LEO}}$ is mass delivered to low Earth orbit. For a maximum thrust $T_{\text{vac}}$, the peak power is then expressed as

$$P = \tfrac{1}{2} T_{\text{vac}} U_e = \tfrac{1}{2}(T_{\text{vac}}/W_0) m_{\text{LEO}} g^2 I_{\text{sp}} \exp(\Delta V / g I_{\text{sp}}) \qquad (3)$$

and the launch cost is then found through Eq. (2).

### Discussion

The quantity $T_{\text{vac}}/W_0$ is related to the initial launch acceleration in gravitational acceleration $g$. A vertical launch system must overcome gravity and also provide vertical and horizontal acceleration. For the space shuttle, $T_{\text{vac}}/W_0 = 1.49\ g$, and for the Saturn $V$, $T_{\text{vac}}/W_0 = 1.43\ g$. For air launch at a 30-deg climb angle with a winged vehicle, it is possible that $T_{\text{vac}}/W_0$ approaches 1.0 $g$.

The $\Delta V$ for vertical and air launch is shown in Fig. 2.[2] The vertical launch is for 28.5-deg inclination (Cape Kennedy), whereas the air launch takes advantage of flying the carrier aircraft to the equator and launching from 0-deg inclination. When systems for

Presented as Paper 2005-2717 at the 1st Space Exploration Conference, Orlando, FL, 30 January–1 February 2005; received 22 February 2005; revision received 12 September 2005; accepted for publication 27 September 2005. 

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**Table 1 System specific impulse for propulsion systems to low Earth orbit**

| Propulsion type | Propellant | Average $I_{sp}$, s |
|---|---|---|
| Solid rocket booster (SRB) | AP/HTPB[a] | 250 |
| RS-27 | LOX/RP-1[b] | 300 |
| Shuttle, SRB + space shuttle main engine (SSME) | AP/HTPB + LOX/$LH_2$[c] | 350 |
| RD-0120 Triprop | LOX/RP-1/$LH_2$ | 400 |
| SSME | LOX/$LH_2$ | 450 |

[a]Ammonium perchlorate/hydroxyl-terminated polybutadiene. [b]Liquid oxygen/rocket propellant 1.
[c]Liquid hydrogen.

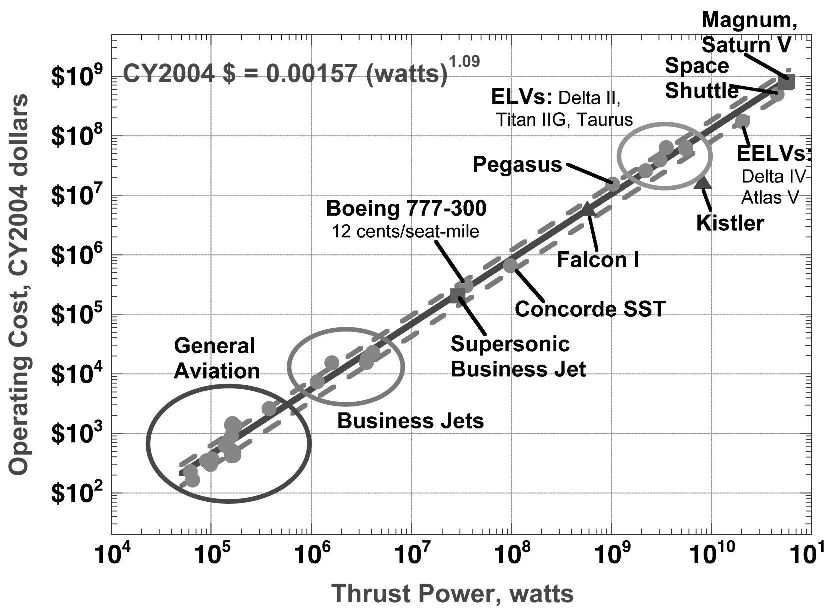


**Fig. 1 Operating cost correlates with propulsive power for aerospace vehicles.**

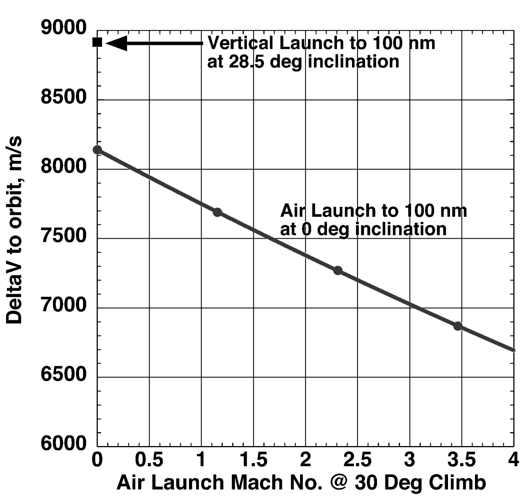


**Fig. 2 Reduction in $\Delta V$ with air launch Mach number.**

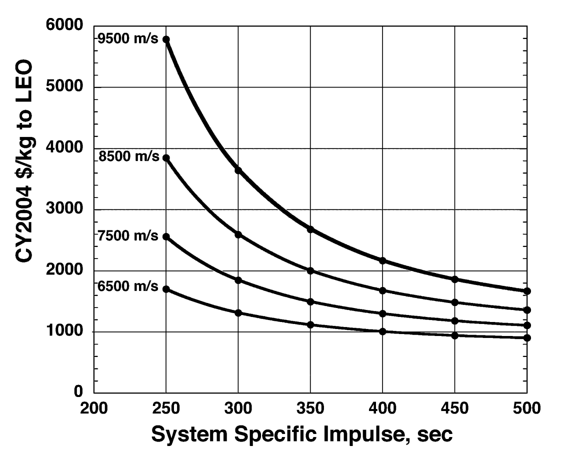


**Fig. 3 Specific cost to orbit, dollars per kilogram, vs specific impulse.**

which the mass delivered to low Earth orbit $m_{LEO}$ is the same are compared, then the principle variables determining power are the thrust/weight $T_{vac}/W_0$, the $I_{sp}$, and the characteristic velocity $\Delta V$. The resulting specific launch cost in dollars per kilogram is plotted vs $I_{sp}$ for chemical boosters in Fig. 3.

Figure 3 shows that for chemical boosters, the launch cost drops significantly with increasing $I_{sp}$ in the 250–450-s range. The highest cost, ~\$5000/kg, is obtained for vertical launch of an all-solid booster from sea level, with $\Delta V$ ~9000 m/s. The lowest cost, <\$1000/kg, is obtained for $\Delta V$ ~6500 m/s, characteristic of supersonic (~Mach 4.0) air launch at the equator, including the reduced $T_{vac}/W_0$ available to horizontal air launch systems. For this launch condition, the cost penalty for using RP-1/LOX (300 s) is small, permitting use of the higher density propellant.

The preceding discussion does not include development costs for a gas turbine-powered launch platform. It is feasible to develop a heavy lift Mach 0.8 platform at low cost, largely based on modifications to existing aircraft. A Mach 4.0 system would be significantly more difficult, and no attempt is made here to estimate the cost of such a platform. However, we note that with savings of as much as \$4000/kg, a \$5 billion development could be paid for in 12 launches at 100 t each.

## Other System Options

Air launch provides other system options, such as architectures for safe and low-cost launch of a crew exploration vehicle (CEV). This system is particularly safe if the launch platform is designed to permit prelaunch in-flight crew ingress and egress. In this scenario, the crew initially rides in the launch platform, and enters the CEV late in the in-flight checkout phase. If a problem develops before separation, the crew can leave the CEV and reenter the launch platform. If the CEV system uses liquid instead of solid propulsion, the propellant can be dumped before return to the takeoff site and the CEV either landed with the crew and launch platform or separated and parachuted into a drop area.

A less obvious benefit of horizontal air launch is the synergistic relationship with air liquefaction cycles. Air launch systems lend themselves to the ability to cruise subsonically while air is liquefied and the oxygen separated and stored for later use as an oxidizer. Liquid hydrogen systems, coupled with new developments in heat exchangers[3] and oxygen separators[4,5] further improve the benefits of this system. Air liquefaction cycles greatly reduce the oxidizer mass carried at takeoff, which in turn allows a larger payload mass at takeoff. The net effect is a significant increase in mass to orbit, or a smaller lift platform for a given mass to orbit. Because of the insensitivity of cost to $I_{sp}$ for supersonic horizontal launch (Fig. 3), oxygen purity does not become a critical issue for these systems.

## Conclusions

The results of this analysis show that the most significant cost factor for Earth-launch boosters may be peak thrust power and that launch cost and peak power may be linearly related. Consequently, minimum-operating-cost systems would be systems with low launch mass. The simultaneous application of well-known mass-reduction techniques, such as high $I_{sp}$ propulsion, air launch at the equator, and trajectory optimization would reduce operating costs by a large factor. In addition, newer developments such as supersonic air launch and air liquefaction propulsion cycles are predicted to further reduce peak power, and thus cost, of Earth launch systems.

## Acknowledgments

The authors appreciate support from the University of Illinois Critical Research Initiatives program and the Center for Space Technology and Research, as well as discussions with Glenn Olson and Dana Andrews.

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