

Appendix 1 to Chapter 3

A Discussion of Spacelift

Note: This appendix provides a basic discussion of spacelift. It is meant to provide the nonexpert with enough of an understanding of future spacelift options to understand the potential of new technologies. It provides a background to better understand the argument in Chapter 3 about the current bottleneck of spacelift.

Will Space Always be so Expensive?

One of the key features of spaceflight and of spacecraft has already been described: high cost. This is the primary inhibitor of expanded commercial, private, and even governmental activities in space.

Some of this cost is understandable in terms of unavoidable requirements for quality, and some of the costs can be attributed to inadequate insight regarding “sub-optimizing” parts of the overall problem without realizing the higher costs imposed on other unconsidered aspects of the entire system.

Another often-overlooked cost driver is the requirement for ultra-high reliability. In practice, if achieving 95% reliability costs a given amount, it may cost an equal amount to increase reliability to 99%, and equal amount more to increase it to, say 99.8%. Consequently, for certain missions, buying three times as many 95% vehicles as 99.8% vehicles (or even ten times as many 70% reliability vehicles) may be a bargain IF the launch costs weren't so intimidating.

The expense of getting into space and operating there has up until now provided a threshold over which only Earth's richest and most serious actors can cross. This “high entry cost” has kept out of space many other players whose presence would at the very least complicate, and at worst endanger, current activities. This threshold appears to be rapidly lowering, and would-be new players are lining up. Of course, while the threshold is lowering, launch cost has remained relatively static.

Getting into space has been done the same way for so long that for many people there's only one conceivable way: fuel-burning rockets. But let's take a minute to examine underlying principles.

Rockets use the Newtonian "action-reaction" effect to push themselves in a desired direction. The higher the exhaust velocity, the greater the "specific impulse" (and efficiency) of the engine, and the less total fraction of propellant is needed for a given space mission. At present, more than 90% of the weight of a space launch vehicle consists of the propellant to bring an object into orbit. Depending on the desired final orbit, the actual payload consists of only 2–4% of the vehicle's liftoff weight.

To date, this "reaction mass" has been expelled almost exclusively in the form of expanding combustion products created by actually burning something in a specially-shaped rocket chamber (one known exception is a small cold-gas jet used for vehicle pointing). However, a number of alternate approaches are technically feasible. The material to be expelled could be super-heated by an onboard nuclear power unit, or by the detonation of small nuclear explosives, or by energy projected from the ground into the thrust chamber. Or it could be expelled with electrostatic charges (ion drive). For low-thrust deep space systems, the mass could quite literally be thrown overboard in a fast-moving chain of magnetically levitated buckets. These and other promising technologies will be researched in coming years.

"Specific impulse" can be calculated as the exhaust velocity divided by the acceleration of gravity, or it can be calculated as proportional to the rocket chamber temperature divided by the molecular weight of the exhaust products (the "reaction mass"). Without the necessity of memorizing these equations, it's enough to know that "as-fast-as-possible" and "as-hot-as-possible" are good things, along with using propellants whose combustion products are "as-light-as-possible."

Solid-fuel boosters have specific impulses of 200 to 300 seconds, and liquid fueled engines can have 300 to 350 seconds (for storable propellants) and up to 450 seconds (for liquid hydrogen fuel).

Nuclear engines developed in the 1960s had specific impulses in the 800–1,000 seconds range and advanced designs could reach 2,000 to 4,000 seconds. Low-thrust but highly efficient ion engines have

specific impulses in the 5,000 to 10,000 seconds range but are only useful for very long duration missions.

More revolutionary non-thrusting propulsion systems have been proposed using kilometers-long space tethers to transfer momentum between vehicles (as happened by accident on a shuttle flight when the tether snapped, flinging an Italian instrument package into a higher orbit). Wide, lightweight “solar sails” could exploit the pressure of reflected sunlight (caused by bounced-off photons, NOT the “solar wind” of charged particles) or distant laser beams for gradually building up to a very impressive speed. For high-G-tolerant payloads, cannon launch from Earth’s surface followed by mid-air snagging by rotating space tethers is an intriguing concept.

For the next decade or two, however, we probably will continue to use old-fashioned rockets. But even in this situation, there are a variety of options and trade-offs open to designers. One deals with expendable versus reusable systems. Another is concerned with single stage versus multi-stage designs. A third design issue weighs the advantages of winged versus ballistic structures.

The expendable versus reusable debate has seen a lot of overblown argumentation and hype, especially of the “miracle cure” and “sub-optimization” varieties. Harsh cost assessments show that up until now it has been cheaper to build a rocket, use it for ten minutes during launch, forget about it, and then build another one for the next launch—despite the negative image of “throwing away a fifty million dollar rocket.” This has been because adding the equipment needed to recover launch vehicle components may cost so much in weight and volume that the effective payload capacity of the vehicle is reduced significantly or vanishes altogether. Furthermore, reusable systems such as the Space Shuttle require so much servicing between missions that it overwhelms any savings in hardware acquisition (and the main engines are indeed expensive—mainly because they have to be reusable). However, the political appeal of “reusability”—especially if processing time can be driven down by an order of magnitude—remains high, even though most reductions in prelaunch processing for a reusable system would also as easily lower the cost of preparations for an expendable system.

Reduction in prelaunch processing is a promising approach to achieving modest reductions in launch costs, and this is being pursued both for existing vehicles and for new vehicles. Newer booster designs, which include components optimized not for weight, power, and cost, but for ease of servicing, may be able to cut launch costs in half over the next decade.

Rocket staging, a concept that goes back to medieval fireworks designers, is the trick that allowed space booster designers to evade the need for impossible “mass fractions” of fuel to payload ratios. Early in the ascent to orbit, you want high thrust from compact fuels and engines. As you gain speed and lessened drag, you want high efficiency but don’t worry as much about volume or thrust. Because each phase of the launch has its own priorities, a multi-stage rocket has each stage employ specific structural designs optimized for their particular flight phases. Early stages are easier to recover and reuse because of lower maximum speeds and altitudes.

Although building everything into one single piece to facilitate recovery and reuse—the Single-Stage-to-Orbit, or SSTO, philosophy—has been a goal of space designers for years, many other space experts seriously question whether it is achievable, necessary, or even desirable. The US Government is currently developing experimental vehicles to explore the technology and economics of this approach. Meanwhile, in the United States and Europe, a number of innovative (and risky) private developmental efforts are aimed at the more achievable “fully reusable” sub-orbital systems that can either carry passengers or eject small rocket stages for the final push into orbit. Within 5–10 years, there will be enough flight experience—and a full range of failures and frustrations—to seriously reconsider whether an SSTO vehicle should be attempted.

Winged versus ballistic designs have also been grounds for vigorous debate. Owed in part to the Air Force concept of aerospace developed in the 1950s, notions of winged craft able to operate in both air and space mediums have been and continue to be entertained by many. Competition between the two schools of thought can be traced back at least as early as 1952. Then, in response to advances in ballistic missile and rocket research airplanes, the National Advisory Committee for Aeronautics (NACA), first proposed a high altitude,

hypersonic system that eventually operated under the auspices of the X-15 NASA program, a decade later.

The advantages to winged craft essentially lie in their ability to optimize aerodynamics within the confines of the Earth's atmosphere for access to and from space to include, ideally, a runway takeoff and landing. To date, however, only limited aspects of this concept have been demonstrated. This includes the ability of a Space Shuttle-type vehicle to glide to landing from orbit, and an ability to access space by piggybacking an aircraft as is the case with Pegasus rocket launches. Attempts at a fully capable "spaceplane" such as the National Aerospace Plane (NASP) have been aborted due to technical obstacles. In lieu of the limited success of winged spacecraft and their relatively high cost, ballistic missile technology proponents argue that the linking of space to air flight is misguided and further consideration of winged vehicle designs is, at best, unnecessary.

One other advantage to a winged vehicle—to any design with a high lift-to-drag ratio—is its ability to steer far out of plane during descent from orbit to Earth's surface. While the conical Apollo and Soyuz vehicles could achieve cross ranges of 50 to 100 km, the winged Space Shuttle routinely reaches airfields more than 1,000 km to the left or right of its orbital track. Advanced re-entry vehicles have been tested with cross range capabilities more than twice that.

This capability becomes highly significant when a descending vehicle needs to have access to essentially any point on the Earth's surface. During the course of a satellite's 90-minute revolution, the Earth's surface can rotate as much as 2,200 km below the satellite's path. The amount of rotation is significantly reduced as one moves away from the equator, so that the spacecraft's orbital inclination can be designed to provide multiple nearby passes of specific targets, e.g. suitable runways for landing. Consequently, an entry vehicle requiring flexible targeting also requires significant lift so that it can bridge the off-to-the-side distance to its desired landing point.

Thus, regarding realistic expectations of future launch costs, it's important to focus on the real goal: lowering the costs of getting services from space vehicles. Lowering launch costs is certainly one obvious approach, but the overall purpose is to carry finite-lifetime functional hardware, not just dead weight. If the weight of that

functional hardware can be reduced, or if its lifetime can be extended, the net gains on operational capabilities are equally profitable as is reducing gross launch costs.

This means that an absolute reduction in launch costs could allow a significant reduction in required payload reliability (and consequent unit cost), leading to a large constellation providing the desired services with greatly enhanced robustness.

Nor is cost the only driver in shopping for launch services. Commercial (and government) customers also must consider other features connected with prelaunch and ascent payload environment (i.e., cleanliness, security, loads and vibration), with responsiveness, reliability, reserve capacity (surge), etc.

Lastly, some government and private entities have found a cheap “back door” into orbit by exploiting a feature of existing large launch vehicles, the occasional availability of excess capability. For missions involving payloads weighing in the several ton range and higher, there is often “spare performance capability” that can be made available for “piggyback” payloads in the tens to hundreds of kilograms range. For many “micro-satellites,” launching costs would be reasonable even when paying the full rate, but because they can be inserted onto rockets that otherwise would carry inert ballast or have empty corners, the actual cost to reach orbit can be as low as zero. The key enabling feature here is making the payload small enough and responsive enough when opportunities arise.

So in summary, the high cost of launching objects into orbit is a major feature—often the dominating feature—of modern space operations. Depending on the requirements and launch vehicle used, costs vary between US\$10,000 and US\$30,000 per kilogram of payload. There has been no measurable improvement in the past 20 years.

Reducing launch costs is now specifically called out in America’s national space policy.¹⁹ Within this directive, DoD and NASA are directed to develop short- and medium-term approaches respectively. The military-led effort is to make use of more efficient expendable launches, while NASA pursues reusable launch vehicle (RLV)

19 National Science and Technology Council. September 1996. *National Space Policy*. Washington, DC.

demonstrations. Both initiatives are to be funded in concert with industry which can then benefit from the commercial application of their efforts. The goal of the military-led Enhanced Expendable Launch Vehicle will be to lower launch costs from approximately \$20,000/kg by 25% to 50% beginning in 2001. This, in essence, will allow the US launch industry to approach the quoted costs of various Russian, French, and Chinese carriers (which are also getting lower).

The goal of NASA's RLV program is to demonstrate the technology necessary to attain launch costs of approximately \$2,000/kg (a 90% reduction over current values) through a series of experimental craft aimed at producing a SSTO launch vehicle. This plan, in fact, harks back to the X-30A or the NASP program. NASP was begun in 1987 as a combination hypersonic air/spacecraft scheduled to demonstrate SSTO flight by 1999. But the program was canceled in 1994 due to the realization that its multiple technologies, including large scale supersonic combustion ramjet (scramjet) engines, were not mature enough to be flight tested in an integrated airframe. In its place NASA, has evolved several separate programs designed to demonstrate various aspects of this integrated approach to space launch: the Hyper-X, X-33, and X-34 demonstrators.

The NASA RLV program is not the only entrant in the RLV race, however. Several completely commercial ventures have emerged recently hoping to capture a share of the proliferating low earth orbit market driven by various communications consortia. These schemes include such innovative solutions as aircraft-assisted launch, mid-flight refueling, and rotary landing systems.

Cheaper rockets are not the only options. Marginal but measurable improvements in launch cost can also be achieved by finding and exploiting "short cuts" on space trajectories. Two notable innovations in 1998 illustrate how this approach can still be surprisingly fruitful: one involved moving the launch vehicle to the equator and the other involved hurling the payload past the moon to take advantage of the moon's gravitational field.

The Earth's eastward spin (nearly 1,600 km/hr at the equator, decreasing by a factor of the cosine of the latitude) can provide a valuable velocity bonus for rockets launched generally eastwards. This alone is a motivation to launch from as near the equator as you

can place your rocket. But for payloads headed for geostationary orbits, there is a second bonus: eliminating the need for making a sharp turn from their usually highly-inclined transfer orbit into the equatorial final orbit, saves a lot of fuel at one of the most expensive phases of the mission, near its end.

Using the highly-automated launch processing design of the Ukrainian “Zenit” rocket, the Boeing-led “Sea Launch” corporation built an ocean-going launch platform to bring the booster and its payload to the equatorial Pacific Ocean, near Christmas Island. By launching due east, the system used both the Earth’s spin to the maximum, and also minimized the normally expensive orbital plane change maneuver. As a result, the booster could place twice the weight into the final orbit, as it would have done from its normal launch site in Central Asia.

Another commercial communications satellite, trapped in its high-inclination transfer orbit by the failure of the booster’s last stage, was successfully maneuvered into the proper equatorial orbit in mid-1998 by a bold, innovative flight plan. Using onboard fuel reserves, the payload was pushed farther out into space, until it twice passed the Moon at an angle planned so that the payload’s orbit was twisted by lunar gravity to more closely match Earth’s equatorial plane. Then most of the remaining onboard fuel was used to slow the payload down into the originally desired 24-hour orbit. The lunar swing-by was so successful that some space experts now expect that future routine launchings from far-northern sites (mostly Russian ones) will prefer to use the lunar option to save fuel on the long (but cheap) road to geosynchronous orbit.

Looking further ahead, launch technologies that would go well beyond the present goal of \$2,000/kg are also being explored. NASA’s Highly Reusable Space Transportation (HRST) study is currently focusing on concepts and technologies that could achieve another order of magnitude decrease, to \$200/kg of payload.

One such concept being studied, the rocket-based combined cycle (RBCC) is a modification to the aforementioned NASP design. Instead of relying primarily on air-breathing engines to boost the craft to near-orbit altitude and speed, the RBCC would combine air-breathing and rocket propulsion systems into a single multi-mode engine.

Technologies that could contribute to such a system include the hypersonic waverider which would make use of the lift properties of supersonic shockwaves; pulse detonation engines that make use of tubes that are periodically filled with fuel and oxygen and then ignited to generate a pulsed thrust; and the maglifter catapult which would provide launch assist through the use of magnetic levitation.

These technologies will become available in the years and decades ahead, through evolutionary advances in technological capabilities. The possibility of revolutionary breakthroughs in transportation cannot be excluded, especially in such a high-tech-intensive theater as space operations. While it may prove feasible for other nations to build “cheaper” rockets, due to locally depressed labor costs, it should be the long-range goal of the United States to always build “better” rockets and eventually be the first to build the vehicles that will make rockets obsolete.