Summary

Several major efforts are aimed at finding ways to reduce the cost of launching spacecraft. However, it typically costs much, much more to build a spacecraft than to launch it to low Earth orbit (LEO). Unless spacecraft costs are reduced, even dramatic reductions in launch costs will have only a small effect on total spacecraft program costs.

This Background Paper reviews four possible approaches to spacecraft design that have been proposed to reduce total spacecraft program costs. Adopting them could change the launch rates, payload capacity, and reliability demanded of conventional launch vehicles, or create a demand for exotic launch systems to launch very small spacecraft cheaply. Conversely, developing new, economical launch systems would strengthen incentives to adopt these new approaches to spacecraft design.

This is one of several publications documenting OTA's broad assessment of space transportation technologies requested by the House Committee on Science, Space, and Technology, and the Senate Committee on Commerce, Science, and Transportation. Previous publications in this assessment examined a variety of future launch options,[1] ways to reduce the costs of launch operations,[2] low-cost, low-technology ("big, dumb") boosters,[3] and options for transporting humans to and from orbit.[4] A final report will be published in 1990.

THE HIGH COST OF SPACECRAFT

Because of the high cost of spacecraft, a dramatic reduction in launch cost alone will not substantially lower spacecraft program costs. Although launching a pound of payload to LEO currently costs about $3,000, procuring that pound of payload typically costs much more. For example, representative U.S. spacecraft busses[5] of types first launched between 1963 and 1978 cost between $130,000 and **$520,000** per pound dry,[6] including amortized program overhead costs. Procurement of the mission payloads carried on those busses cost about 50 percent more—about $200,000 to $800,000 per pound.[7] Reducing launch costs from $3,000 to $300 per pound of payload, a goal of the Advanced Launch System program,[8] would reduce the total cost of procuring and launching a dry spacecraft (half bus, half mission payload) by less than 2 percent.

A spacecraft bound for a high orbit or another planet requires an upper stage, which when fueled is typically more than twice as heavy as the spacecraft but costs less. Even so, a payload consisting of a Centaur upper stage (about $2,250 per pound) and a spacecraft weighing a third as much (half bus, half mission payload) might cost from $40,000 to $160,000 per pound. Reducing launch costs to $300 per pound would

[1] U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide*, OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988).

[2] U.S. Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices*, OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988).

[3] U.S. Congress, Office of Technology Assessment, *Big, Dumb Boosters: A Low-Cost Space Transportation Option?* (Washington, DC: U.S. Congress, Office of Technology Assessment, International Security and Commerce program, February 1989).

[4] U.S. Congress, Office of Technology Assessment, *Round Trip to Orbit: Human Spaceflight Alternatives*, OTA-ISC-419 (Washington, DC: U.S. Government Printing Office, August 1989).

[5] The "bus" of a spacecraft consists of the structure, power sources, and other subsystems required to support the mission payloads it carries.

[6] Unfueled.

[7] *Space Systems and Operations Cost Reduction and Cost Credibility Workshop, Executive Summary* (Washington, DC: National Security Industrial Association, 1987), p. 3-10, fig. 3.7.3. These estimates were derived by amortizing nonrecurring costs (e.g., for development) over four satellites; some programs procure more than four while others procure only one. OTA inflated the estimated costs, which were in 1982 dollars, to 1987 dollars using the GNP inflator from table B-3 of *the Economic Report of the President*, January 1989, and then to 1989 dollars by assuming 4.2 percent annual inflation in 1987 and 1988.

[8] 101 Stat. 1067.

reduce the total cost of procuring and launching such a payload by only 2 to 6 percent.

APPROACHES TO REDUCING PAYLOAD COSTS

To reduce payload costs, and for other reasons, novel approaches to payload design and fabrication have been proposed:

- Design payloads to fit launch vehicles leaving size and weight margins of about 15 percent
- Allow payloads to be larger and heavier: Fatsats
- Allow satellites to be simpler, and make them lighter: Lightsats
- Design Microspacecraft to be launched like artillery shells

Each type of spacecraft—fatsat, lightsat, or microspacecraft-would impose unique launch demands. New, large launch vehicles would be needed to launch the heaviest satellites. Lightsats could be launched on existing launch vehicles, but new, smaller launch vehicles might launch them more economically. In wartime, small launch vehicles could be transported or launched by trucks or aircraft to provide a survivable means of space launch. Microspacecraft could be launched on existing launch vehicles, but they might instead be launched by more exotic means such as a ram cannon, railgun, coilgun, or laser-powered rocket. Some of these might be proven feasible in the next decade.

Weight margin: Designing payloads to fit launch vehicles while reserving ample size and weight margins can reduce the risk of incurring delay and expense after assembly has begun.

It is often the case that satellites grow substantially heavier than expected as they proceed from design to construction. For example, dry weights of military spacecraft have been about **25** percent greater, on the average, than initially predicted. Growth in estimated weight may be caused by underestimating the weight of a spacecraft (especially one designed to use the most advanced technology) or by changing mission requirements during development (requiring hardware to be added). If a payload grows so heavy during assembly that it threatens to "gross out" its assigned launch vehicle (i.e., cause its weight to equal or exceed the maximum allowable gross lift-off weight), the payload must be redesigned to cut its weight. This causes delay and increases cost.

To reduce the risk of exceeding vehicle payload capacity, program managers could require designers to design each payload to fit its assigned launch vehicle with room to spare and to weigh substantially less than the maximum weight the vehicle can launch to orbit. However, this design philosophy would lead to more stringent size and weight constraints than would otherwise be imposed. If a mission simply could not be performed by payloads predicted to be small enough to fit the largest launch vehicles with adequate size and weight margins, new, larger launch vehicles would have to be developed to provide the desired margin. In many cases, however, sufficient margin could be provided by clever design, e.g., by designing several smaller single-mission payloads instead of a single multimission payload, or developing and using an electric-powered or space-based orbital transfer vehicle (OTV) instead of a conventional OTV.[9]

Fatsats: If payloads were allowed to be heavier for the same capability, some could cost substantially less. For example, OTA estimates that Titan-class payloads that cost several hundred million dollars might cost about $130 million less if allowed to be five times as heavy.

[9]To place a satellite in a high orbit, a launch vehicle must carry both the satellite and either an upper stage to take the satellite directly to the high orbit, or an OTV to take the satellite from a low-altitude parking orbit to the high orbit. A conventional OTV weighs two or three times as much as the satellite it carries. An electric-powered OTV could weigh less than a conventional OTV of comparable capability, creating more weight margin. A space-based OTV could be launched separately from its payload, allowing the payload to weigh as much as its launch vehicle could carry while reserving the desired weight margin. However, operation of space-based OTVs would be complex and require costly infrastructure.

If payloads were allowed to be much heavier, a manufacturer could forego expensive processes for removing nonessential structural material, as well as expensive analyses and tests for assuring the adequacy of the remaining structure. Standardized subsystems, which could be produced economically in quantity, could be used instead of customized subsystems designed to weigh less.

The savings that might be realized are uncertain. In principle, they could be estimated by comparing the costs of a heavy payload and a light payload that perform the same functions with the same capability. However, the United States has never designed and built two payloads, one heavy and the other light, that perform the same functions equally well, in order to compare actual costs. A few estimates have been derived by comparing the cost and weight of an actual spacecraft with the estimated cost and weight of hypothetical heavier spacecraft of comparable capability. Designers have also compared the estimated costs and weights of hypothetical spacecraft of comparable capability and different weights. All such studies predict payloads could cost less if allowed to weigh more, but the estimates of savings differ.

An accurate estimate of potential savings requires a detailed trade-off analysis for each payload. Achieving these savings will probably require giving spacecraft program managers, and those who establish mission and spacecraft requirements, incentives crafted specifically for the purpose, and may require developing new launch or orbital-transfer vehicles to carry the spacecraft.

Lightsats: If allowed to be less capable, reliable, or long-lived, payloads could be both lighter and less expensive. Useful functions such as communications and weather surveillance could be performed by payloads small enough to be launched on small rockets from airborne or transportable launchers.

Small, simple, and relatively inexpensive civil and military satellites have been, and still are, launched at relatively low cost on small launch vehicles or at even lower cost, sometimes for free, as "piggyback" payloads on larger launch vehicles.

The Department of Defense is considering whether the increased survivability and responsiveness such spacecraft could provide would compensate for possibly decreased capability. Some missions might be accomplished as well by a swarm of several small satellites as by a single large one. If so, a swarm would be less expensive in many cases, because smaller satellites typically cost much less per pound than do large ones. Even if the satellites were launched individually, which would increase total launch cost, total mission cost might be lower.

Microspacecraft: Spacecraft weighing only a few pounds could perform useful space science missions and might be uniquely economical for experiments requiring simultaneous measurements (e.g., of solar wind) at many widely separated points about the Earth, another planet, or the Sun.

These could be launched on existing launch vehicles. Eventually, it may be possible to launch them on laser-powered rockets or, if they are as rugged as a cannon-launched guided projectile,[10] with a ram cannon or an electromagnetic launcher. Within the next decade, experiments now being planned may establish the feasibility of some of these launch systems. Their costs cannot be estimated confidently until feasibility is proven, but at high launch rates they might be more economical than conventional rockets. An electromagnetic launcher could also be constructed in orbit to launch microspaceprobes to outer planets; they would arrive years earlier than if they were propelled by conventional rockets.

[10] A cannon-launched guided projectile is an artillery shell equipped with a system (e.g. TV camera and computer) for recognizing a target and movable fins or other means for steering the projectile toward a target. The Army's M712 Copperhead is an example.

OPTIONS FOR CONGRESS

What can Congress do to promote spacecraft cost reduction and, thereby, reduce the cost of space programs? Some options deal directly with spacecraft design; others would promote the development of launch systems that could launch small, inexpensive spacecraft at low cost or heavy spacecraft with generous weight margins.

Options for Influencing Spacecraft Design

Option 1:

Congress could order a comprehensive study of how much the Nation could save on space programs by:

- *designing payloads to reserve more weight and volume margin on a launch vehicle;*
- *allowing payloads to be heavier, less capable, shorter-lived, or less reliable;*
- *designing standard subsystems and buses for use in a variety of spacecraft;*
- *designing spacecraft to perform single rather than multiple missions; and*
- *using several inexpensive satellites instead of a single expensive* one.

Lockheed completed such a study in 1972;[11] anew one should consider current mission needs and technology. It would complement the Space Transportation Architecture Study (STAS) and more recent and ongoing studies[12] that compare space transportation options but not payload design options.

As noted above, to estimate potential savings accurately, a detailed trade-off analysis must be done for each payload, or more generally, for each mission. So, for greater credibility:

Option 2:

Congress could require selected spacecraft programs--for example, those that might require a new launch vehicle to be developed--to award two design contracts, one to a contractor who would consider the unconventional approaches mentioned above.

Option 3:

Congress could require both the Department of Defense and NASA to refrain from developing a spacecraft if the expected weight or size of the spacecraft, together with its propellants, upper stage, and support equipment, would exceed some fraction of the maximum weight or size that its intended launch vehicle can accommodate. Public Law 100-456 required the Department of Defense to require at least 15 percent weight margin in fiscal year 1989.[13] New legislation could extend this restriction to NASA and could require size margins in future years.

Options for Promoting the Development of Launch Systems

Option 4:

Congress could fund the development of the Shuttle-C cargo launch vehicle, the Advanced Launch System, liquid-fueled rocket boosters for the Shuttle, or a larger Titan launch vehicle.[14] Any of these vehicles could launch payloads larger and thus less expensive (for comparable performance) than payloads designed to fly on Shuttles or Titan IVs. Alternatively, if payload size and weight are not increased, these proposed launch vehicles could provide greater size and weight margins, thereby reducing the risk of needing costly weight-reduction efforts. However, their greater payload capacity would also enable payload pro-

[11] Lockheed Missiles and Space CO., *Impact of Low-Cost Refurbishable and Standard Spacecraft Upon Future NASA Space Programs*, NTIS N72-27913, Apr. 30, 1972.

[12] E.g., the Air Force's Air *Force-Focused STAS*, NASA's *Next Manned Space Transportation System* study, the Defense Science Board's *National Space Launch Strategy* study, and the *Space Transportation Comparison* study for the National Aero-Space Plane Program.

[13] See S. Rept. 100-326, p. 36, and H. Rept. 100-989, p. 282.

[14] The costs and benefits of these launch systems would differ; see U.S. Congress, op. cit., footnote 1, and the forthcoming final report of this assessment.

gram managers to forego these potential savings and instead pursue greater payload performance by increasing payload size or weight. If they do so and weight overrun occurs, it would probably cost more to trim the weight of a larger payload than it would to reduce the weight of a lighter payload by the same percentage. Requiring weight margins, as described above, would reduce this risk.

Option 5:

Congress could continue to fund the development of the Standard Small Launch Vehicle (SSLV[15]) and the Sea Launch and Recovery (SEALAR) system[16] to provide survivable means of launching military lightsats. The Department of Defense probably will not allow operational lightsats to be designed for such launch vehicles until the vehicles are operational. Hybrid rockets, which can use liquid oxygen to burn nonexplosive solid propellant similar to tire rubber, could also be designed to launch lightsats from transportable launchers. Such hybrids would have some safety advantages and might be allowed where conventional solid- or liquid-fuel rockets are not. Later—perhaps by 2005-NASP-derived vehicles might be able to launch 20,000-pound payloads in wartime.[17] With continued funding, the National Aero-Space Plane Program would continue to develop technology for NASP-derived vehicles.

Option 6:

Congress could fired the development of a laser or a direct-launch system (e.g., a railgun, coilgun, or ram cannon) for launching microspacecraft at high rates economically. Many uses have been proposed, but to date only the Strategic Defense Initiative Organization (SDIO) has identified a plausible demand for high-rate launches of microspacecraft. However, demand for launches of scientific, commercial, and other microspacecraft could increase, perhaps dramatically, if launch costs could be reduced to a few hundred dollars per pound and payloads were inexpensive. The SDIO estimates development and construction of a laser for launching 44-pound payloads would require about $550 million over 5 or 6 years. The SDIO estimates it could launch up to 100 payloads per day (more than 20 Shuttle loads per year) for about $200 per pound.

Railgun proponents predict a prototype railgun capable of launching 1,100-pound projectiles carrying 550 pounds of payload could be developed in about 9 years for between $900 million and $6 billion, including $50 million to $5 billion for development of projectiles and tracking technology. If produced and launched at a rate of 10,000 per year, the projectiles (less payload) would cost between $500 and $30,000 per pound (estimates differ). The cost of launching them might be as low as $20 per pound—i.e., $40 per pound of payload.

[15] The SSLV is being developed by the Defense Advanced Research Projects Agency (DARPA).

[16] SEALAR is being developed by the U.S. Naval Research Laboratory.

[17] U.S. Congress, op. cit., footnote 4, pp. 67 and 74.