Fatsats

Many experts find it plausible that a payload could be designed to perform a function at lower cost if it were allowed to be heavier. However, there have been few attempts to estimate just how much cheaper payloads could be, if allowed to be heavier, or how much they should weigh in order to minimize the total cost of producing and launching a payload.

The first section of this chapter discusses one of several ways in which payloads could be made less expensive if allowed to be heavier: standard subsystems could be used in lieu of customized subsystems designed to minimize weight. The next section describes how a high-altitude satellite could be allowed to be heavier (and hence less expensive) without using a larger launch vehicle: by using an orbital transfer vehicle with electric engines (e.g., arcjets). The third section discusses estimation of cost versus weight trade-offs, with subsections describing parametric and bottom-up methods and comparing parametric with bottom-up estimates. The final section discusses some organizational obstacles to reducing cost by allowing payload weight growth.

STANDARDIZING SUBSYSTEMS

One of several ways to trade off cost for weight is to use standard spacecraft subsystems or busses.[2] The use of a standard or previously developed subsystem may result in a heavier spacecraft but allow a satellite program to avoid paying part or all of the substantial nonrecurring costs of developing a custom subsystem. In addition, because of learning and production-rate effects, it helps reduce the recurring cost of producing the standard subsystem.

Using a standard subsystem could reduce subsystem cost by a factor roughly equal to 1 plus the ratio (expressed as a Ii-action) of nonrecurring to recurring cost. For example, the ratio of nonrecurring cost to recurring cost is typically 2/1 for a spacecraft bus (see table 3-l), so the nonrecurring cost of developing a spacecraft bus is about twice the recurring cost of producing a bus. If a mission requires one spacecraft, the cost of developing and producing a custom bus would be about three times the cost of producing a suitable previously developed bus. By using a previously developed bus, one could therefore save about two-thirds of the cost of a customized bus.[3] The cost would be reduced by a factor of 3, i.e., by 1 plus the ratio of nonrecurring cost to recurring cost (2/1).

More could be saved on subsystems with higher ratios. For example, the cost of structure, which has ratios ranging from 5/1 to 8/1, could be reduced by a factor of at least 6, and possibly 9.

The amount saved could be a small percentage of total spacecraft program costs, which also include the costs of mission-peculiar payloads and program overhead, etc. A 1972 Lockheed study[4] concluded that development and use of standard subsystems could save only about 4 percent of the cost of 91 payload programs, when used in addition to low-cost design methods and payload refurbishment. The savings attributable to standardization would be about 6 percent of the program costs already reduced by low-cost design and refurbishment.[5]

Manufacturers have estimated that 95 percent learning might be achieved, i.e., every time the cumulative number of units produced is doubled, the incremental unit cost would decrease 5 percent.[6] The Air Force has assumed 95 percent learning in estimating first-unit production costs from lot sizes

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1See, e.g., Lockheed Missiles and Space Co., *Impact of Low-Cost Refurbishable and Standard Spacecraft Upon Future NASA Space Programs*, NTIS N72-27913, Apr. 30, 1972.

2A spacecraft "bus" consists of those spacecraft subsystems—e.g. structure, thermal control, telemetry, attitude control, power, and propulsion—that are not peculiar to a particular mission, as cameras or radio relays would be.

3The cost of integrating an off-the-shelf subsystem into a spacecraft is small. The Boeing Company's Parametric Cost Model predicts that the cost of integrating an off-the-shelf subsystem into a spacecraft would be about 3 percent of the cost of designing anew subsystem for the spacecraft. [Boeing Aerospace Co., May 1989]

4Lockheed Missiles and Space Co., op. cit., footnote 1.

5In this study, Lockheed assumed a "mission model" now recognized as highly inflated; this probably led to overestimation of the potential savings from standardization. On the other hand, the percentage savings attributable to standardization might have been greater if refurbishment had not been assumed.

6F.K. Fong et al., *Unmanned Spacecraft Cost Model*, 5th ed., SD-TR-81-45 (Los Angeles AFB, CA: Headquarters, Space Systems Division, U.S. Air Force Systems Command, June 1981); NTIS accession number AD-B060 824L; distribution limited to U.S. Government agencies only.

Table 3-l-Ratios of Nonrecurring to Recurring Cost of Spacecraft Subsystems

If a previously developed subsystem can be used in a new spacecraft in lieu of a custom-designed subsystem, subsystem cost could be reduced by a factor roughly equal to one plus the ratio of nonrecurring to recurring cost-e.g., threefold for a spacecraft bus (a spacecraft without its mission payload).

Subsystem	Ranges of ratios nonrecurring Cost/ recurring cost
Structure	5/1 to 8/1
Propulsion (apogee kick)	2/1 to 6/1
Thermal control	4/1 to 40/1
Attitude control	1/1 to 2/1
Electrical power	1/1 to 2/1
Telemetry, tracking, & command	2/1 to 3/1
Spacecraft (less mission payload)	about 2/1
Communications mission payload	2/1 to 3/1

SOURCE: U.S. Air Force Systems Command, Space Systems Division.

and prices,[7] but there have been too few buys of each type of U.S. spacecraft to demonstrate learning conclusively.

UPPER STAGES AND ORBITAL-TRANSFER VEHICLES

Often a payload has an upper stage or an orbital-transfer vehicle (OTV) in addition to a spacecraft. Some analysts have considered options for reducing the costs of upper stages by allowing them to be heavier.[8] Others are considering the opposite approach: making OTVs smaller-and perhaps more expensive--in order to save money by using a smaller launch vehicle, allowing the spacecraft to be larger, or providing more margin for spacecraft weight growth. Space-based OTVs have also been proposed;[9] they could be reused and would not be launched together with the spacecraft, which could therefore be larger. However, refueling and maintaining them could be complicated and might require the development and maintenance of costly space- or ground-based infrastructure.

Electric propulsion could be used to make OTVs smaller and lighter while at the same time increasing the mass they could deliver to a high orbit. They could use photovoltaic ("solar") cells to generate electricity[10] to power an electrostatic ion thruster, an arcjet thruster, or an electric engine of some other type (many are possible) that has an exhaust velocity much greater than that of a chemical rocket. This would reduce the mass of fuel required for orbital transfer, increasing the payload that could be transferred. The "dry weight" of an electric OTV (EOTV) could also be smaller than that of a chemical OTV of comparable total impulse, further increasing the payload that could be transferred.

There would be drawbacks. An EOTV would produce little thrust, so transfer of a payload from a low-altitude parking orbit to geostationary orbit might take 3 to 6 months. Before reaching its destination orbit, the payload would age a few months and, more important, might degrade because of its longer transit through the Van Allen radiation belts. An EOTV would be designed to tolerate such a transit, but some satellites might not be. A near-term solution would be to shield sensitive satellites against the radiation, but this would reduce the maximum satellite mass that could be carried.

The longer transfer time could also be detrimental to security. A military satellite on an EOTV would remain longer at low altitude and within range of low-altitude anti-satellite weapons than if it rode a conventional OTV to its destination orbit. If a critical satellite fails or is damaged, an EOTV might not be able to replace it without a serious lapse in mission performance.[11] These drawbacks could be mitigated by launching military satellites on schedule rather than on demand. That is, near the end of its projected useful life, each satellite would be deactivated, maintained as a spare, and replaced by a new satellite, which could have been launched months earlier.

The Air Force Systems Command Space Systems Division estimates that EOTVs would be more economical than conventional OTVs for selected

7p. Hillebrandt et al., *Space Division Unmanned Space Vehicle Cost Model, Sixth Edition*, SD TR-88-97 (Los Angeles AFB, CA: Headquarters, Space Systems Division, U.S. Air Force Systems Command, November 1988); distribution limited to U.S. Government agencies only.

8Dani Eder, "Why Spacecraft Should Get Less Expensive If Launch Costs Decrease," unpublished, undated, marked "D582-1(X)03-1." Boeing presented results of this analysis at the ALS Phase 1 System Requirements Review, and to OTA in a briefing, "ALS program Development." See also Hughes Aircraft Co., Space and Communications Group, *Design Guide for ALS Payloads*, October 1988.

9E.g., see Lockheed Missiles and Space Co., *Final Report---payload Effects Analysis Study*, LMSC-A990556 (Sunnyvale, CA: June 1971), NTIS accession number N71-3749630; and J.M. Sponable and J.P. Penn, "Electric Propulsion for Orbit Transfer: A Case Study," *Journal of Propulsion and Power*, vol. 5, No. 4, July-August 1989, pp. 445451,

10Nuclear power was once considered more promising; see Lockheed Missiles and Space Co., Op. Cit., footnote 9.

11However, in some scenarios, neither could a conventional OTV.

missions. For example, a 5,250-pound spacecraft could be launched to geostationary orbit either on a Titan IV launch vehicle with an Inertial Upper Stage for about $250 million or on a Delta II launch vehicle with a solar-electric OTV for about $124 million,[12] saving about $126 million. A Titan IV with an EOTV could launch a 30,000-pound spacecraft to geostationary orbit for an estimated cost of $269 million. The Space Systems Division is planning to demonstrate an expendable solar-powered EOTV, probably with an experimental payload, sometime between 1993 and 1995.

ESTIMATING POTENTIAL COST REDUCTION

There have been few attempts to estimate how much cheaper spacecraft could be, if allowed to be heavier, or optimal weights for minimal production and launch costs. Analyses of historical data show that heavier spacecraft are typically costlier than lighter spacecraft;[13] usually, however, heavier spacecraft are also more capable than lighter spacecraft. They perform more functions, more difficult functions, or similar functions better.[14] So these analyses do not answer the important questions:

1. How heavy should a payload[15] be in order to minimize the combined costs of payload production and launch on a currently operational launch vehicle? Are payload weights actually optimized for current launch vehicles?
2. How heavy should a payload be in order to minimize ‘combined production and launch cost, if the launch cost per pound of payload were reduced, or the maximum payload weight that could be launched were increased, by some factor? By what factor would total payload production and launch cost be reduced?

Answering these questions requires comparing the costs of heavy payloads and light payloads that perform the same function equally well. Unfortunately, such data do not exist; there are no two payloads, one large and the other small, designed at the same time (and hence with comparable technology available) to perform the same set of functions equally well. The few analyses that have estimated how much cheaper a payload could be if allowed to be heavier have been hypothetical. They are based on both “bottom-up” and parametric estimates.

Bottom-up estimates are obtained by designing two or more versions of a payload to perform the same functions at minimum cost without exceeding weight or size limits, which differ from version to version. For example, two versions of a communications satellite could be designed: one to be launched on a Scout launch vehicle, the other on an Atlas-Centaur. Each version would be designed to minimize production and launch cost. Comparing the costs of the two different versions would indicate how much less expensive the larger version would be.

Bottom-up estimates are time-consuming and expensive to derive, and there may be no basis for assuming the cost-versus-weight trade-offs derived would apply to versions larger or smaller than those designed or to payloads that must perform different functions. For example, there is no rationale for expecting that bottom-up estimates of costs and weights of communications satellites of comparable capability could be used to illustrate cost-versus-weight trade-offs for remote-sensing satellites of comparable capability.

Parametric estimates are obtained by assuming that if the weight of a payload were allowed to increase, the minimum cost at which it could be built would vary in some qualitative way-e. g., approach a limit, or decrease exponentially. The parameters of the relationship-e.g., the minimum costs for particular weight limits—are chosen to make the hypothetical relationship fit historical cost and weight data, bottom-up cost and weight estimates, or both, as well as possible.

The fit will not be exact, however;[16] it may be a good fit on the average, with some payloads costing

[12]Including $3 million for RDT&E.

[13]P. Hillebrandt et al., op. cit., footnote 7, and figure 4-1 of Lockheed Missiles and Space Co., Op. cit., footnote 9.

[14]See Lockheed Missiles and Space Co., op. cit., footnote 9.

[15]The *payload* of a launch vehicle may be a spacecraft (e.g., a satellite or planetary probe) together with an upper stage (to propel it to a transfer orbit or escape trajectory) and support equipment for attaching them to and releasing them from the launch vehicle, Some launch vehicles (e.g., the Space Shuttle and sounding rockets) sometimes carry payloads (e.g., scientific instruments) that remain attached to the launch vehicle.

[16]Unless there are so many parameters (i.e., statistical degrees of freedom) in the model that the available data are too few to estimate them with statistical significance.

more, and others less, than predicted by the relationship (the "model"). The fact that the model represents only average costs and cost-versus-weight trends may be an advantage in studies, such as this one, which focus on such averages and trends. However, it would be a limitation if accurate cost-versus-weight trade-offs for a specific mission were required. If the functions to be performed by the payload were specified in detail, and if resources permitted detailed engineering design of several alternative versions of different weights or sizes, then bottom-up estimation could be used and should provide greater accuracy.

Thus bottom-up estimation and parametric estimation are complementary approaches to cost estimation.[17] Neither approach by itself would be of general value: a bottom-up estimate is applicable only to a specific payload, and parametric estimates are abstract and hence useless unless fitted to bottom-up estimates of cost and weight.[18]

The bottom-up and parametric approaches are exemplified by two analyses produced almost two decades ago: a parametric model developed by Carl Builder at the Rand Corp.,[19] and a bottom-up analysis by Lockheed Missiles and Space Co.[20] Both were cited in congressional debate on the merits of the Space Shuttle.[21]

A Parametric Analysis

Builder did not estimate cost reductions for particular payloads; he described a procedure for doing so using data or assumptions about payload cost and launch cost. He assumed average launch cost would vary as the payload capability of the launch vehicle raised to some power A (this is called a "power-law" relationship) and payload cost would vary as the payload weight raised to some power B. To use Builder's model, one must specify the exponent A and the initial cost and weight of a payload designed to minimize payload plus current launch cost. *One need not specify what the payload does;* in theory, it should make no difference. If launch costs are reduced by some factor,[22] the optimum weight and the cost of a functionally equivalent payload designed to minimize payload plus reduced launch cost may be calculated using formulas derived by Builder. The difference between the old and new minimum total costs is the savings obtainable if launch costs are reduced by the specified factor, assuming payloads are reoptimized to take advantage of the new launch costs.[23]

OTA derived an estimate of the exponent A used in Builder's model by fitting a straight line to points on a log-log plot of the payload capabilities[24] and average launch costs[25] of Delta, Titan, and the Space Shuttle. Figure 3-1 shows the three points and the line obtained as a least-squares fit to the points. The slope of the line corresponds to a value of 0.74 for the exponent A, implying that average launch cost would increase by two-thirds if the payload weight were doubled.

Figure 3-1 also shows a point representing the predicted payload capability of the Pegasus air-launched vehicle (see figure 4-6) and the price charged by its operator, Orbital Sciences Corp. (OSC), for the launches and launch options purchased by the Defense Advanced Research Projects Agency. The line fitted to Delta, Titan, and Shuttle costs and payload capabilities accurately predicted the cost (to the government) of a Pegasus launch.

If launch cost is assumed to vary with payload weight in the way described above,[26] Builder's model predicts that a payload that would cost $1 billion if designed to weigh 39,000 pounds could be

[17] 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), app. A.

[18] As noted above, there is seldom more than one historical "data point" for the cost and weight of fictionally identical spacecraft.

[19] Carl H. Builder, *Are Launch Vehicle Costs a Bottleneck to Economical Space Operations?* Rand working document D-19482-PR, December 1969.

[20] Lockheed Missiles and Space Co., op. cit., footnote 9.

[21] See the remarks of Senator Mondale in the *Congressional Record—Senate*, May 26, 1971, pp. 17100-17106, and the remarks of Senator Anderson in the *Congressional Record-Senate*, Apr. 20, 1972, pp. 13786-13790.

[22] By the same factor, regardless of payload weight.

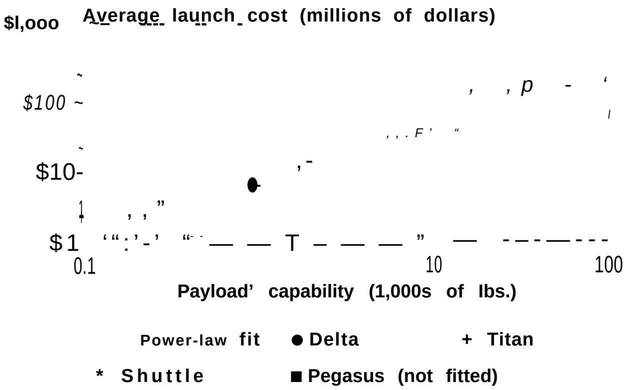
[23] More precisely, "assuming payloads are optimally sized for minimum total cost in both cases." Builder, op. cit., footnote 19.

[24] To a 100 n.mi.-high orbit inclined 28.5 degrees. 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), table 2-1.

[25] Including amortized fixed annual launch cost. OTA assumed launch at the maximum rate estimated in table A-1 of ibid. and used the nominal cost-estimating relationships in that table.

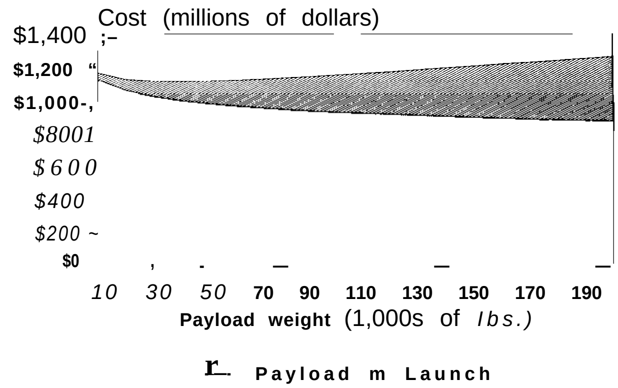
[26] I.e., in proportion to the payload capability of the launch vehicle raised to the Power 0.74.

Figure 3-l—Average Launch Cost v. Payload Capability



SOURCE: Office of Technology Assessment and Orbital Sciences Corp., 1988.

Figure 3-2-Cost for Hypothetical Mission With Current Launch Cost Trend



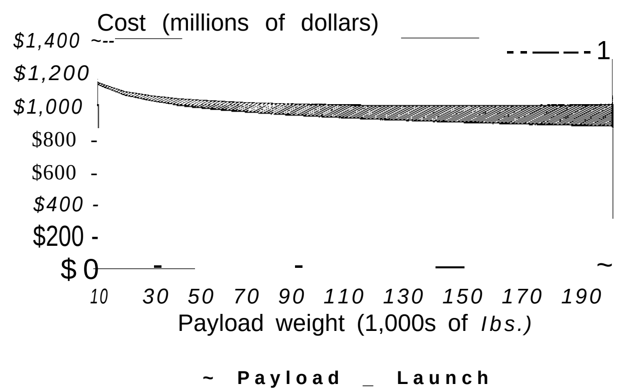
SOURCE: Office of Technology Assessment, 1990.

made for 5.8 percent less if it were allowed to be twice as heavy. More generally, if allowed to be heavier or designed to be lighter, the cost of such a payload would be proportional to its weight raised to the power –0.086 (the exponent B in Builder's model). Figure 3-2 shows how the payload cost and the launch cost would vary with the payload weight. Designing the payload to weigh 39,000 pounds would minimize the total cost.

Figure 3-3 shows how the payload cost and the launch cost would vary with the payload weight if launch cost were reduced by a factor of 3—i.e., by 67 percent. It illustrates that total cost is insensitive to weight for weights between 80,000 pounds and (at least) 200,000 pounds. The optimal weight would be about 150,000 pounds. Reducing the launch cost by 67 percent would reduce the total cost by only 11 percent. *It should be emphasized that this is the estimated cost reduction achievable by allowing payload weight to grow without changing payload performance. It assumes that the baseline payload was designed to minimize total cost.* If a baseline payload was not designed to minimize total cost, redesigning it (possibly to weigh more) could save money even if launch costs are not reduced. If launch costs are reduced, additional savings could be obtained by allowing weight growth; these additional savings are the savings estimated by Builder's model.

Figure 3-4 shows these results in a different form along with results of similar analyses of other hypothetical payloads initially weighing 39,000 pounds but costing $2 billion, $3 billion, and $4

Figure 3-3-Cost for Hypothetical Mission if Launch Costs Are Reduced 67 Percent

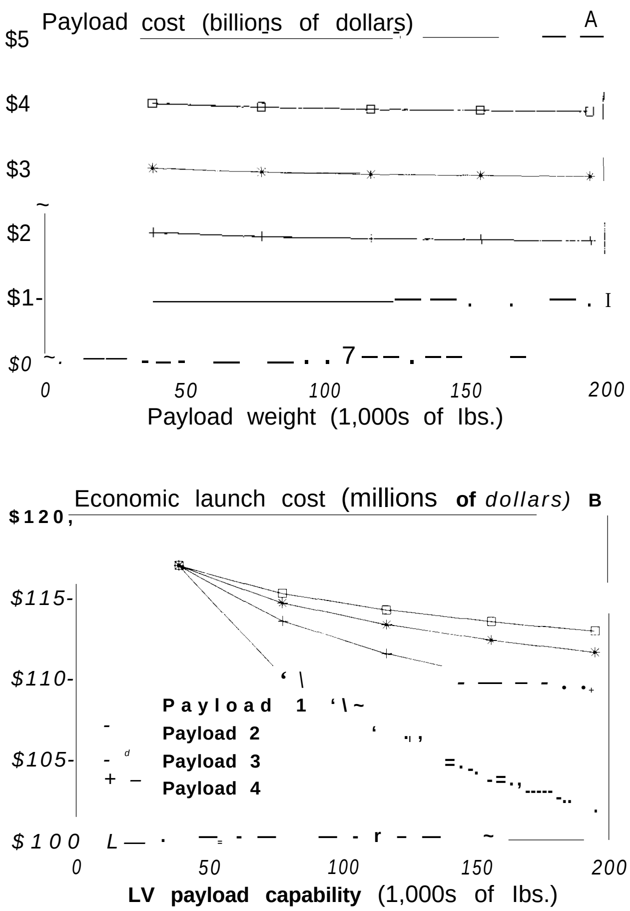


SOURCE: Office of Technology Assessment, 1990.

billion. Figure 3-4a shows how these costs could be reduced, according to Builder's model, if the weights were allowed to grow. For each weight, figure 3-4b shows the ("economic' launch cost at which that weight would be optimal. These estimates predict that allowing the weight of a Titan-IV-class payload to increase by 400 percent (for example) would reduce payload cost by an amount that is nearly the same for a $1-billion payload as for a $4-billion payload. The estimates also predict that the lower the initial cost of a payload, the more the cost per launch must be reduced to justify increasing its weight by a large factor.

Builder's assumption about the relationship between payload weight and launch cost would lose

Figure 3-4-Payload Cost v. Weight Trade-offs and Economic Launch Costs



SOURCE: Office of Technology Assessment, 1990.

validity if extrapolated to extremely heavy payloads.[27] It would imply that the average cost of launching a pound of payload could be made as low as desired--even lower than the cost of the fuel required to launch a pound of payload—by building a launch vehicle of sufficiently large payload capability. But his assumption fits the estimates of Pegasus, Delta, Titan, and Shuttle launch costs in figure 3-1 very well. The cost-versus-payload curve fitted to Delta, Titan, and Shuttle launch costs predicted the cost of Pegasus accurately, even though the payload capability of Pegasus is eightfold smaller than that of the smallest vehicle (Delta) on which the curve is based. The curve could probably be extrapolated with comparable validity to a payload capability of 200,000 pounds.

Similarly, Builder's assumption about the relationship between payload weight and payload cost would also lose validity if extrapolated to extremely heavy payloads.[28] It would imply that they could be built at a lower cost per pound than that of the bulk structural material (e.g., aluminum) from which they are made. However, this is not a problem for the ranges of payload weights and costs-shown in figure 3-4.

Bottom-Up Analyses

Lockheed used bottom-up analysis to estimate how much the cost of building, launching, and operating selected payloads could be reduced by making them larger[29] and by other measures.[30] Lockheed considered three payloads, selected to span a range of costs, that had been built and launched and for which design and cost data were available. The least expensive was the Lockheed P-1 1 subsatellite, which could be modified for use as a Small Research Satellite (SRS). The most expensive was the Orbiting Astronomical Observatory, the redesigned version of which was designated OAO-B. The other was the Lunar Orbiter, which could be modified for use as a Synchronous Equatorial Orbiter (SEO), four of which could perform Earth resources observation.

Lockheed estimated how much the costs[31] of the OAO-B and SEO payload programs could be reduced if the payloads were redesigned to be launched on unmanned expendable launch vehicles or to be launched on a (then) proposed version of the Space Shuttle.[32] The savings estimated for the first

27 If A is less than one.

28 If B is less than one.

29 Lockheed used parametric methods to estimate cost-versus-weight trade-offs for payload subsystems. Lockheed assumed the cost-versus-weight trade-off curve for each subsystem was a hyperbola which, for an extremely heavy subsystem, approached a minimum cost per pound and, at the other extreme, approached the minimum weight achievable.

30 E.g., repairing or refinishing them in orbit or retrieving them to be repaired or refurbished on Earth.

31 Including costs of research, development, testing, and evaluation (RDT&E), production, launch, operation, and replacement (or, if the Shuttle were used, refurbishment) of satellites.

32 Lockheed considered two versions.

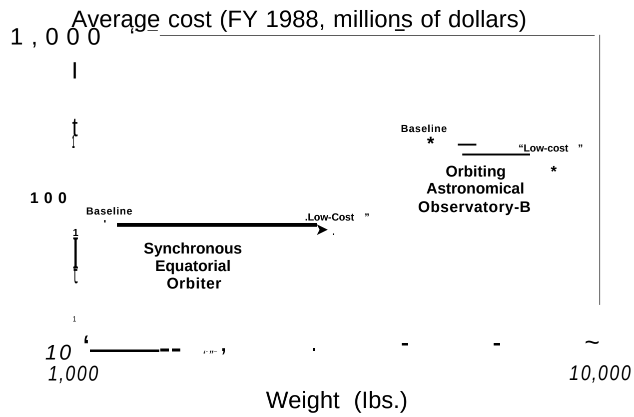
case were attributed to payload growth.[33] However, Lockheed did not redesign the baseline versions of OAO-B and SEO to minimize cost without exceeding the baseline weight, hence Lockheed attributed to weight growth some cost reduction that should have been attributed to improved design. The amount of cost reduction misattributed to weight growth cannot be determined from Lockheed's report, so the cost reductions Lockheed attributed to weight growth should be considered upper bounds on cost reductions achievable by allowing weight growth.

Figure 3-5 compares Lockheed's estimates of the weights and the average unit costs[34] of the baseline OAO-B and SEO with Lockheed's estimates of the weights and costs of "low-cost" versions designed to be launched on expendable launch vehicles. The potential savings in fiscal year 1988 dollars would be $10.1 million (21.3 percent) and $43 million (15.2 percent) for SEO and OAO-B, respectively. The estimated weight growth required to achieve such savings would be 170 percent and 69 percent, respectively.

A more recent bottom-up analysis by Boeing Aerospace Co. estimated the cost of a "typical" payload could be reduced by a large percentage if weight growth by a modest percentage were allowed, and that it would save money to allow such weight growth if launch cost per pound were reduced.[35] For example, Boeing estimated the cost could be halved if the weight were allowed to grow 30 percent (see figure 3-6).[36]

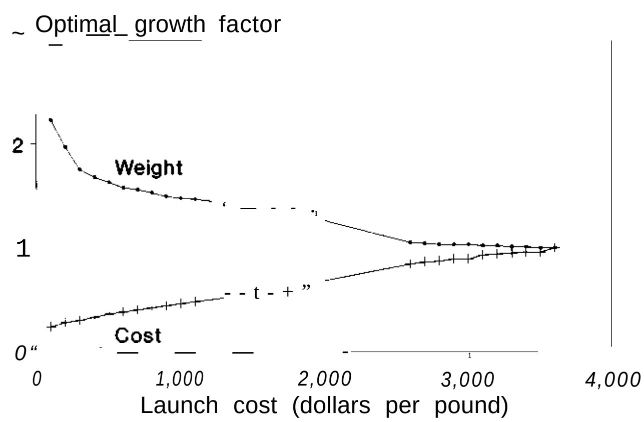
Boeing actually considered a payload consisting of an upper stage and a hypothetical spacecraft using specific subsystem technologies and with subsystem weights in an assumed ratio.[37] Boeing claimed the hypothetical spacecraft was typical, implying that similar cost reductions could be expected for other types of spacecraft. However, some of the subsystem technologies Boeing assumed for the spacecraft were atypical. For example, the analysis estimated

Figure 3-5-if a Satellite Were Allowed To Be Heavier, It Could Cost Less



SOURCE: Estimates from Lockheed Missiles and Space Co., 1971, plotted by Office of Technology Assessment, 1990.

Figure 3-6-The Effect of Reducing Launch Cost on the Optimal Weight and Cost of a Payload



Boeing Aerospace Co. estimated that, if average launch cost per pound were reduced from $3,600 per pound, it would be economical to redesign a hypothetical payload to allow it to be heavier by the weight-growth factor indicated and less costly by the cost-reduction factor indicated. Boeing assumed that the original design minimized the sum of payload and launch costs at a launch cost of $3,600 per pound, and that the average launch cost per pound does not depend on the payload weight.

SOURCE: Boeing Aerospace Co., 1988.

[33] Only part of the savings estimated for the second case was attributed to payload growth; the rest was attributed to reduced launch cost and to services that only a reusable vehicle such as the Shuttle could provide: intact abort capability, on-orbit checkout, repair, and refurbishment. Additional savings in both cases were attributed to use of improved technology.

[34] Total program costs, excluding launch costs, divided by the number of satellites launched (6 OAO-B, 20 SEO), inflated to fiscal year 1988 dollars by OTA.

[35] Eder, *op. cit.*, footnote 8.

[36] Advanced Launch System (ALS) program officials have misquoted this result, saying a 50-percent cost reduction would require 70 percent weight growth. See, e.g., Thomas M. Irby, "Status of the ALS Program," *Space Systems Productivity and Manufacturing Conference-V* (El Segundo, CA: The Aerospace Corp., 1988), p. 30.

[37] The ratio was allowed to change when the payload was redesigned with relaxed weight constraints.

the cost and weight of the satellite's electric power subsystem by assuming it consisted entirely of solar cells (which typically dominate the *cost* of a satellite's power subsystem), with no batteries (which typically dominate the *weight* of a satellite's power subsystem).

Some of the proposed cost-reducing and weight-increasing substitutions Boeing proposed--e. g., substitution of commercial-grade solar cells for spacecraft-grade (S-class) solar cells—would decrease payload reliability and expected lifetime to an extent not estimated by Boeing. Thus Boeing did not estimate weight-versus-cost trade-offs for equal reliability; some of the savings Boeing attributed to weight growth should have been attributed to reduced reliability .38 Therefore, the savings Boeing attributed to weight growth may be upper bounds for spacecraft of the type Boeing considered.

Another recent bottom-up analysis estimated cost-versus-weight trade-offs for some subsystems but not for complete payloads.[39] Like earlier studies by Lockheed[40] and the Aerospace Corp.,[41] it identified payload "cost drivers"—i.e., costly payload components or testing-and recommended changes in payload design, components, testing, or operations that might reduce space program cost. Many of these changes would require increasing the weight of the payload (the "fatsat" approach discussed here) or specifying a simpler or easier mission, or fewer missions (the "lightsat" approach discussed in chapter 4).

A Comparison of Parametric and Bottom-Up Analyses

Estimates differ on how much cheaper payloads could be if they were allowed to grow to a specified weight, and how much they should grow if cost per launch were reduced to a specified amount. One parametric estimate by OTA predicts that a hypothetical expensive payload as heavy as a Titan IV could launch could cost about $130 million less if allowed to be five times as heavy. It would be economical to design the payload to be so heavy if it could be launched for less than about $100 million.[42] Less would be saved if the baseline payload cost were comparable to or less than the average Titan IV launch cost, estimated hereas$117 million. The only bottom-up estimate that could be compared to these is one by Boeing, which predicts much greater savings (at least 76 percent, or $760 million for a billion-dollar payload) but is based on a conceptual design for a payload that is atypical in important respects; moreover, the redesigned payload was allowed to use less reliable components, and launch cost per pound was assumed to be independent of payload weight.

OTA also derived parametric estimates to compare to detailed bottom-up estimates by Lockheed for two spacecraft. Lockheed estimated 66 percent greater savings for one spacecraft (SEO), and 360 percent greater savings for the other (OAO-B), but attributed to weight growth some savings that should have been attributed to optimization of the baseline designs. However, these discrepancies are comparable to the unexplained statistical variations often encountered in spacecraft cost estimation. The less detailed Boeing estimate, if applicable, would predict much greater savings than predicted by OTA: 530 percent more for OAO-B, and at least 630 percent more for SEO, at the weight growth factor proposed by Lockheed.[43]

ACHIEVING POTENTIAL COST REDUCTION

Realizing most of the potential savings predicted by these estimates will probably require creation of incentives to dissuade satellite program managers and designers from adding capability, and thereby weight, until launch vehicle lift margin, engine-out

38Lockheed did so and estimated how man, satellites would be required to provide comparable mission performance for 10 years. Lockheed concluded that use of S-class components, which would maximize expected satellite life and minimize the number of replacements required, would be most cost-effective.

39Hughes Aircraft Co., op. cit., footnote 8.

40Lockheed Missiles and Space Co., op. cit., footnote 9.

41*Spacecraft Cost* Drivers *Study—Final Report: Phase 1* (El Segundo, CA: The Aerospace Corp., October 1983).

42The Advanced Launch System is intended to launch such payloads for much less.

43However, Boeing estimated that it would not be economical to seek the extreme cost reduction predicted for SEO unless launch cost per pound were reduced by a factor of 36.

Box 3-A—Fatsats: The Good and Ugly, and the Bad

HEAO—During a budget crunch, NASA took steps to repackage its High-Energy Astronomical Observatory instruments, designed for two Titan payloads, into three Atlas-Centaur payloads. This reduced launch costs by about 2 x $125K -3 x $60K = $70K in today's dollars, by TRW's calculation. It also created extra weight margin. This allowed designers to design the spacecraft with high safety factors (strength margin etc.), so that they could dispense with the costly construction and testing of model and qualification spacecraft.[1]

Phobos 1 & 2-In July 1989, two science spacecraft, Phobos 1 and Phobos 2, were launched from the Soviet Union toward Phobos, the larger of the two moons of Mars. Their busses were designed and built in the Soviet Union, as were some of their instruments; other instruments were designed in Austria, France, Sweden, Switzerland, West Germany, and several East European nations participating in Project Phobos. Some of the Soviet instruments were designed with generous weight margins. Jochen Kissel, a West German member of the project's scientific council, said, "We could use standard printed circuit boards rather than ultraminiaturized parts . . . It made everything cheaper and simpler.

Nevertheless, because of greater-than-expected weight growth, some instruments were removed from one or the other spacecraft. The two spacecraft were originally intended to carry identical suites of instruments, so that Phobos 2 could perform all functions of Phobos 1 in case Phobos 1 failed, or vice versa.

As it happened, Phobos 1 did fail. More accurately, contact with Phobos 1 was lost late in 1988, because an erroneous command was transmitted to Phobos 1 from the ground. To compensate for the loss, mission directors planned to command Phobos 2 to rendezvous with Phobos rather than proceeding to the smaller Martian moon, Deimos, as it would have had Phobos 1 succeeded. Phobos 2 lacks the radar mapper, neutron spectrometer, and solar x-ray and ultraviolet telescopes of Phobos 1, but carries an infrared spectrometer and a hopping lander which Phobos 1 lacks.[3]

Ironically, contact with Phobos 2 was also lost on March 27, 1989, about two weeks before the planned encounter with Phobos was to occur (on April 9-10).[4] Nevertheless, Phobos 2 gathered a significant amount of data before this failure. This anecdote illustrates the value of generous weight margins on some instruments, the cost of negative weight margins on other instruments and on the spacecraft as a whole, the value of redundant spacecraft, and the risks of human errors and compound failures.

Milstar-Milstar is an advanced communications satellite being built for the Department of Defense. A few will be built—fewer than originally planned—allowing nonrecurring program costs to be amortized over a few satellites. Aside from this economy, Milstar appears to exemplify the antithesis of the fatsat philosophy: it is designed to be large in order to cram it with capability, not to reduce its cost. It has had to be redesigned at least once to reduce its estimated weight and add margin. Costly edge-of-the-art technologies have been adopted to reduce weight, and some are so risky that additional greater-than-expected cost and weight growth could occur.

Milstar was made fatter to be better, not cheaper, and its gross weight kept growing. A subsystem designer quipped, "Milstar is going to gross everybody out. "

[1] TRW, briefing, Nov. 16, 1989. See also *Science, vol.* 199, Feb. 24, 1978, p. 869, and *Astrophysical/Journal, vol.* 230, June 1, 1979, P. 540.

[2] Eric J. Lerner, "Mission to Phobos,'' *Aerospace America*, September 1988, pp. 34-39.

[3] Ibid., and ''Phobos 1 Loss to Change Mars Mission,'' *Aviation Week and Space Technology*, Oct. *3, 1988,* p. 29.

[4] ''Soviets Lose Contact With Phobos 2 Spacecraft," *Aviation Week and Space Technology*, Apr. 3, 1989, p. 22.

capability, and reliability are reduced, requiring expensive weight reduction programs for redress. The managers of satellite programs funded by line-item appropriations have little incentive to spend less than the amount appropriated. When funding allows, spacecraft purchasers, with rare exceptions, opt to increase performance rather than reduce cost.