Weight and Volume Margins

As payloads progress from the drawing board (or computer-aided design workstation) to the launch pad, their volumes tend to expand to fill the payload fairings of their betrothed launch vehicles, and their weights tend to grow to the maximum that the launch vehicles can launch. Dry weights of representative U.S. military satellites have been about 25 percent greater, on the average, than the estimates of dry weight made when they were proposed.[1] On occasion, satellites grow so heavy that their assigned launch vehicles would be unable to place them in the desired orbits. When this happens, drastic and expensive efforts are undertaken to reduce the weight of the satellite—and sometimes of the launch vehicle as well. A TRW executive has said, “We have to spend numbers like $150,000 a pound trying to get the last few pounds out of a spacecraft. ”[2]

A contract for spacecraft development and production typically specifies that the spacecraft perform certain functions and not weigh more than a specified maximum weight. Usually this maximum weight is chosen to be less than the maximum weight a particular launch vehicle can place in the desired orbit. The difference between these two values provides a margin that allows for contingencies such as less-than-expected launch vehicle thrust.

The spacecraft designer initially tries to design the spacecraft to perform the specified functions and not weigh more than the specified maximum weight, *minus*

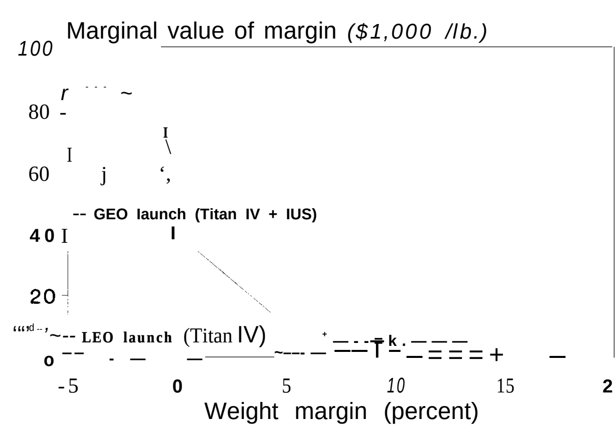
1. a “*contingency*” amount by which the estimated weight of the spacecraft is *expected* to grow as the design matures, and
2. a “*weight margin*” representing greater-than-expected growth in the estimated weight as the design matures.

Based on its experience producing high-tech government spacecraft and spacecraft subsystems, TRW expects weight to grow ultimately 15 percent larger than initial estimates and hence budgets a contingency of 15 percent initially. As the design matures and the estimated weight increases as expected, the contingency budget is decreased.

TRW may also allow a margin of 15 percent or more for greater-than-expected weight growth, initially. TRW estimates that the value of weight margin increases with decreasing margin, from zero at 15 percent margin, to $5,000 to $10,000 per pound at 5 to 10 percent margin, to $40,000 per pound at O percent margin, to as much as $100,000 per pound at negative margin, depending on the time remaining before launch (figure 2-l). Margins are seldom negative at an early design stage; if margin becomes negative shortly before the spacecraft is to be launched, expensive redesign may be required to reduce the spacecraft weight below the maximum weight specified in the contract, and TRW estimates that it maybe worth up to about $100,000 per pound to avoid this. This is much greater than the cost of transporting a typical spacecraft to its operational orbit: about $15,000 to $30,000 per pound to geosynchronous orbit, as estimated by TRW.[3]

TRW notes that spacecraft designed to incorporate advanced-technology subsystems can consume weight margins with unusual rapidity, leading to redesign (which may require 3 or 4 months), increased risk, and possibly additional redesign, as well as downward revision of ‘requirements. Two

Figure 2-I—Value of Weight Margin



SOURCE: TRW (*plotted* by OTA).

[1] P. 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), p. VIII-6; distribution limited to U.S. Government agencies only.

[2] G.W. Elverum, Jr., “Reliability Up/Coats Down Through Simplicity,” *Space Systems Productivity and Manufacturing Conference IV* (El Segundo, CA: Aerospace Corp., 1987), pp. 175-1%.

[3] Clark Kirby, TRW, personal communication, Nov. 16, 1988.

redesign cycles totaling 6 to 8 months could lead to a 10 to 25 percent cost growth. TRW also notes that volume constraints are also costly.

How much margin should be reserved? Reserving too little increases the risk of delay and cost overrun, should redesign become necessary, because weight growth exceeds expectations late in a development program. Yet reserving too much margin imposes an opportunity cost: one either foregoes the opportunity to add extra fuel or equipment, and hence capability, to the payload, or one foregoes the opportunity to make the payload less expensive by allowing it to be heavier. In the latter case, the opportunity cost is tangible and can be estimated.[4] The optimal margin will be that at which the marginal opportunity cost of not making the payload a pound heavier equals the marginal value that the additional margin would provide by reducing risk of cost overrun and schedule slippage.

If the marginal value of weight margin is as estimated by TRW (see figure 2-1), then a margin of 11 to 12 percent would be optimal for a Titan IV payload.[5] This is comparable to the margin (15 percent) that Public Law 100-456 required the Department of Defense to reserve for satellites DoD approves for development in fiscal year 1989. In reporting on the National Defense Authorization Act for fiscal year 1989, the Senate Committee on Armed Services proposed requiring that

> *. . . the Under Secretary of Defense for Acquisition shall not approve for development a new satellite if the proposed payload weight exceeds 85 percent of the lift capacity of the launch vehicle(s) identified with the proposed satellite, and shall not approve for development a block change if the proposed payload weight exceeds the weight of the existing payload.*[6]

This language was endorsed in conference and signed into law.[8]

The expectation that increasing weight margins would reduce cost risk does not imply that it would save money to build a new launch vehicle large enough to launch the heaviest payloads with increased weight margins. Predicting whether it would save money would require comparing the cost of developing the vehicle with the total benefits it would provide—including the reduction in cost risk that increased weight margins would provide. Ironically, building larger launch vehicles could increase this risk: Without discipline, payloads might still be designed to allow little margin, and margins could still be tight or negative, but with greater consequence. To eliminate a l-percent negative margin, one would have to trim 2,000 pounds from a 200,000-pound payload, compared to only 390 pounds in the case of a 39,000-pound payload. In some cases this could be done by carrying less fuel than planned and accepting reduced payload performance. If not, reducing the dry weight of a 200,000-pound payload by 1 percent would cost $240 million more than reducing the dry weight of a 39,000-pound payload by 1 percent, if weight reduction costs $150,000 per pound. This illustrates why allowing margin for, and controlling, weight growth will be much more important for large payloads (such as proposed heavy-lift launch vehicles could carry) than for smaller ones.

[4] See "A Parametric Analysis" in ch. 3.

[5] Viz. a payload that would cost between $100 million and $5 billion if built to weigh 39,000 pounds—i.e., to reserve no margin.

[6] S. Rept. 100-326, P. 36.

[7] H. Rept. 100-989, P. 282.

[8] S. Rept. 100-326 did not specify whether the [estimate of] proposed satellite weight should include expected weight growth in addition to the nominal weight estimated from the design for the satellite. If so, Public Law 100-456 would require at least a 15 percent weight margin in addition to whatever weight growth is expected. If the payload consisted solely of an unfueled satellite, 25 percent weight growth would be expected [P. Hillebrandt et al., op. cit., footnote 1, pp. VIII-6], so Public Law 100-456 would require a 40 percent weight margin in addition to the nominal weight estimated from the design for the satellite.