Chapter 3

Space Transportation Demand and Costs

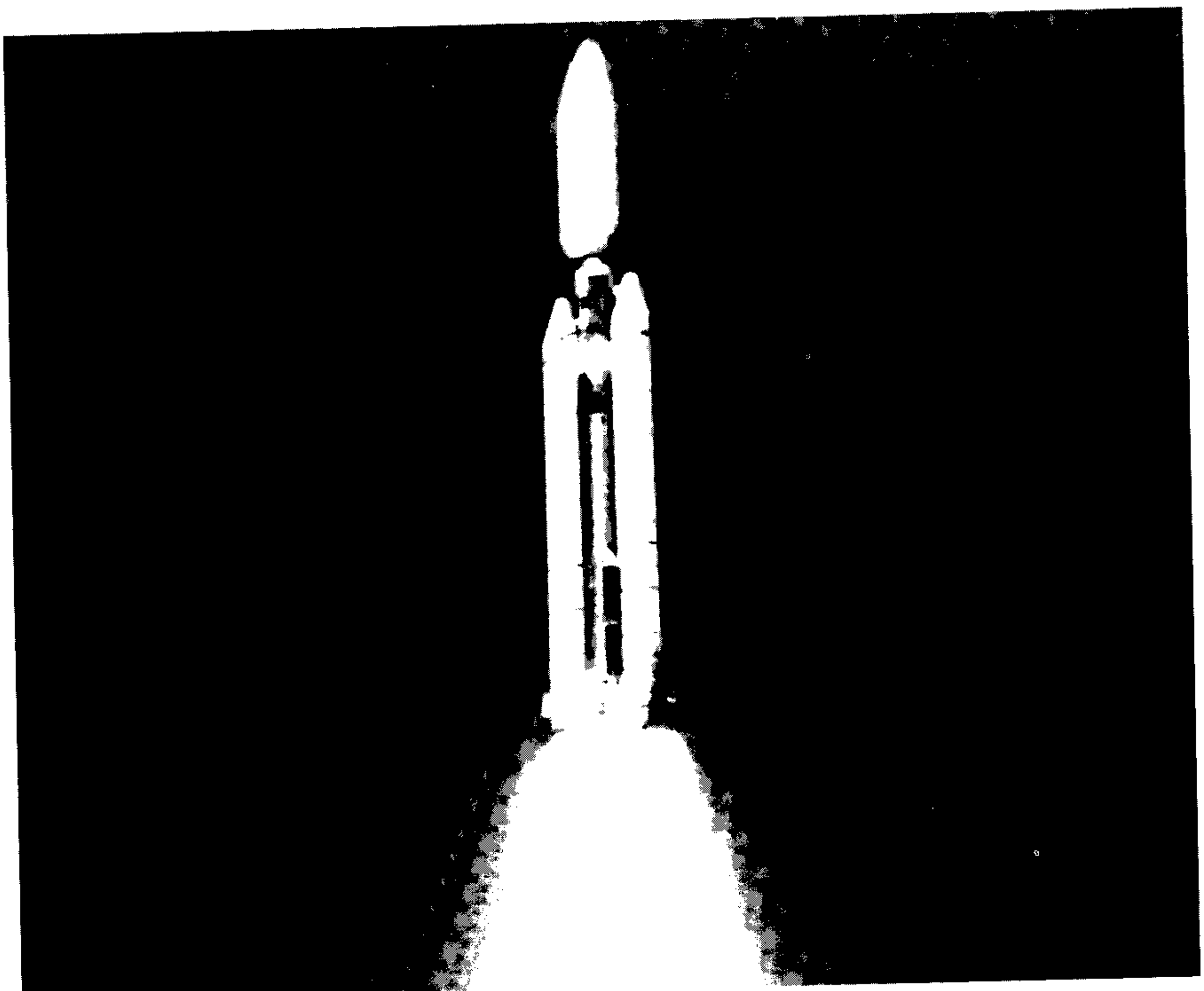


Photo credit: U.S. Air Force

The Titan IV launch vehicle lifts off from Space Launch Complex 41 at Cape Canaveral Air Force Station. This launcher will be the workhorse launcher for the Air Force for at least the next decade.

Space Transportation Demand and Costs

Projections of demand for U.S. transportation to and from low Earth orbit vary from about 600,000 pounds to more than 4 million pounds of payload per year. The lower projections are based on an assumption that the tonnage launched annually will grow slowly for the next two decades. The higher projections are based on an assumption that the United States will undertake an ambitious space initiative, such as deployment of a space-based missile defense system, establishment of a manned base on the Moon, or a manned expedition to Mars. Because there is no broad consensus on the desirability of these proposals and on the willingness to pay for them (nor even on how much they would cost), post-1995 demand for U.S. space transportation is highly uncertain.[1] This uncertainty makes rational choice among options for improving the Nation's space transportation systems extremely difficult. Nevertheless, failing to choose an alternative now could leave the United States incapable of meeting future needs, or paying for excess capacity.

In the face of such uncertainty, OTA analyzed the space transportation needs for three scenarios (called mission models) for growth of demand:

- *Low-Growth:* launch rate grows about 3 percent per year to 41 launches per year by 2010, then remains constant through 2020.
- *Growth:* launch rate grows about 5 percent per year to 55 launches per year by 2010, then remains constant through 2020.
- *Expanded:* launch rate grows about 7 percent per year to 91 launches per year by 2010, then remains constant through 2020.[2]

These mission models represent, respectively, the approximate demand that would likely result from efforts to:

— maintain the existing course of NASA and DoD space programs (option 1),[3]

— deploy the Space Station in the mid-1990s while expanding the NASA science program and continuing the trend of launching heavier military satellites (options 4 or 5), *or*

— send humans to Mars and establish a base on the Moon, or deploy a layered ballistic-missile-defense system in orbit (options 3 or 6).

The mission models differ only in demand for heavy-cargo launches; they are identical in postulated demand for light-cargo launches and piloted missions. By largely ignoring the weights, sizes, and destinations of individual payloads, these simplified mission models help focus OTA's broad-brush analysis on the sensitivity of costs to gross demand.[4]

OTA calculated the life-cycle cost of servicing the demand postulated by each mission model with each of five different combinations of types ("fleets" of launch vehicles—box 3-A).[5] Although intangible benefits such as "space leadership" may be weighed in comparing the options, the most appropriate *economic* yardstick is life-cycle cost (box 3-B), discounted to reflect the opportunity cost to the Nation of diverting funds from competing demands on the Federal budget.

THE MOST ECONOMICAL OPTIONS

Figure 3-1 shows OTA's estimate of the discounted life-cycle cost of each of five space transportation options in each of the three OTA mission models. Estimated life-cycle costs increase with increasing demand, even though cost per pound of payload (not shown) would decrease with increasing demand.

[1] Estimates of demand through 1995 are relatively accurate, because the lead time for payload development is so long.

[2] Presumably, Government demand for space transportation would depend on space transportation costs, but there have been few efforts to forecast the price elasticity of demand for space transportation. For two examples, see DoD and NASA, *National Space Transportation and Support Study 2995-2010, Annex* B: Civil Needs Data Base, Version 1.1, Volume I-Summary Report, Mar. 16, 1986, pp. 3-31,3-32; and Gordon R. Woodcock, "Economics on the Space Frontier: Can We Afford It?" *SSI Update* (Princeton, NJ: Space Studies Institute, May/June 1987).

[3] Option 2 would fit within this scenario, but would save about $10 billion by reducing the total mass of payload launched to orbit.

[4] A more detailed analysis would examine the sizes and weights of expected payloads and match them Up with expected launch vehicles. However, in most cases, pursuing such a detailed analysis for periods beyond 5 or 10 years would yield no additional insight, as the characteristics of payloads that far in the future are extremely poorly known.

[5] See also 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 1-1.

Box 3-A--Mixed Fleet Options

In the future, as in the past, the United States will probably want to perform such a variety of missions in space that a variety of types of launch vehicles—a "mixed fleet' '-will be needed, for operational flexibility if not economy. The current mixed fleet includes the Scout, Delta, Atlas, and Titan launchers (including several versions of each), as well as the Shuttle and a few new, small, privately developed launch vehicles such as the Conestoga and Pegasus. In the near future, most payloads will be carried by the Titan, Shuttle, and Medium Launch Vehicles (the Medium Launch Vehicle is derived from the Delta, and the Medium Launch Vehicle II from the Atlas).

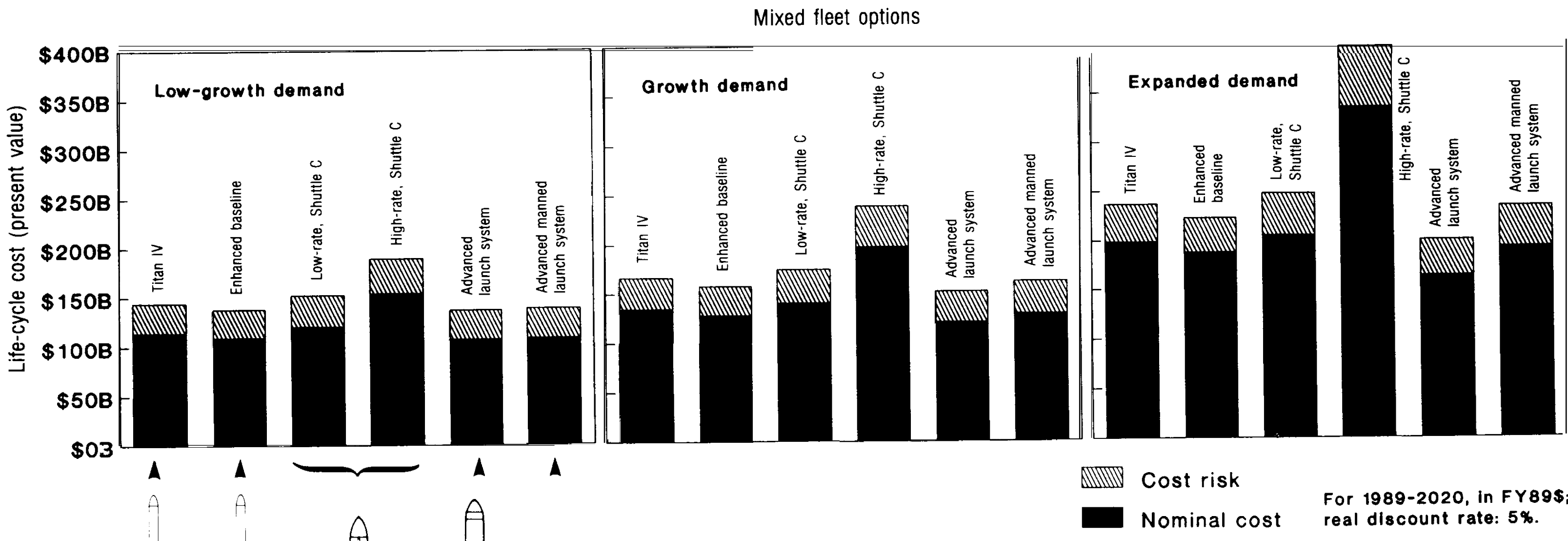
To estimate whether improving these launch systems, or developing a new one would be economical, OTA has estimated and compared the life-cycle costs of servicing postulated Government demand with each of five different mixed fleets. OTA considered using one of the mixed fleets in two different ways; hence a total of six mixed-fleet options were considered (see figure 3-1). Although most options were named after the new system under consideration, or the primary cargo vehicle (e.g., Titan IV), a mixed fleet of crewed and unmanned launch vehicles would be used in each option:

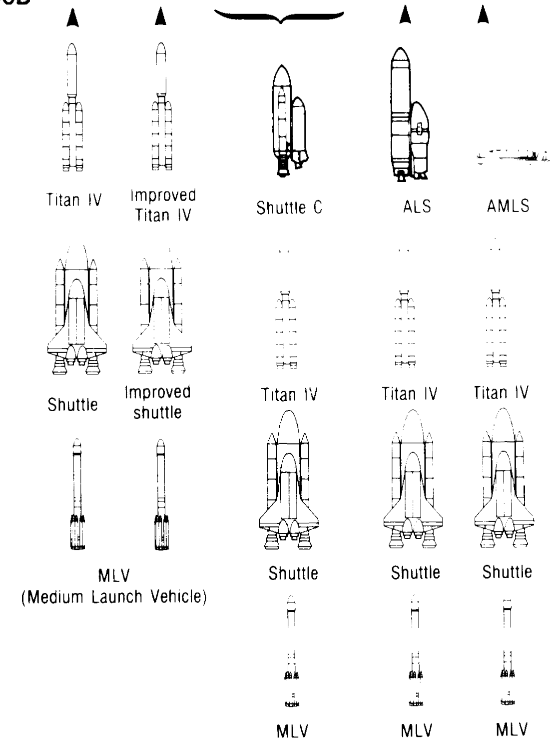
- *Titan IV:* Continue to use Titan IVS for heavy cargo, Delta II and/or Atlas-Centaur II Medium Launch Vehicles for light cargo, and Space Shuttles for round-trip missions (manned launches or return of cargo to Earth).
- *Enhanced Baseline:* Immediately begin upgrading Titan IVs and Space Shuttles to increase reliability and reduce cost. Meanwhile, use Titan IVs for heavy cargo, Delta II or Atlas-Centaur II Medium Launch Vehicles for light cargo, and Space Shuttles for round-trip missions.
- Low-rate Shuttle-C: Immediately begin developing Shuttle-C expendable, unmanned, heavy-cargo launch vehicles. In 1995, begin launching three per year to carry some cargo that would otherwise be launched on Titan IVs, Medium Launch Vehicles, and Space Shuttles. Continue to use Titan IVs, Medium Launch Vehicles, and Space Shuttles for the remaining missions,
- *High-rate Shuttle-C:* Immediately begin developing expendable, unmanned, Shuttle-C heavy-cargo launch vehicles. In 1995, begin launching them at whatever rate is required to replace Titan IVs. They would also carry some cargo that would otherwise be launched on Medium Launch Vehicles and Space Shuttles. Continue to use Medium Launch Vehicles and Space Shuttles for the remaining missions.
- *Advanced Launch System:* Begin developing unmanned Advanced Launch System (ALS) vehicles and facilities in time for them to supersede Titan IVs in 2005, They would also carry some cargo that would otherwise be launched on Medium Launch Vehicles and Space Shuttles. Continue to use Medium Launch Vehicles and Space Shuttles for the remaining missions.
- *Advanced Manned Launch System:* Begin developing Advanced Manned Launch System (AMLS) vehicles and facilities in time for them to supersede Space Shuttles in 2005. Continue to use Titan IVs and Medium Launch Vehicles for one-way missions.

Small launch vehicles-such as the Scout Conestoga, and Pegasus-are expected to carry a small fraction of total Government payload and contribute a small fraction of total launch cost. They were not explicitly included in the mixed-fleet options for this reason, not because of any judgment that they would be uneconomical for selected missions.

SOURCE: Office of Technology Assessment, 1990.

Figure 3-1—Discounted Life-Cycle Costs of Space Transportation Options





This figure shows the present value, in fiscal year 1989 dollars, of the estimated life-cycle cost of each of six space transportation options in each of three scenarios* for growth of U.S. Government demand for transportation to and from low Earth orbit:

- *Low-Growth*: launch rate grows about 3 percent per year to 41 launches per year by 2010, then remains constant through 2020.
- *Growth*: launch rate grows about 5 percent per year to 55 launches per year by 2010, then remains constant through 2020.
- *Expanded*: launch rate grows about 7 percent per year to 91 launches per year by 2010, then remains constant through 2020.

All options assume continued use of current vehicles—Titan IVs for heavy cargo, Delta II and/or Atlas-Centaur II Medium Launch Vehicles for light cargo, and Space Shuttles for round-trip missions (piloted launches or return of cargo to Earth)—except as noted:

- *Titan IV*: no exceptions.
- *Enhanced Baseline*: upgrade Titan IVs and Shuttles to increase reliability and reduce cost.
- *Low-rate Shuttle-C*: develop the Shuttle-C expendable, unmanned, heavy-cargo launch vehicle, and launch three per year starting 1995.
- *High-rate Shuttle-C*: develop the Shuttle-C and launch them at whatever rate is required to replace Titan IVs, starting 1995.
- *Advanced Launch System*: develop unmanned Advanced Launch System (ALS) vehicles and launch them at whatever rate is required to replace Titan IVs, starting 2005.
- *Advanced Manned Launch System*: develop Advanced Manned Launch System (AMLS) vehicles and launch them at whatever rate is required to replace Shuttles, starting 2005.

*Demand for piloted and light-cargo launches is the same in all scenarios; the scenarios differ only in demand for heavy-cargo launches.

SOURCE: Office of Technology Assessment, 1990.

Box 3-B--Cost Components

Life-cycle cost-appropriately discounted to reflect risk and opportunity cost—is the most important economic criterion by which to compare different launch vehicle architectures. For each mission model examined here, the option that has the lowest discounted life-cycle cost would be must economical, if the assumed discount rate were appropriate and if the required funding were available. However, the most economical launch architecture might be deemed unaffodable if it would require more spending in a particular year than the Executive would budget or than Congress would authorize and appropriate for the purpose.

Life-cycle costs include both nonrecurring and recurring costs. The nonrecurring costs include costs of design, development testing, and evaluation (DDT&E), production of reusable vehicle systems, and construction and equipping of facilities. The recurring costs include all costs of planned operations, including production of expendable vehicle systems, as well as expected costs of failures. In general, early nonrecurring investment is required to reduce total discounted life-cycle cost.

Failure cost, a component of life-cycle cost, deserves special mention because: 1) it can be as great as the balance of life-cycle cost, 2) it is sometimes excluded from cost estimates, and 3) it is random-hence uncertain-and depends sensitively on the reliabilities of the launch vehicles used. These reliabilities are themselves very uncertain--even for vehicles that have been launched more than a hundred times, and especially for vehicles that have never been launched. Expected costs of failures are calculated from estimates of vehicle reliabilities and estimates of the costs that would be incurred in the event of a failure (see box 3-C).

Cost risk is included in the cost estimates quoted here. Cost risk was defined in the Space Transportation Architecture Study (STAS) as a subjectively estimated percentage increase in life-cycle cost (discounted at 5 percent) that the estimator expects would be exceeded with a probability of 30 percent, assuming certain ground rules are met. Basically, cost risk is intended to represent likely increases in life-cycle cost caused by unforeseen circumstances such as difficulties in technology development or facility construction. However, cost risk as defined in the STAS does not include risks of cost growth due to mission cancellations, funding stretch-outs, or standdowns after failure, which were excluded by the ground rules of the study. The cost risk estimates by OTA also exclude risks of mission cancellations, funding stretch-outs, and standdowns after failures; estimation of these risks in a logically consistent manner will require more sophisticated methods than were used here, or in the STAS. However, OTA's cost risk estimates do include the risk of greater-than-expected failure costs.

SOURCE: Office of Technology Assessment, 1990.

Box 3-C-Failure Costs

The cost of failures makes a substantial contribution to understanding the life-cycle costs of a launch system relative to any other. A system with a high purchase cost may nevertheless be cheaper in the long run than a lower-cost system if the former exhibits much higher reliability. Even if both reliability and acquisition costs are equivalent the life-cycle costs could be very different if one system requires a much longer standdown for analyzing and correcting a failure than another.

The expected cost of failures of launch vehicles are calculated by multiplying the number of launches planned by the estimated probability of failure on a single launch (one minus the estimated reliability), then multiplying the result by the estimated cost per failure. Cost per failure will generally include cost of accident investigation and corrective action. It may also include costs of replacing and reflying lost payloads, replacing reusable vehicle components, and delays pending completion of accident investigation.

In the Space Transportation Architecture Study (STAS), operations costs were estimated assuming that operations would be continuous (i.e., no "standdowns"), and failure costs were estimated assuming that all lost payloads would be replaced and reflown. The same assumptions were made in this report. Accident **investigation costs were** included, *but launch operations were not assumed to be suspended pending* their completion. To assume that a fleet would stand down pending completion of accident investigation requires that the opportunity costs of delaying missions be estimated. Moreover, because some missions would be canceled as a result of the delay, life-cycle costs would have to exclude missions not flown.

SOURCE: Office of Technology Assessment, 1990.

If facilities and fleets are sized for demand appropriate to the Low Growth scenario, all of the options OTA considered would have comparable life-cycle costs. The estimates of expected life-cycle costs of different options differ by only a few percent of the estimated uncertainties (“cost risk”) in those estimates. Moreover, the theoretically most economical choice depends on the accounting horizon assumed (i.e., the last year for which estimated recurring costs are cumulated). Building an Advanced Launch System (ALS) to supersede Titan IVs is most economical for the nominal accounting horizon (2020), but improving current vehicles[7] would be most economical if the accounting horizon were instead 2010 (see figure 3-2).

The probability that building an ALS would be most economical increases with increasing demand. In the Expanded demand scenario, the ALS is estimated to yield savings (relative to continued use of Titan IVs) comparable to the estimated cost risk of the ALs option.

If demand for cargo flights were as in the Low-Growth mission model but crew-carrying flights were limited to 8 per year (policy option 2), all mixed-fleet options would cost between $9 billion and $10 billion less than indicated in figure 3-1 for the Low-Growth mission model, except that the AMLS option would cost about $7 billion less.

Thus **demand for launch services is the most important determinant of the economic value of investing in new launch systems. An** ALS is likely to be most economical at high launch rates, but if, instead, demand grows slowly above current launch rates, all of the options OTA considered would have comparable life-cycle costs. **The reader is cautioned that current methods of estimating launch system costs are subjective and unreliable, and that large development projects for new space transportation systems are not likely to achieve their cost or technical objectives without continuity in commitment and funding.**

The costs of options that include operational aerospace planes are highly uncertain and should be estimated by methods designed specifically to account for such uncertainties (see below).

Cost Estimation

OTA derived the estimates in figure 3-1 using the methods described in *Launch Options for the Future.*[8] *The* nominal cost-estimating relationships were used, but those for Shuttle-C, the ALS, and the AMLS have been revised.

OTA now assumes Shuttle-C development will cost $985 million, in fiscal year 1988 dollars.[10] A Shuttle-C could be launched with two or three engines; if it carries no more payload than a two-engine Shuttle-C could carry, a three-engine Shuttle-C could tolerate a failure of one of its Space Shuttle Main Engines (SSMEs) and hence could be more reliable than a two-engine Shuttle-C. OTA’s cost estimates are for a three-engine Shuttle-C, which NASA estimates would cost $424 million per launch, if launched with engines that have been used one time on a Shuttle flight.11 NASA has not estimated the reliability of a three-engine Shuttle-C;[12] OTA’s cost estimates are based on an assumed reliability of 97 percent.[13] NASA estimates a first launch could be attempted 54 months after authority to proceed (with development) is granted;[14] OTA assumes operational launches will begin in 1995.

6Congress prohibited development of the Transition (or Interim Advanced) Launch System; see 101 Stat. 1066.

7The Shuttle, Titan IVs, and Delta IIs or Atlas-Centaur IIs.

8U.S. Congress, Office of Technology Assessment, op. cit., footnote 5. *Launch Options for the Future* contained some errors, most notably:(1) The inadvertent use of Design, Development, Testing and Evaluation (DDT&E) cost for the cost of procuring reusable hardware led to overestimation of the costs of the Transition, ALS, and Shuttle options. The magnitude of the errors in life-cycle cost estimates was smaller than the estimated uncertainty; correcting them did not change the rank of the most economical option for each mission model. OTA is indebted to Mitch Weatherly of General Dynamics Space Systems Division for pointing out anomalies that led to OTA’s discovery of this error. (2) The statement on p. 40 that “Shuttle-C would pay for itself after being used for Space Station deployment alone” is incorrect; cf. box 7-3 on p. 69: “Shuttle-C . . . could provide useful flexibility . . . at a small premium in life-cycle cost.”

9Ibid., table A- 1, p.82.

10$1,114.3 million in fiscal year 1991 dollars-Jack Walker, MSFC, facsimile transmission, Jan. 11, 1990.

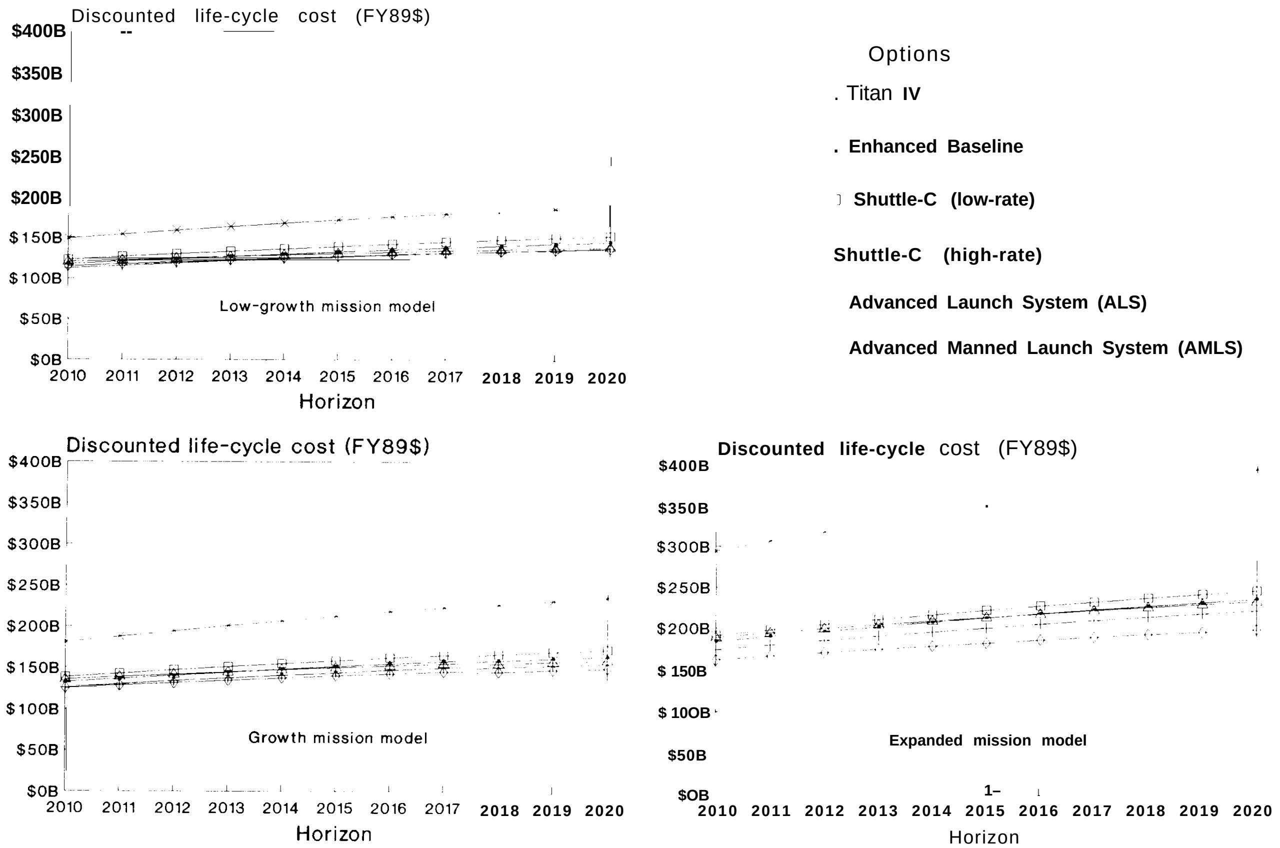
11$479.5 million in fiscal year 1991 dollars-ibid.

12Ed Gabris, NASA HQ, Code MD, personal communication, Jan. 17, 1990.

13“Shuttle/Shuttle-C Operations, Risks, and Cost Analyses,” LSYS-88-008 (El Segundo, CA: L Systems, Inc., July 21, 1988), postulated a reliability between 97.5 and 98.9 percent, with 98 percent the “average.” OTA multiplied this “engineering estimate” by 99 percent to account for the unreliability of humans and other unmodeled systems and processes. See U.S. Congress, Office of Technology Assessment, footnote 5, p. 85.

14Ed Gabris, NASA HQ, Code MD, personal communication, Jan. 17, 1990.

Figure 3-2-Sensitivity of Life-Cycle Costs to Accounting Horizon



SOURCE: Office of Technology Assessment, 1990.

OTA now assumes ALS development will cost $7.3 billion (in fiscal year 1988 dollars), facilities (including one pad) will cost $3.9 billion plus $150 million times the peak annual ALS launch rate in excess of 25 per year, operations will cost $70 million per launch (of which about $17 million will be for the expendable launch vehicle), and the "engineering estimate' of reliability on ascent is 98.4 percent.[15] The estimates of recurring cost per launch and reliability are for a liquid-fueled version of the proposed ALS expendable launch vehicle at a rate of 10 per year.[16]

OTA assumes Advanced Manned Launch System (AMLS) costs will be as estimated for the proposed Shuttle II described in *Launch Options for the Future* but now assumes AMLS will begin operating in 2005. NASA is considering several alternative concepts as follow-ons to the Shuttle, including the AMLS and Personnel Launch System (PLS).[17] NASA has awarded Rockwell International a contract to flesh out several alternatives, estimate their costs, and help weed out the less promising ones.

The estimates in figure 3-1 include costs incurred from 1989 to 2020. In *Launch Options for the*

[15] The ALS Joint Program Office estimates that operation could begin in 1998, but a recurring cost of $70 million per launch would not be achieved until 2005.

[16] As before, and as for other launch vehicles, OTA assumes the operational reliability on ascent will be 99 percent of the engineering estimate of reliability, and the operational reliability on return, given successful ascent, will be 99 percent.

[17] See ch. 7. For a more detailed description of these alternatives, see: U.S. Congress, Office of Technology Assessment, *Round Trip To Orbit: Human Spaceflight Alternatives—Special Report*, OTA-ISC-419 (Washington, DC: U.S. Government Printing Office, August 1989), pp. 53-56.

Future, OTA did not accumulate recurring costs after 2010, because demand after 2010 is highly uncertain. However, not accumulating costs beyond 2010 might unfairly penalize options that include advanced systems, because it allows only 5 years for the annual savings expected from an ALS or AMLS to pay back the substantial initial investment that would be required to reduce annual costs. Hence it is also instructive to compare life-cycle costs over a longer life cycle. Figure 3-2 shows the life-cycle costs of the same options for accounting horizons ranging from 2010 to 2020, and shows that extending the accounting horizon did not significantly affect the ranking of the options: all are roughly comparable at Low-Growth launch rates, while an ALS is estimated to be significantly less costly than the other options at Expanded launch rates.

AEROSPACE PLANES

OTA has considered an option for developing and using aerospace planes incorporating NASP technology to supersede the Shuttle and complement Titan IVs. Aerospace planes, if successful, could be operated with greater responsiveness, flexibility, and economy than could rocket-powered launch vehicles.

However, it is not yet possible to estimate the life-cycle cost of such an option in the conventional manner, which depends on extrapolating or interpolating curves showing how subsystem costs depend on design parameters, such as subsystem weight. Similar curves are obtained for the costs of operational procedures as functions of labor and equipment requirements. Such curves are obtained by fitting a curve of a given type---g.,., a line—to points representing the costs and weights (etc.) of technologically similar subsystems that have been built and the costs of which are known.[18] However, the experimental X-30 and operational vehicles derived from NASP technology, which would use air-breathing engines for propulsion most or all of the way to orbit, would have systems so unlike any previously developed that no data points exist to which cost curves for key systems, such as engines, could be fit. Further, the feasibility of such aerospace planes remains unproven. Hence subjective engineering judgment must play a greater role than usual in estimating the costs of operational vehicles.

Moreover, the reusability of operational vehicles would make the average cost per flight extremely sensitive to parameters such as maintenance manhours per sortie and the probability of catastrophic failure, both of which OTA regards as extremely uncertain. These quantities were underestimated in the case of the Space Shuttle, the orbiter of which was designed for 100 flights. This led to underestimation of average cost per flight. As currently envisioned, operational aerospace planes would be designed to last 500 flights, so their average cost per flight will be more sensitive to greater-than-expected probability of catastrophic failure. Current] y, the NASP Joint Program Office assumes that the probability of catastrophic failure will fall between 0.1 percent and 0.5 percent. The average cost per flight will also be sensitive to shorter-than-expected wearout life. Airplanes, of course, are designed for many more uses, but extensive reliability and maintenance data for technologically similar airplanes is usually available.

Building and flying X-30S would demonstrate the feasibility of single-stage, air-breathing, rocket-assisted, reusable launch vehicles and would provide data for anchoring cost estimates. It would also provide data on which reliability estimates could be based. Partially subjective but logically consistent methods will be needed to predict operational aerospace plane reliability on the basis of X-30 flight test data (see app. A).

Making aerospace planes extremely reliable will be important for reasons other than cost, because they might fly many—perhaps half---of the missions that Titans would otherwise fly, as well as the missions that the Shuttle or an AMLS could accept. Thus aerospace plane crews would have greater *exposure* to risk than would Shuttle or AMLS crews.

The life-cycle cost of an option that includes spaceplane development, flight testing, and—if successful—production and operation, will depend not on] y on the actual reliability of the plane but also on the reliability the plane is required to demonstrate in flight tests and on the type and level of confidence with which it is required to demonstrate that reliability (see app. A).

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[18] See 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, for a discussion of cost-estimating relationships.