Chapter 7
costs

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INTRODUCTION

This chapter compares estimated life-cycle costs of using the options described in chapters 2-5 across a range of demand levels. These estimates do not include the very substantial costs of payloads and upper stages, which can be several times more costly than the vehicles that launch them.[1] These costs, as well as those of launch systems, must be reduced to foster economy, affordability, and growth of space activity.

In conducting its analysis of the costs of space transportation system hardware, facilities, and services, OTA relied initially on data and estimation methods developed by the Boeing Aerospace Company for the Space Transportation Architecture Study (STAS) and the Advanced Launch System (ALS) program. These initial estimates were adjusted to include OTA's estimate of failure costs, cost risk, and reliability. A detailed description of the cost estimation methods used to derive the figures contained in this chapter can be found in appendix A.

The cost-estimating formulae used by OTA were reviewed by NASA, the Air Force, Boeing Aerospace Company, General Dynamics, Hughes Aircraft Company, Martin Marietta Denver Aerospace, McDonnell Douglas Corporation, Rockwell International Corporation, and United Technologies Corporation. These reviewers suggested important additions and corrections, and two suggested alternative formulae for estimating the costs of developing, producing, and launching the launch vehicles considered. OTA produced alternative estimates of life-cycle cost based on the formulae proposed by two of the reviewers; the section below on "Alternative Cost Estimates," shows the ranges spanned by these formulae and the OTA estimates derived from them.

Estimates of costs of launch vehicle development and operations are necessarily uncertain because development can take longer and cost more (or less) than assumed, or demand might grow more slowly (or increase more rapidly) than assumed. For this reason, OTA **cannot assure the accuracy of the estimates contained in this chapter. However, OTA does maintain that the estimates are reasonable given the stated ground rules and assumptions, and that the methodology used here is representative of the state of the art.**

ESTIMATED COSTS OF OPTIONS

Baseline

To give the reader a basis upon which to compare the options discussed in this report, OTA defined a "Baseline" (in chapter 2). The Baseline features current vehicles **launched at rates limited only by the constraints imposed by existing manufacturing** and ground facilities. Limiting the Baseline to existing facilities means that it could not even fly all the missions in the Low-Growth mission model. Although the Baseline might

1 Some spacecraft cost several hundred thousand dollars per pound; see <u>Space Systems and Operations Cost Reduction and Cost Credibility Workshop</u>, Executive Summary (Washington, DC: National security Industrial Association, 1987), fig. 3.7.3.

Box 7-1. - 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 most economical, if the assumed discount rate were appropriate and if the required funding were available. However, the most economical launch architecture might be deemed unaffordable 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. To help the reader compare the long- and short-term advantages of the various options, this chapter displays their funding profiles for each mission model in constant 1988 dollars. Funding profiles in current ('{then-year") dollars are exhibited in appendix B.

Life-cycle costs include both non-recurring and recurring costs. The non-recurring 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 operation% including production of expendable vehicle systems, as well as expected costs of failures. 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 7-2, '*Failure Costs," and appendix A).

In general, early non-recurring investment is required to reduce total discounted life-cycle cost. Trade-offs between investment and savings are discussed below in the section, **"Trade-Offs between 'Up-Front' and 'Out-Year' Costs."**

Cost risk is included in some of 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 groundrules are met. Basically, cost risk is intended to represent likely increases in life-cycle cost caused by unforeseen difficulties in technology development, facility construction, etc. However, cost risk as defined in the STAS does not include risks of cost growth due to mission cancellation% funding stretch-outs, or standdowns after failure, which were excluded by the groundrules 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 (see box 7-2, **"Failure Costs,").**

Because cost risk is defined in terms of life-cycle cost and not annual cost, cost risk is excluded from the funding profiles in this chapter but included in the histograms comparing life-cycle cost. Cost risk is also excluded from the estimates of savings on page 75, because all options use common vehicles (Shuttle, Titan IV, and MLV) and facilities, and their cost overruns (if any) maybe correlated. OTA has not attempted to estimate these correlations and their resultant savings in cost risk.

be adequate for the near-term – representing **growth from 1985 launch rates in all** categories (piloted, light cargo, and heavy cargo) —29 of 161 post-1999 heavy cargo missions in the Low-Growth mission model would have to be cancelled. Because Baseline vehicles and facilities cannot launch all the missions in the Low-Growth mission model, its life-cycle cost for doing so cannot be calculated.

Enhanced Baseline Option

The Enhanced Baseline Option features an improved Shuttle with advanced solid rocket motors (ASRMs), improved Titan IVs with new solid rocket motors and fault-tolerant avionics, MLVs, and an extra Titan IV pad to handle the peak Titan IV launch rate in the Low-Growth mission model (16 per year).

Box 7-2. –Failure Costs

Expected launch vehicle failure costs are the product of the expected failure frequency (calculated from vehicle reliability estimates) and the estimated failure cost per vehicle (based on historical experience). Cost per failure will generally include cost of accident investigation and corrective action. It may include costs of replacing and reflying lost payloads, replacing reusable vehicle components, and delays pending completion of accident investigation.

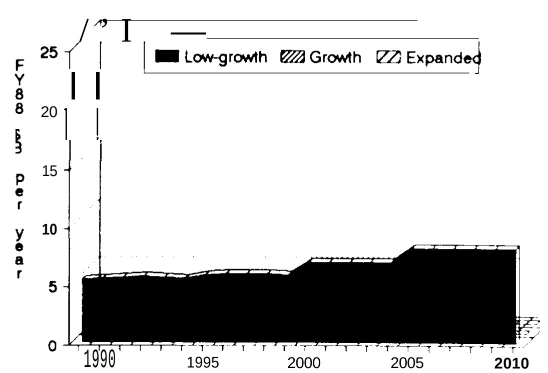
In the Space Transportation Architecture Study (STAS), operations costs were estimated assuming that operations would be continuous (i.e. no “standdowns”), and failure costs were estimated assuming that all lost payloads would be replaced and reflown. The same assumptions were made in this report. Accident 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, since some missions would be cancelled as a result of the delay, life-cycle costs would have to exclude missions not flown.

In addition to calculating expected failure costs, OTA has estimated the expected statistical variations in failure costs. One measure of such variations is the standard deviation of failure costs. A related measure, 1.9 times the standard deviation, is the difference between the expected failure cost and the 70th percentile of failure cost, i.e. the excess failure cost which would be exceeded with a probability of only 30 percent. This cxcess failure cost has been included in OTA’s estimates of cost risk, along with the cost risk as defined in the STAS. For a more detailed discussion of the cost estimation methodology employed in this report, see appendix A.

Enhanced Baseline Option costs are estimated only for the Low-Growth mission model. To fly all missions in the Growth mission model, which has a peak Titan IV launch rate of 30 per year, would require about five new Titan IV pads. As noted in chapter 3, about 14 new Titan IV pads would be needed to launch 66 Titan IVs per year in the Expanded mission model. Because existing launch sites could accommodate at most four new Titan IV pads,[2] and construction of the facilities infrastructure for an additional ten pads would represent a radical rather than incremental change in launch facilities and operations, we assume that the Enhanced Baseline Option – conceived as an evolutionary enhancement — could not accommodate Growth or Expanded peak launch rates.

Figure 7-1 shows the estimated funding profile in 1988 dollars for the Enhanced Baseline Option sized for the Low-Growth mission model. The funding profile is relatively flat. Forty to fifty percent of the annual expenditure is for failure costs; about half of the rest ($1.3B per year) is the fixed cost of improved Shuttle operations.[3] The second largest contributor is the incremental cost of improved Titan IV launches ($95M per launch). The fixed cost of Titan IV operations and the incremental cost of improved Shuttle launches are relatively small. There

Figure 7-1. – Funding Profile for Enhanced Baseline Option



2 This includes one launch pad at Vandenberg Air Force Base, one at Cape Canaveral Air Force Station, and two at Kennedy Space Center,

3 Annual operations costs have a variable component, which depends on the number of launches during the year, and a fixed component, which does not. In this special report, total (fixed plus variable) annual operations costs are defined as recurring costs.

is a barely noticeable hump of development and facility construction costs in the early 1990s. Because fixed costs are such a large fraction of total annual costs, total annual costs increase only about 50 percent as the combined-fleet launch rate doubles between 1989 and 2010.

The funding profile for the Enhanced Baseline Option– and all other options discussed in this chapter—includes expected failure costs but not cost risk. The analysis assumes that operations would continue after failures. Appendix A describes the cost estimation methodology and other assumptions in greater detail.

Table 7-1. – Cost Summary– Enhanced Baseline Option

Life-cycle cost in FY88 $B	
- discounted 570 per year:	$83B
- undiscounted:	$150B
Peak funding rate and year	
- in FY88 $	$8B in 2005
- in current $	$21B in 2010

Interim Option with Titan IV

The Interim Option with Titan IV assumes that the United States could build as many new Titan IV launch facilities as are necessary to accommodate the peak launch rate for each mission model. Note that here, and in the options that follow, OTA has named the option according to the largest cargo system in the option. Although each option actually supports a mixed fleet of vehicles, this option, for example, includes existing facilities and launch vehicles that are now operational or in production (the Shuttle, Titan IVs with new solid rocket motors, and MLVs).

Figure 7-2 shows estimated funding profiles for this option for all three OTA mission models. The funding profile for the Low-Growth mission model is relatively flat, with expected failure costs consuming almost half the annual expenditures, and with fixed costs of Shuttle operations taking up almost half of the remainder. The second largest contributor is the incremental cost of Titan IV launches ($100M per launch). The fixed cost of Titan IV operations and the incremental cost of Shuttle launches are relatively small. There is a barely noticeable hump of facility construction costs for the Low-Growth model, and greater increases in the Growth and Expanded mission models, but no development costs. As in the Enhanced Baseline Option, fixed costs are a large fraction of total annual costs, therefore total anual costs hardly change as the combined-fleet launch rate doubles between 1989 and 2010 in the Low-Growth mission model and only double as the launch rate more than quadruples — and as the heavy cargo launch rate increases tenfold – in the Expanded Mission Model.

This option assumes that additional on-shore or off-shore Titan IV launch sites can be found that are acceptable in terms of safety, security, and environmental impacts and risks, and that these pads can be built at a cost comparable to the cost of new Titan IV pads at Vandenberg Air Force Base or Kennedy Space Center. This assumption is most critical for the Expanded mission model,

Figure 7-2.– Funding Profiles for Interim Option with Titan IV

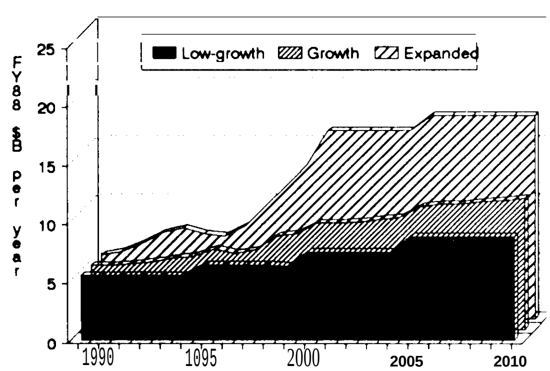


Table 7-2. – Cost Summary– Interim Option with Titan IV

	mission model		
Life-cycle cost (1989-2010) in FY88 $B	Low Growth	Growth	Expanded
- discounted 5% per year:	$87B	$100B	$150B
- undiscounted:	$150B	$180B	$270B
Peak funding rate and year			
- in FY88 $ per year	$8.7B in 2005	$11B in 2010	$17B in 2005
- in current $ per year	$22B in 2010	$29B in 2010	$45B in 2010

which will require the most new sites. OTA has not examined the reasonableness of these assumptions,[4] but, as mentioned in the Enhanced Baseline Option, we note that there is little room at Vandenberg for expansion.

Interim Option with Titan V

The interim Option with Titan V features the Titan V – a proposed heavy-lift (100,000-pound class) launch vehicle derived from the Titan IV; it also includes unimproved Shuttles, MLVs, unimproved Titan IVs (until Titan Vs became operational in 1996), and additional launch facilities as required to fly all missions.

Figure 7-3 shows the estimated funding profiles for the interim Option with Titan V in the Low-Growth, Growth, and Expanded mission models, in fiscal year 1988 dollars. The investment costs are comparable to those of the Interim Option with Titan IV. Titan Vs could use converted Titan IV pads. This analysis assumes that for $500M all Titan IV pads could be modified to launch Titan Vs at a maximum annual launch rate of 12 per year, the assumed current maximum annual Titan IV launch rate.

The out-year costs, also comparable to those of the Interim Option with Titan IV, are attributable largely to the incremental cost of

Figure 7-3. – Funding Profiles for Interim Option with Titan V

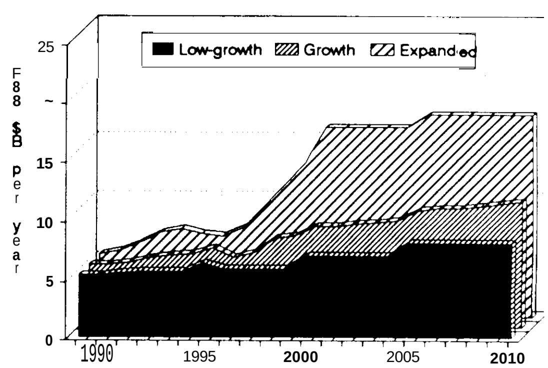


Table 7-3. – Cost Summary– Interim Option with Titan V

	mission model		
Life cycle cost (1989-2010) in FY88 $B	Low Growth	Growth	Expanded
- discounted 570 per year:	$85B	$98B	$140B
- undiscounted:	$150B	$180B	$270B
Peak funding rate			
- in FY88 $ per year	$8.1B in 2005	$11B in 2010	$17B in 2005
- in current $ per year	$21B in 2010	$27B in 2010	$44B in 2010

4 It should be noted that off-shore options might require additional infrastructure to handle hazardous fuels or provide transportation to an off-shore location.

Titan V launches, which is estimated as $160M per launch –60 percent greater than that of Titan IV, although 20 percent fewer launches would be required to fly payloads off-loaded from Titan IVs. The fixed annual cost of Titan V launches is also estimated to be substantial –about $270M per year, as compared to $200M per year for Titan IV.

Interim Option with Shuttle-C

The Interim Option with Shuttle-C features the expendable Shuttle-C cargo vehicle proposed by NASA and includes unimproved Shuttles, MLVs, unimproved Titan IVs (until Shuttle-C is operational in 1995), and additional launch facilities as required to fly all missions. Figure 7-4 shows the estimated funding profiles for the Interim Option with Shuttle-C in the Low-Growth, Growth, and Expanded mission models, in 1988 dollars.

These profiles show a modest early hump of investment in Shuttle-C development—$1.2B over 6 years – and construction of additional Shuttle pads, which Shuttle-C could use with minimal modification (not costed here). They also show high annual costs in the out-years, especially at high cargo launch rates. The high annual out-year cost is attributable primarily to the high estimated incremental operations cost of Shuttle-C: about $235M per launch, less savings realized by using depreciated Space Shuttle Main Engines (SSMEs), which NASA will no longer fly on the Shuttle.[5] By replacing Titan IV, Shuttle-C launches would outnumber Shuttle launches in all the mission models, so savings from flying depreciated SSMEs would be small.[6] In the out-years of OTA's mission models, the estimated incremental cost per Shuttle-C flight would exceed fourfold that of Shuttle, twice that of Titan IV, and sevenfold

Figure 7-4. – Funding Profiles for Interim Option with Shuttle-C

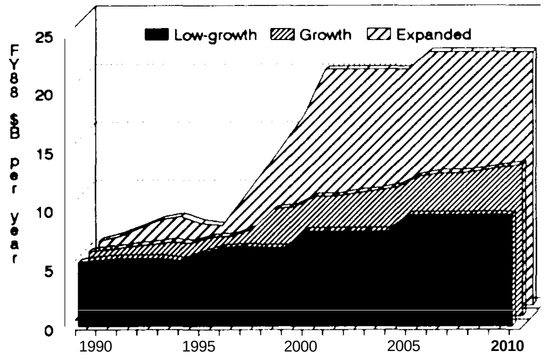


Table 7-4.– Cost Summary– Interim Option with Shuttle-C

	Mission model		
Life-cycle cost (1989-2010) in FY88 $B	Low Growth	Growth	Expanded
- discounted 5% per year:	$92B	$110B	$170B
- undiscounted:	$160B	$200B	$330B
Peak funding rate			
- in FY88 $ per year	$9.4B in 2005	$13B in 2010	$22B in 2005
- in current $ per year	$24B in 2010	$33B in 2010	$55B in 2010

5 A new SSME costs about $40 million. Boeing assumed that SSME lifetime on the Shuttle would increase from 10 flights (ea. 1985) to 20 flights (1989-1995), and 40 flights (post-1995). Based on this assumption, Boeing estimated that the equivalent of four fully depreciated SSMEs would be available in 1989, when the OTA mission models begin. NASA has assumed a 10-flight lifetime. Assuming a shorter engine life reduces the estimated cost per Shuttle-C flight; this should be reflected in higher cost per Shuttle flight. The actual cost difference resulting from the diverging assumptions is not great (see appendix A).

6 The SSME credit would be only $2M per flight in the out-years of the Low-Growth mission model,5 or $0.5M in the out-years of the Expanded mission model.

Box 7-3. - Shuttle-C Low-Launch-Rate Option

At only three launches a year, Shuttle-C could simplify and improve Space Station assembly by launching outfitted Space Station modules too heavy for the Shuttle or Titan IVs to carry. It could provide redundant means of launching heavy cargo and hence increase operational flexibility. OTA has estimated the costs of using Shuttle-C for only three launches a year after 1994, and using Titan IVs and the Shuttle fleet for other traffic. OTA assumed that in each year after 1994:

- Shuttle-C would replace the Shuttle on 20 percent of the Shuttle flights in the [non-HLLV] mission models.
- The remaining Shuttle-C flights (0,6-1.4per year) would carry cargo offloaded from Titan IVs; four Shuttle-C flights would replace five Titan IV flights.
- MLV flights would be reduced by 30 percent of the heavy cargo vehicle flights in the mission model which are flown by Shuttle-C (i.e., not counting the flights on which Shuttle-C substitutes for the Shuttle).

This option would require more investment than would the Titan IV or Shuttle-C options, because both a Shuttle-C and another cargo vehicle would be needed. However, it would have essentially the same discounted life-cycle cost – no more than about 1 percent greater in any mission model. Hence although Shuttle-C would not be cost-effective as the primary U.S. heavy-lift launch vehicle, it could provide useful flexibility– especially for selected NASA missions– at a small premium in life-cycle cost.

Cost Summary

Life-cycle cost in FY88 $	Low Growth	Growth	Expanded
- discounted 5% per year:	$87B	$100B	$150B
- undiscounted:	$150B	$180B	$280B
Peak funding rate			
- in FY88 $ per year	$8.2B in 2005	$10B in 2010	$16B in 2005
- in current $ per year	$21B in 2010	$27B in 2010	$42B in 2010
Comparision with Titan IV			
- extra nonrecurring cost	$860M	$900M	$900M
- extra life-cycle cost	$460M	$690M	$1.7B

that of the Advanced Launch System.[7] Most of the costs are not engine-related; they include the costs of the payload module ($55M, including payload cradles), the boattail in which the engines are mounted ($55 M), and other parts ($56M, including an external tank). No costs of using, recovering, and refurbishing Orbital Maneuvering Vehicles (OMVs) for docking Shuttle-C to the Space Station are included.

In this option, Shuttle-C is assumed to be the Nation's primary heavy cargo vehicle; this contrasts with NASA’s proposal that Shuttle-C be used only for a few selected missions, such as Space Station deployment. NASA concedes that an expendable Shuttle-C would not be economical at high launch rates; partially reusable versions, which have been considered by NASA and the Air Force, might be. The box “Shuttle-C Low-Launch-Rate Option” estimates costs for an option in

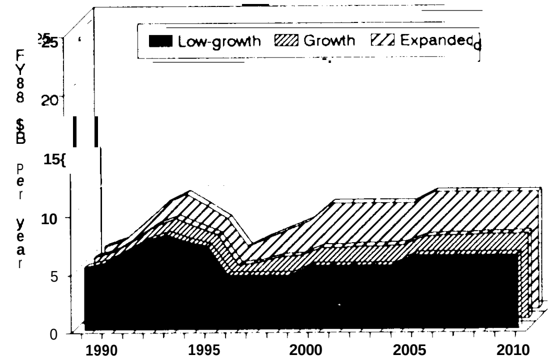
7 See appendix A.

which Titan IVs would launch most heavy cargo, and Shuttle-C would be launched only three times per year beginning in 1995. This option is less expensive than the Interim Option with Shuttle-C and competitive with the Interim Option with Titan IV. At essentially the same life-cycle cost of the Titan IV option, Shuttle-C could simplify Space Station assembly by launching outfitted Space Station modules too heavy for the Shuttle or Titan IVs to carry. **Hence Shuttle-C appears economical for selected missions (i.e, Space Station module launches) but does not compare well as the principal U.S. heavy-lift launch vehicle.**

Interim Option with Transition Launch Vehicle

The Interim Option with Transition Launch Vehicle features a proposed partially reusable unpiloted launch vehicle with recoverable engines that burn liquid hydrogen and oxygen; for reliability, it uses no solid-fuel engines. The option also includes unimproved Shuttles, MLVs, unimproved Titan IVs (until they are superseded by Transition vehicles in 1996), and additional launch facilities as required to fly all missions. Figure 7-5 shows the estimated funding profiles for the Interim Option with Transition Launch Vehicle in the Low-Growth, Growth, and Expanded mission models, in 1988 dollars.

Figure 7-5.– Funding Profiles for Interim Option with Transition Launch Vehicle



These profiles show higher and longer investment humps than for Shuttle-C, but very little growth in out-year costs, even while launch rates double (in the Low-Growth mission model) or more than quadruple (in the Expanded mission model). Although the initial investment is greater for this launch option, its life-cycle cost is relatively low. Average launch cost (life-cycle cost divided by total number of launches) is especially low at high launch rates, because it is assumed that the early investment has resulted in very low incremental costs ($54 M) for launches.

Advanced Option with Advanced Launch System

This option features the Advanced Launch System design proposed by Boeing Aerospace Company for launching large cargo payloads economically at high launch rates. It also includes the Shuttle, MLVs,

Table 7-5. – Cost Summary– Interim Option with Transition Launch Vehicle

	mission model		
Life-cycle cost (1989-20111 in FY88 $B	Low Growth	Growth	Expanded
- discounted 5% per year:	$81B	$87B	$l10B
· undiscounted:	$130B	$150B	$190B
Peak funding rate			
- in FY88 $ per year	$8.2B in 1993	$8.7B in 1993	$10B in 2005
· in current $ per year	$16B in 2010	$19B in 2010	$26B in 2010

unimproved Titan IVs (until replaced by the Advanced Launch System in 20008), and additional launch facilities as required to fly all missions.

The Advanced Launch System program has not yet selected a vehicle design, but designs currently under consideration include vehicles capable of launching payloads substantially heavier than 50,000 pounds. The cost estimates quoted in this section refer to a partially reusable vehicle featuring a flyback booster burning liquid oxygen and hydrocarbon propellants; a core stage with expendable tanks and payload fairing; and a recoverable payload/avionics module with engines that burn liquid oxygen and hydrogen. OTA's selection of this vehicle for purposes of cost estimation should not be construed as an endorsement of this particular configuration. OTA did not examine all proposed vehicles.

Figure 7-6 shows the estimated funding profiles for the Advanced Option with Advanced Launch System in the Low-Growth, Growth, and Expanded mission models. These profiles show substantial investment humps even for the Low-Growth mission model, but low out-year costs that grow little with increasing heavy cargo traffic. Compared to the Shuttle II option, the Advanced Launch System option is much more economical because its new vehicle is optimized for carrying heavy cargo to orbit, not for piloted sorties or return of cargo.

This analysis makes the key assumption that the incremental cost of ALS operations will be $33M per launch – much lower than that of Titan V ($160M) or Shuttle-C (about $235 M), and just under 1/3 that of Titan IV ($100M). The ALS program is required by law[9] to seek to lower recurring launch cost per pound by a factor often compared to current ELV launch costs, which were assumed to be about $3000 per pound to low-Earth orbit in 1987 dollars. An ALS launch vehicle must be able to lift 110,000 pounds to low-Earth orbit to fulfill this goal, if its incremen-

Figure 7-6. – Funding Profiles for Advanced Option with Advanced Launch System

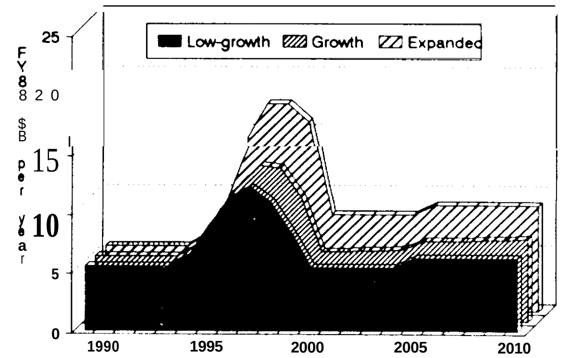


Table 7-6. - Cost Summary-Advanced Option with Advanced Launch System

	mission model		
Life-cycle cost (1989-2010) in FY88 $B	Low Growth	Growth	Expanded
- discounted 5% per year:	$89B	$95B	$120B
- undiscounted:	$150B	$160B	$200B
Peak funding rate			
- in FY88 $ per year	$llB in 1997	$12B in 1998	$16B in 1998
- in current $ per year	$17B in 1997	$19B in 1998	$24B in 1999

8 Boeing assumed an initial launch capability of 1996; OTA considers 2000 more plausible. A sensitivity analysis indicates that the rank order of option costs is insensitive to the change.

9 Public Law 100-180, Department of Defense Authorization Act, 1988/1989, Sec. 256 (101 Stat. 1066).

tal launch cost is $33M per launch. However, it is unclear that there would be many payloads or feasible combinations of payloads that large. As a result, actual cost savings could be much smaller than the theoretical maximum savings.

The uncertainties in estimates of Advanced Launch System costs are particularly high because of the uncertainty about which vehicle configuration would be selected. To indicate the impact of selecting a different configuration on the cost of this option, OTA also estimated the cost of an Advanced Launch System featuring an expendable launch vehicle with a lower development cost, no cost of procuring reusable elements, a lower fixed annual operations cost, but a higher incremental cost per launch. OTA assumed this option would be available earlier (1996 v. 2000) at lower cost risk. Its payload deployment reliability is estimated to be slightly lower, but it need not be recovered and therefore has no risk of failure during recovery. This and other cost estimates, are discussed in the section on "Alternative Cost Estimates."

Advanced Option with Shuttle II

The Advanced Option with Shuttle II features a proposed fully reusable piloted launch vehicle derived from the current Shuttle. Although Shuttle 11 is not a firm concept, this analysis assumes that it can carry payloads comparable to those carried by the Shuttle and that it will replace the Shuttle in the year 2000. This option also includes unimproved Titan IVs, MLVs, and additional launch facilities as required to fly all missions.

Figure 7-7 shows the estimated funding profiles for the Advanced Option with Shuttle 11 in the Low-Growth, Growth, and Expanded mission models. Each profile shows a prominent hump of spending for Shuttle 11 development and facilities from 1994 to 1999. These calculations assume that expenditures for Shuttle II development and facility construction would be delayed until 1994 and completed in 1999 so that Shuttle II could be launched in 2000. Shuttle 11 could use converted rather than new pads. This analysis assumes that for $lB all Shuttle pads could be modified to launch Shuttle 11 vehicles at a

Figure 7-7. – Funding Profiles for Advanced Option with Shuttle 11

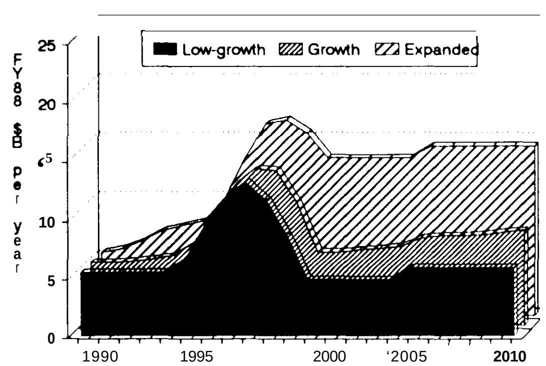


Table 7-7. – Cost Summary– Advanced Option with Shuttle II

	mission model		
Life-cycle cost (1989-2010) in FY88 $B	Low Growth	Growth	Expanded
- discounted 570 per year:	$89B	$1OOB	$150B
- undiscounted:	$150B	$170B	$270B
Peak funding rate			
- in FY88 $ per year	$13B in 1997	$13B in 1997	$17B in 1998
- in current $ per year	$19B in 1997	$21B in 2010	$37B in 2010

maximum combined annual launch rate of 16 per year, the maximum Shuttle launch rate sustainable with current facilities, in Boeing's estimate. The profiles for the Growth and Expanded mission models show smaller humps of earlier spending (1989-1994) for Titan IV launch facilities.

Compared to the Interim Options with Titan IV or Titan V, the out-year costs of the Shuttle II option are lower, because the fixed annual operations cost of Shuttle II would be much lower than that of the Shuttle, which it would replace, and the expected failure cost of Shuttle II would be lower because it is expected to be more reliable than the Shuttle. Annual operations cost would be reduced by the same amount in all three mission models, because the mission models differ only in launch rates for heavy cargo vehicles.

Although OTA's analysis assumes Shuttle 11 to be much more economical than the current Shuttle, the Advanced Option with Shuttle 11 would not be as economical as other options, because of the predominance of cargo traffic in OTA's mission models. Only the Shuttle-C option would be more expensive. If demand for piloted flights were to increase and demand for cargo launch were to decrease, the Advanced Option with Shuttle 11 could become more economical than the other options considered here. In any case, **sometime early in the next century, the current Shuttle will begin to exceed its useful lifetime or will become obsolete. At this point, a replacement for the current Shuttle will be necessary whether or not it is competitive at launching cargo with then existing or planned cargo vehicles.**

COMPARISONS

Cost Comparison

The histogram in Figure 7-8 compares the expected life-cycle cost and cost risk of each option in 1988 dollars discounted at 5 percent, for the Low-Growth mission model. The bottom portion of each bar represents the expected life-cycle cost, excluding failure costs. The middle portion of each bar represents the expected cost of failures. The to portion of each bar represents the cost risk.[11] The figure shows that at Low-Growth launch rates, no option promises savings with confidence, and that cost is relatively insensitive to choice of option. Figures 7-9 and 7-10 are similar comparisons for the Growth and Expanded mission models, respectively. Figure 7-10 shows that in the Expanded mission model, clear-cut savings are possible with some options, while other options would be wasteful. That is, cost is more sensitive to choice of option at Expanded launch rates than at Low-Growth launch rates.

Figure 7-11 is a superposition of figures 7-8, 7-9, and 7-10, showing the sensitivities of cost to mission model as well as to choice of option.

These cost comparisons suggest the following conclusions:

- Low **Growth:** If the future U.S. space program resembles the Low-Growth mission model considered here, then it is not possible to distinguish meaningfully among the options examined. Uncertainties of cost estimation obscure the small estimated differences in savings be-

10 NASA estimates a maximum sustainable Shuttle launch rate of 14 per year; OTA's mission models assume no more than 12 Shuttle flights per year.

11 The cost risk in dollars is the cost risk in percent, divided by 100, times the expected cost of the option.

Figure 7-8. – Cost Comparison – Low-Growth Mission Model

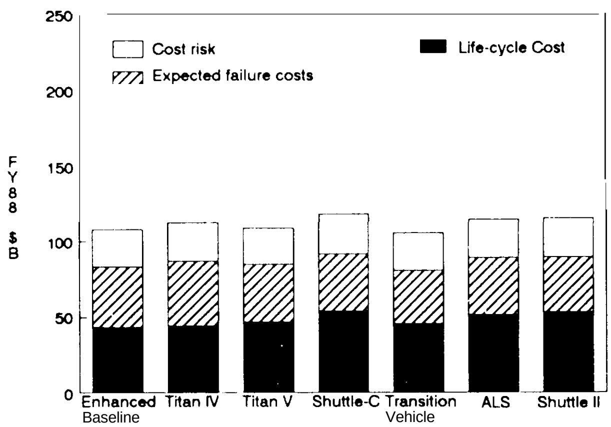


Figure 7-9.– Cost Comparison – Growth Mission Model

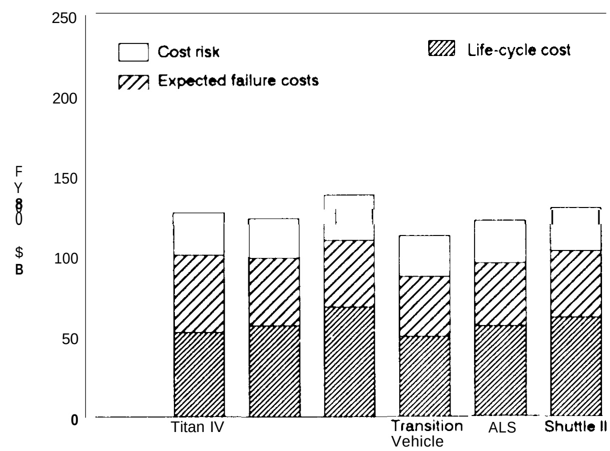


Figure 7-10. – Cost Comparison – Expanded Mission Model

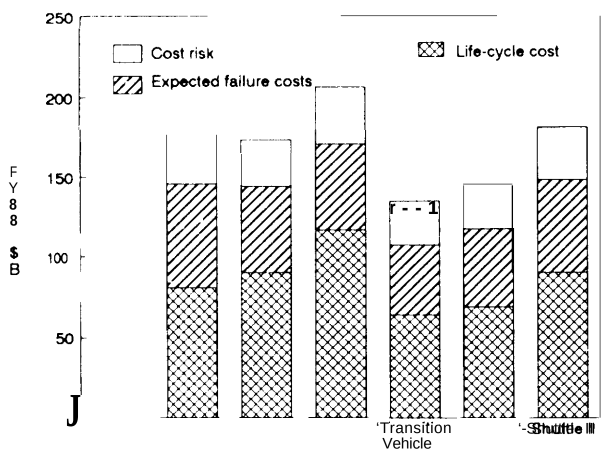
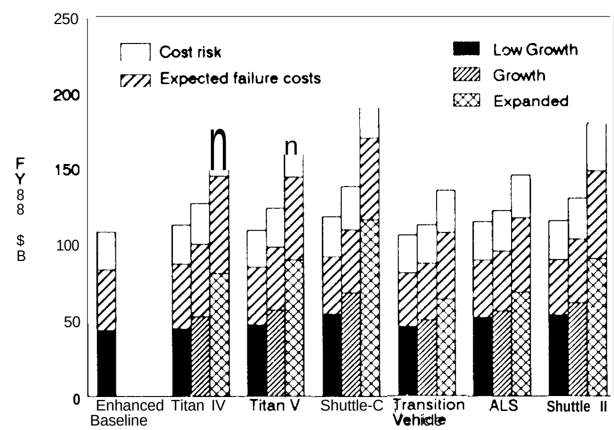


Figure 7-11.– Cost Comparison –All Mission Models



tween the options. In short, at Low-Growth launch rates, life-cycle cost is insensitive to choice of option and is unlikely to be reduced significantly by any option OTA considered. Development of a new cargo vehicle would, however, present an opportunity to increase the reliability of cargo delivery.[12] This would also increase the operational availability and resiliency of launch systems without requiring that downtimes after failures be reduced. It would increase the probability of access to space and hedge against a greater than expected growth in launch demand in the late 1990s. If continuation of piloted spaceflight were of paramount importance, a Shuttle II might be appropriate.

- **Growth:** If the U.S. space program expands to resemble the Growth mission model, then Transition Launch Vehicles would seem to be the best choice. The other options — except use of Shuttle-C as the primary cargo vehicle —would be economically competitive, though here again estimated differences in savings are obscured by uncertainties of cost estimation. The Transition Launch Vehicle or Advanced Launch System options could maximize the reliability of cargo delivery.

12 Increases in reliability are limited by probabilities of human error and catastrophic component failures not avoidable through redundancy.

- **Expanded: For a greatly expanded launch demand, the Transition Launch Vehicle option** or an Advanced Launch System would be appropriate. These options have the lowest estimated life-cycle costs, and their primary cargo vehicles are intended to provide greater reliability of cargo delivery.

Trade-Off's Between "Up-Front" and "Out-Year" Costs

In addition to choosing which technologies and launch vehicles to pursue, Congress must also determine the most appropriate plan for funding these capabilities. Much has been written about how restrictions on the "up-front" Shuttle development costs resulted in the current high operations costs.[13] The Administration and the Congress now face similar trade-offs between reducing the up-front costs of developing the next generation of launch vehicles and facilities reducing the "run out" costs of operating them. One way to illustrate the trade-offs available is to show the potential savings, relative to that of a reference option, obtainable by investing in development, facility construction, and fleet **procurement for the other options. For each mission model, table 7-8 shows the expected** investment required to fly all missions with each option and the expected potential savings in discounted life-cycle cost relative to the Interim Option with Titan IV. Cost risk is not included in the calculation of life-cycle costs.[14]

The table shows that at Low-Growth traffic levels, the Transition Vehicle, Enhanced Baseline, and Titan V options are expected to yield savings that are at most a small fraction of the cost risk of each option. The Enhanced Baseline Option is expected to have the greatest cost leverage (savings to investment ratio). Some options would require greater investment *and* save less money, if any. At traffic levels reflective of the Growth model, the Transition Vehicle, Titan V, and Advanced Launch System options are all expected to yield savings. At the high cargo launch rates of the Expanded mission model, the Titan V, Transition Vehicle, and Advanced Launch System options are expected to yield savings. Because estimates of cost and savings are both quite uncertain, small differences in the estimates should not be regarded as meaningful.

13 See, for example, John Logsdon, "The Decision to Develop the Space Shuttle," Science, vol. 232, May 1986, pp. 1099-1 105; NASA, Technology Influence on Space Shuttle Development (Houston, TX: NASA JSC, June 8, 1986); and Boeing Aerospace Operations, Shuttle Ground Operations Efficiencies/Technologies Study, May 4, 1987.

14 Cost risk is not included in the calculation of life-cycle costs, because correlations among errors in estimates of non-recurring and recurring costs of different options must be known to calculate the cost risk of savings; it cannot be calculated simply by subtracting the cost risk of each option from the cost risk of the Interim Option with Titan IV,

Table 7-8. –Trade-offs: Investment versus Savings

Mission Model	Option	Nonrecurring Cost [a]	Savings or (Loss)[a,b]
Low-Growth	Enhanced Baseline	$1.2B	$3.5B
	Interim option with		
	Titan IV	$0.39B	$0B
	Titan V	$1.7B	$2.2B
	Shuttle-C	$1.3B	($4.8B)
	Transition Vehicle	$8.OB	$6.2B
	Advanced option with		
	Advanced Launch System	$14B	($2.lB)
	Shuttle II	$17B	($2.7B)
Growth	Interim option with		
	Titan IV	$2.OB	$OB
	Titan V	$3.OB	$2.0B
	Shuttle-C	$2.6B	($9.3B)
	Transition Vehicle	$9.3B	$13B
	Advanced option with		
	Advanced Launch System	$15B	$4.7B
	Shuttle II	$18B	($2.7B)
Expanded	Interim option with		
	Titan IV	$6.4B	$OB
	Titan V	$6.5B	$0.91B
	Shuttle-C	$6.lB	($25B)
	Transition Vehicle	$13B	$38B
	Advanced option with		
	Advanced Launch System	$18B	$28B
	Shuttle II	$23B	($2.7B)

[a] In Fiscal Year 1988 dollars
b Relative to the Interim Option with Titan IV.
SOURCE: OTA and Boeing Aerospace Co.

ALTERNATIVE COST ESTIMATES

As noted earlier, the cost estimates quoted above are based in part on cost-estimating relationships (CERs) developed by Boeing Aerospace Company in the course of its work on the Space Transportation Architecture Study and the Advanced Launch System program, modified by OTA's and Boeing's estimates of reliability, failure cost, and cost risk. Two reviewers suggested alternative CERs, which in some cases, differ significantly from those provided by Boeing. Using these alternative CERs, OTA produced two alternative estimates of life-cycle cost.

Figure 7-12 shows the range spanned by the nominal and alternative estimates of option life-cycle costs (including failure costs and cost risk). Estimates for the Interim Option with Shuttle-C at Expanded launch rates lead to the greatest cost discrepancy. Estimates for the Interim Option with Titan IV also span a large range at Expanded launch rates.

The differences between estimates for most options are comparable to the cost risk of the option as estimated by OTA and Boeing (see figure 7-1 1).

Figure 7-12. – Ranges of Estimated Costs