Appendix A

Cost Estimation Methodology

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Appendix A

Cost Estimation Methodology

SOURCES OF COST ESTIMATES

The nominal cost estimates quoted in chapter 7 were derived by OTA using data, estimates, and estimation methods developed by the Boeing Aerospace Company for the Space Transportation Architecture Study (STAS) and the Advanced Launch System program. OTA adjusted Boeing's estimates of failure costs for consistency with estimates of operations costs; OTA also estimated parameters not estimated by Boeing: cost risk (defined below) and reliabilities of 1) unmodeled systems (e.g. humans, weather) during ascent and payload deployment and 2) recovery of reusable vehicle systems.

The cost-estimating formulae developed by Boeing and used by OTA were reviewed by NASA, the Air Force, and the major launch vehicle producers. Several reviewers suggested important additions or corrections, and two suggested alternative formulae for estimating the costs of developing, producing, and launching some of the launch vehicles considered. Tables A-5 and A-7 summarize the formulas and the alternative suggestions. Using the alternative cost-estimating formulae proposed by the reviewers, OTA produced two alternative estimates of the life-cycle cost of each option in each mission model. These are tabulated in tables A-6 and A-8, along with estimates of failure cost and cost risk estimated by OTA. The ranges spanned by the OTA estimates and these alternative estimates are shown in figure 7-12.

COMPONENTS OF COST ESTIMATES

The major categories of costs are non-recurring and recurring costs. Non-recurring costs (investment) include costs of system design, development, testing, and evaluation (DDT&E), launch facility construction, and production of reusable flight hardware (e.g., Shuttle orbiters). Recurring costs include costs of planned operations and the expect cd costs of failures (including unplanned reflights). Table A-1 shows the cost-estimating relationships (CERs) used to estimate the costs of development, facilities, fleet procurement, and operations for each option.

DDT&E, Facility, & Fleet Production Costs

Incremental costs of new facilities are estimated as $150M per unit increase in annual launch rate capability above the current annual launch rate capability. This is roughly the cost of a new pad divided by the annual launch rate capability of a new pad. Actual costs of facilities must be incurred in larger increments – per pad, not per unit increase in annual launch rate capability.

Because they could usc converted rather than new pads, Shuttle 11 and Titan V are assumed to have lower incremental costs of facilities for the first several units of annual launch rate capability: about $63M and $42M, respectively, per unit increase in annual launch rate capability to 16 per year for Shuttle II and 12 per year for Titan V. More precisely, it is assumed that for $lB all Shuttle pads could be modified to launch Shuttle II vehicles at a maximum annual launch rate of 16 per year. Similarly, it is assumed that for $500M all Titan IV pads could be modified to launch Titan Vs at a maximum annual launch rate of 12 per year. Additional Shuttle 11 or Titan V pads are assumed to cost $150M per unit increase in annual launch rate capability.

Non-recurring expenditures for DDT&E or facilities were assumed to be spread over a six-year period with 4 percent of the undiscounted cost incurred in the first year, 13 percent in the second year, 23 percent in the third year, 28 percent in the fourth year, 22 percent in the fifth year, and 10 percent in the sixth year. Spending on DDT&E for a vehicle ends the year before the assumed date of its initial launch capability (ILC). Spending on facility construction ends the year before an increased launch rate capability is required to fly all flights in the mission model.

In many types of serial production, the cost of producing an additional unit (the incremental unit cost) is lower than the cost of producing the previous unit. This effect is called the learning effect. The estimates of reusable element production costs in Table A-1 assume no learning.

Table A-l.– Nominal Cost-Estimating Relationships

Costs in Fiscal Year 1988 Dollars

Fleet	Dev.	Fac.	Limit	Prod.	Operations[a] per year	Operations[a] per launch
Shuttle	0	x	16/yr	0	$1,336M	$53M
Improved Shuttle	$0.6B	x	16/yr	0	$1,336M	$43M
Shuttle 11	$12B	$lB + X	16/yr	3 X $1,500M	$59M	$33M
Shuttle-C	$1.2B	X	16 - STS	0	0	$236M - C
MLV	0	N/A	12 +/yr	0	0	$35M
Titan IV	0	x	12/yr	0	$200M	$100M
Improved Titan IV	$0.4B	x	12/yr	0	$200M	$95M
Titan V	$1.2B	$0.5B + X	12/yr	0	$267M	$157M
Transition Vehicle	$3.9B	x	0	3 x $11OM	$228M	$54M
ALS	$9.5B	x	0	4 X $425M	$241M	$33M

Dev.: development cost.
Fac,: launch facility conversion or construction cost.
Limit: maximum annual launch rate attainable without new facilities.
Prod.: cost of producing reusabIe elements.
X: $0.15B per unit increase in annual launch rate limit.
C: SSME credit: $80M if both SSMEs have flown on Shuttles until fully depreciated; pro-rated otherwise. A new SSME is assumed to cost $40M; its allowed lifetime on the Shuttle is assumed to be 10 flights until 1989, 20 flights from 1989 to1995, and 40 flights thereafter.
[a]Includes cost of producing expendable elements.

Operations costs

Operations costs include costs of producing expendable flight hardware (e.g., Titan IVs) and costs of planned launch, mission control, and recovery operations. The annual operations cost of an option is the sum of the annual operations costs of each fleet (type of launch vehicle) in the option. Annual fleet operations costs are assumed to have a freed component, which must be paid each year regardless of the fleet launch rate, and a variable component equal to the fleet launch rate times an incremental cost per launch.

Operations costs were estimated using the cost-estimating relationships in Table A-1, which approximate more detailed relationships derived by Boeing Aerospace Company using its proprietary Ground Operations Cost Model. The Boeing model was based on operations cost data supplied by NASA and the Air Force and expendable hardware cost estimates obtained from -Boeing's proprietary Internal Parametric Cost Model.[1]

The cost-estimating relationships in Table A-1 approximate the annual operations cost of each fleet as the sum of a freed annual cost and a variable cost which, except for Shuttle-C, is proportional to the number of launches during the year. The incremental cost per launch (sometimes, imprecisely, called the "marginal" cost per launch) is therefore constant, except for Shuttle-C. The MLV and Shuttle-C fleets were assumed to have no fixed annual cost.

The incremental cost per launch includes the cost of producing expendable hardware. Because the incremental operations cost estimates in Table A-1 are constant (except for Shuttle-C), they reflect no rate effect.[2] Nevertheless, they reflect a decline in average unit cost as the production rate (mirroring the launch rate) is increased, because capital assets are more fully

1 The Boeing Internal Parametric Cost Model is a set of cost-estimating relationships based on costs of Boeing products such as Saturn launch vehicles and the Inertial Upper Stage.

2 In many types of serial production, the incremental unit cost declines when the production rate is increased; this effect is called a rate effect.

utilized and their cost can be amortized over a larger number of units.

Shuttle-C operations cost is a special case, because Shuttle-C vehicles arc assumed to use fully depreciated (i.e. free) Space Shuttle Main Engines (SSMEs) whenever they arc available. An SSME becomes available after it has been used on the Shuttle for a "lifetime" — the maximum number of flights NASA deems safe for piloted missions. This lifetime has varied, and may continue to vary, in response to operational experience. Designed to have a 55-flight lifetime,[3] SSMEs have been qualified for only 20 flights, and NASA has indicated its intention to retire them after only 10 flights.[4,5] Boeing assumed a SSME lifetime of 10 flights (pre-1989), 20 flights (1989-1995), and 40 flights (post-1995). Based on (his assumption, Boeing estimated that the equivalent of four fully depreciated SSMEs would be available at the beginning of the OTA mission models (in 1989), and that eight additional fully depreciated SSMEs would be available by 1995, the assumed year of initial launch capability (ILC) for Shuttle-C.

Boeing assumed that when SSMEs are not available, new SSMEs will be purchased for Shuttle-C at an estimated cost of $40M each. Without the SSME credit (which would be only $2M per flight in the out-years of the Low-Growth mission model, or $0.5M in the out-years of the Expanded mission model), the incremental operations cost of Shuttle-C would be $236M per launch –over four times the assumed incremental operations cost of the current Shuttle, over twice the assumed incremental operations cost of Titan IV, and over seven times the assumed incremental operations cost of the Advanced Launch System. Non-engine-related incremental costs of Shuttle-C include $55M for the payload module (including payload cradles), $55M for the boattail, and $56M for other parts. No costs of using, recovering, and refurbishing Orbital Maneuver Vehicles (OMVs) for docking Shuttle-C to the space station arc included.

Costs **of Failures**

Operations costs estimated by OTA include expected costs of failure. These are not included in the operations CERs of Table A-1, but must be calculated separately using estimates of vehicle reliabilities and expected cost per failure of each type of vehicle. Costs of failure include costs of replacing the launch vehicle and payload, attempting to determine and correct the cause of failure, and the costs of downtime (e.g., salaries and wages for launch vehicle and payload operation and maintenance personnel).

The expected failure cost per flight for each type of vehicle is the product of the probability of failure (in a single launch attempt) and the expected cost per failure for that type of vehicle. Multiplying this product by the number of flights to be attempted with that type of vehicle in a particular year yields the expected annual failure cost for that fleet in that year. Adding the expected annual failure costs of all other fleets in an option yields the annual failure cost expected for the option, which is a component of the funding profiles exhibited in chapter 7. It is also multiplied by a discount factor to obtain the discounted annual failure cost for the option. The discounted failure costs for each year in the mission model arc then added to obtain the present value of failure costs for the option, which is shown in figures 7-8– 7-11.

Reliability estimation: The most difficult and least credible part of this procedure is estimating the probability of failure for each vehicle. This is particularly true for proposed vehicles that have not been fully designed, much less built, tested, and flown. The only completely objective method of estimating a vehicle's probability y of failure is by statistical analysis of t he number of failures observed in actual launches of identical vehicles under conditions representative of those under which future launches will be attempted. Such an analysis cannot ascertain the reliability with perfect accuracy and confidence, but it can determine, for example, that the reliability is within a certain range of possible values (called a confidence interval) with a corresponding statistical confidence.[6] As more launches are observed, the confidence interval corresponding to a given confidence level becomes narrower (i.e., the reliability is known with greater accuracy), and the confidence level corresponding to a given confidence interval becomes greater (i.e., the reliability is known with greater confidence). However, a large number of launches must be observed to confirm that reliability is high with high confidence,

For example, if one failure were observed in 1000 attempted launches, one could conclude that the reliability was 99.3 percent with 99.3 percent confidence. One would not be justified in concluding that the reliability was the observed success rate (99.9 percent). If one required confirmation of 99.9 percent

3 NRC, Assessment of Constraints on Space Shuttle Launch Rates (Washington, DC: National Academy Press, April 1983), p. 22.

4 Dale D. Myers, Deputy Administrator, NASA, letter to Robert K. Dawson, Associate Director for Natural Resources, Energy and Science, EOP, OMB, January 26,1988.

5 As lifetime decreases, Shuttle costs rise and Shuttle-C costs fall.

6 Y. Fujino, Biometrika vol. 67, no. 3, 1980, pp. 677-681; C.R. Blyth & H.A. Still, Journal of the American Statistical Association, vol. 78, no. 381, March 1983, pp. 108-116.

reliability (or better) with 99.9 percent confidence (or better), there must be no failures in 6905 attempted launches; but there would be a 99.9 percent chance of at least one failure in any series of 6905 launch attempts if the vehicles were 99.9 percent reliable. Hence it would be virtually impossible to demonstrate 99.9 percent reliability in a flight test program.

Hence although this method may provide useful, objective information about the reliability of vehicles with long operational histories, using it to confirm the estimated reliabilities of new vehicles before they become operational would require a prohibitively long flight test program. And of course strict statistical estimation cannot be used at all to estimate the reliabilities of vehicles not yet built.

The **design reliability** of proposed vehicles is generally estimated using:

- data from laboratory tests of vehicle systems (e.g., engines and avionics) and components that have already been built;
- engineers' judgments about the reliability achievable in systems and components that have not been built;
- analyses of whether a failure in one system or component would cause other systems and components, or the vehicle, to fail; and
- assumptions (often tacit) that:
  - the laboratory conditions under which systems were tested precisely duplicate the conditions under which the systems will operate,
  - the conditions under which the systems will operate are those under which they were designed to operate,
  - the engineers' judgments about reliability are correct, and
  - the failure analyses considered all circumstances and details that influence reliability.

Such "engineering estimates" of design reliability are incomplete and subjective. However, the subjectivity and uncertainty often are not exhibited. There are methods for assessing and exhibiting the uncertainties of experts called upon to estimate reliabilities of components,' and probabilistic risk assessment (PRA) methods for estimating risks posed by unreliability, considering the uncertainties in the estimates of components' reliabilities.[8] However, it is more difficult and time-consuming to use them than to provide a single "best estimate" of reliability showing no uncertainty, so the latter has been standard engineering practice except for tasks – such as safety analysis of nuclear reactors — for which the increased rigor has been deemed worth the effort.[9]

In the wake of the Challenger accident, the National Research Council Committee on Shuttle Criticality Review and Hazard Analysis Audit has recommended that NASA use probabilistic risk assessment methods to assess Space Transportation System risks and hazards quantitatively, even if partially subjectively. Some PRA methods (e.g., Bayesian methods[10]) are well-suited for reliability estimation throughout a vehicle's life cycle, because they allow reliability of unbuilt components of proposed vehicles to be estimated subjectively— but quantitatively— at first, on the basis of engineering judgement, and they allow these estimates to be adjusted later, in a logically consistent manner, on the basis of laboratory tests of components and, later still, on the basis of vehicle flight experience. Probabilistic risk assessment methods also make subjectivity and uncertainties explicit and auditable.

Resource limitations precluded OTA from using such methods to estimate the reliability assumed in calculating the expected failure costs shown in chapters 1 and 7 and in this appendix. For these estimates, OTA used engineering estimates of vehicle design reliability for payload deployment; these are shown in Table A-2. These component reliabilities are estimated from test data and flight experience when relevant data were available.

7 For a recent review and critique, see T, Mullin, "Experts' estimation of uncertain quantities and its implications for knowledge acquisition," IEEE Transactions on Systems, Man, and Cybernetics [to be published Jan./Feb. 1989].

8 See, for example, S. Kaplan and B.J. Garrick, "On the quantitative definition of risk," Risk Analysis, vol. 1, no. 1, 1981, pp. 11-27, and National Research Council Committee on Shuttle Criticality Review and Hazard Analysis Audit, Post-Challenger Assessment of Space Shuttle Risk Assessment and Management (Washington, DC: National Academy Press, January 1988), Appendix D.

9 E.J. Lerner, "An Alternative to 'Launch on Hunch,' " Aerospace America, May 1987, p. 40.

10 National Research Council Committee on Shuttle Criticality Review and Hazard Analysis Audit, op. cit., Appendix D, provides a tutorial overview. David A. Schum, Evidence and Inference for the Intelligence Analyst (New York: University Press of America, 1987), provides a longer, epistemological critique of Bayesian inference, See also M.W. Merkhofer, "Comparative Evaluation of Quantitative Decision-Making Approaches," contractor report prepared for the National Science Foundation (Springfield, VA: National Technical Information Service, April 1983).

*

Table A-2. – Engineering Estimates of Reliabilities

	Solid Rockets			Liquid Rockets			Avionics			Vehicle
	No.	FT?	Rel.	No.	FT?	Rel.	No.	FT?	Rel.	
Shuttle	2	No	.994	3	No	.988	5	**Yes**	neg	.982
Impr. Shuttle	2	No	.998	3	No	.988	5	Yes	neg	.986
Shuttle 11	0	--	--	9	Yes	.999	many	Yes	neg	.999
Shuttle-C	2	No	.994	2	No	.992	"?	Yes	neg	.986
Titan IV	2	No	.997	3	No	*988	1	No	.988	,972
Impr. Titan IV	2	No	.992	3	No	.988	many	Yes	neg	.976
Titan V	2	No	.998	6	No	,976	many	Yes	neg	.974
Transition	O	--	--	9	Yes	.999	many	Yes	neg	.999
ALS	0	--	--	9	Yes	neg	many	Yes	neg	,999 +
MLV	9	No	.989	2	No	.994	some	some	.992	.975

Vehicle.: reliability of ascent and payload deployment.
No.: number of rockets or independent "strings" of electronic systems which perform the same function.
FT: fault-tolerant.
Rel.: net reliability, considering redundancy.
neg: negligible contribution to unreliability, assuming other vehicle systems are 99.95 percent reliable.
SOURCE: Boeing Aerospace Co.

The estimated payload-deployment reliability of each vehicle does not include the unreliability of down-cargo return or recovery of reusable vehicles or components. Moreover, it includes only unreliability due to design faults; it excludes unreliability due to induced faults (e.g., negligence or sabotage) or operations under conditions (e.g. temperature) outside of specified limits. Hence these engineering estimates must be regarded as partially subjective, displaying more certainty than can be justified on the basis of strictly objective statistical inference.[11]

To estimate the total failure probability, OTA multiplied Boeing's estimates of payload deployment reliability by 0.99 to reflect a 1 percent probability (assumed by OTA) of failure during ascent or payload deployment caused by phenomena not modeled in the engineering estimates — e.g., human error, negligence, or malice, or unexpected weather or lightning, etc. OTA also assumed a 1 percent probability of failure during recovery of reusable vehicle elements. TableA-3 shows the resulting reliability estimates used by OTA to estimate failure costs. OTA is not confident that 1 percent is the correct probability of failure during recovery, or of unmodeled failure during ascent; these assumed probabilities are actually optimistic compared to reliability inferred objectively from historical data. For example, a history of 24 successful Shuttle orbiter recoveries in 24 attempts indicates only that the reliability of Shuttle orbiter recovery has been between

Table A-3.– OTA Estimates of Reliabilities

Vehicle	Reliability
Shuttle	96.2%
Improved Shuttle	96.6%
Shuttle 11	97.9%
Shuttle-C	96.6 %
Titan IV	96.2%
Improved Titan IV	96.6 %
Titan V	96.4 %
Transition	97.9 %
ALS (flyback)	97.9 %
(expendable)	97.9 %
MLV	96.5 %

11 Objective uncertainties in the reliabilities of tested vehicles are indicated by confidence intervals quoted in (e.g.) Boeing Aerospace cu., Launch Systems for the Strategic Defense Initiative – Data Book, (Los Angeles, CA: Headquarters, Space Division, U.S. Air Force Systems Command, 1986), pp. 6-84- 6-8S, and U.S. Congress, Office of Technology Assessment, Reducing Launch Operations Costs: New Technologies and Practices, OTA-TM-lSC-28 (Washington, DC: U.S. Government Printing Office, in press 1988), appendix B.

90.6 percent and 100 percent with 90.6 percent confidence.

Cost per failure: Estimating the average cost per failure is also difficult. For one thing, there will generally be intangible costs (e.g. risk to national security) as well as cash outlays (e.g., to replace a payload or launch vehicle). Assessment of intangible costs such as risk to national security is difficult and would be controversial, because it would require quantitative value judgments.[12] Intangible costs could be largely averted by purchasing spare vehicles and payloads and flying missions "at risk" after failures. Otherwise, costs of delays after failure would include intangible costs and would depend on decisions on grounding fleets of vehicles with common critical components and on returning fleets to operational status. Such decisions are not now made on the basis of probabilistic risk assessment.

The cost of the Challenger failure has been estimated at over $13.5 billion by Boeing. About half of this cost was attributed to delays in Shuttle operations and payload processing. The second largest contribution ($3.7 billion) was for miscellany– added costs of debt service, insurance, special order production, etc. The third largest contribution ($1,5 billion) was for replacement of the launch vehicle, and a nearly equal amount ($1.4 billion) was spent for accident investigation, corrective action, and reflight. The smallest contribution ($260 million) was for replacement of the cargo.

Based on this estimated cost per failure, Boeing recommended assuming that a manned mission failure (Shuttle or Shuttle II) would cost $10 billion on the average. This would be a reasonable assumption if the effect of downtime on option life-cycle cost were modeled in a consistent manner. However, Boeing estimated life-cycle costs for OTA's options by assuming uninterrupted operations, so for consistency OTA assumes a Shuttle failure cost of $7 billion, i.e., the costs of delay due to downtime are excluded [as they were in the Space Transportation Architecture Study]. Consistency also requires that vehicle replacement cost be interpreted as the cost of procuring a spare vehicle in advance so that Shuttle launch rates will not be reduced after a failure.[13] These assumptions are likely to be violated; most likely, no spare orbiter will be procured, and if another failure occurs, the Shuttle fleet will stand down, and some lost payloads may not be replaced and reflown. However, it would be more difficult to pose and analyze the implications of consistent alternative assumptions about the length and costs of downtime and the effect of corrective action on reliability; such an effort was not attempted in the Space Transportation Architecture Study and has not been attempted by Boeing or OTA.

Boeing also recommended assuming an average failure cost of $2 billion for heavy cargo vehicles and $300 million for MLVs. For consistency, OTA reduced the estimated failure cost of heavy cargo vehicles except Shuttle-C by $100 million– the estimated operations cost for the Titan IV fleet at a launch rate of zero for six months, the average Titan 34D downtime observed to date. Boeing's operations cost model (table A-1) assumes that Shuttle-C and MLV fleets have no fixed operations costs (i.e. while not launching), so OTA did not reduce the costs estimated by Boeing for Shuttle-C and MLV failures.

Finally, OTA assumed the average cost per failure of a partially reusable heavy cargo vehicle (a Transition launch vehicle or an Advanced Launch System launch vehicle) during recovery is about $1.5 billion. This represents the approximate cost of replacing one of two recoverable elements (propulsion/avionics module or flyback booster) and expenses of accident investigation and corrective action, etc.

To summarize, OTA assumed average costs per failure of $7 billion for the Shuttle or Shuttle II on ascent or return, $2 billion for Shuttle-C, $1.9 billion for other heavy cargo vehicles ($1.5 billion for a recovery failure, if partially reusable), and $300 million for MLVs.

Assuming further that failure costs are incurred in the year of failure, OTA also calculated the present value of the expected failure cost of each option, discounted at 5 percent. These are included in the histograms comparing life-cycle costs in chapters 1 and 7. OTA also calculated the 70th percentile of the discounted failure cost of each option; the 70th percentile minus the expected discounted failure cost is used as the component of cost risk (see below) due to more failures than expected.

Cost Risk

Cost risk was defined in the Space Transportation Architecture Study as the cost overrun, expressed as a percentage of the estimated present value of life-cycle cost (discounted 5 percent per year), that is expected with a subjectively estimated probability y of 30 percent,

12 U.S. Congress, Office of Technology Assessment, Anti-Satellite Weapons, Countermeasures, and Arms Control, OTA-ISC-281 (Washington, DC: U.S. Government Printing Office, 198S), p. 33.

13 It is implausible to assume that every payload flown would be, or should be, backed up by a spare. Including payload replacement and reflight cost in the failure cost could represent either the cost of a spare or, if there is no spare, the utility cost of a failure.

Table A-4. – Cost Risk[a]

Option	Non-Recurring Cost Risk	Recurring Cost Risk
Enhanced	0%	13%
Titan IV	0%	14%
Titan V	2%	13%
Shuttle-C	4 %	17%
Transition LV	14%	17%
ALS		
— with fly-back booster	14%	*17%*
–with expendable LV	2%	*13%*
Shuttle II	29%	18%

[a] "STAS component" – excludes risk of greater-than-expected failure costs.

assuming the Space Transportation Architecture Study groundrules are met. Higher overrruns are judged less probable. Cost risk was intended to represent likely increases in life-cycle cost caused by unforeseen difficulties in technology development, facility construction, etc. However, it did not include risks of cost growth due to mission cancellations, funding stretch-outs, or standdowns after failure, which were excluded by the Space Transportation Architecture Study groundrules.

The cost risk quoted by OTA in chapters 1 and 7 includes cost risk as defined in the Space Transportation Architecture Study as well as a risk of greater-than-expected failure costs. It excludes risks of cost growth due to mission cancellations, funding stretch-outs, or standdowns after failures.

The "STAS component" of cost risk includes the risk of growth in costs of DDT&E, facilities, and production (adjusted for changes in inflation and production rate). OTA assumes that the STAS component of each option's cost risk has non-recurring and recurring components as estimated by Boeing Aerospace Company[14] for corresponding STAS options (see Table A-4) featuring similar or identical launch vehicles, as well as backup launch vehicles and upper stages not considered here. This analysis also assumes that the errors in the estimates of non-recurring and recurring costs of an option are normally distributed and uncorrelated.[15]

Failure cost risk represents expected fluctuations in failures per year, assuming vehicle reliabilities are known.[16] The total failure cost risk for an option the sum of the failure cost risks for each fleet. OTA defines the failure cost risk for each fleet as the difference between its expected failure cost and the 70th percentile of failure cost.

Mission cancellations, funding stretch-outs, or standdowns after failures could have diverse, complicated, poorly-understood, and policy-dependent effects on life-cycle cost. They could **decrease** life-cycle cost while increasing average life-cycle cost per launch and causing intangible costs of delaying mission capabilities to be incurred. These intangible costs should be considered a cost of the space transportation system only if they are caused by the space transportation system (e.g. by a standdown).

Mission cancellations could be caused by the space transportation system (e.g. greater-than-expected vehicle processing time), payload production delays, lack of need (e.g. greater-than-expected longevity of satellites scheduled for replacement), or funding stretch-outs.

14 Boeing Aerospace Company, Space Transportation Architecture Study – In-Progress Review Number 5, Apr. 7, 1987.

15 Boeing assumed that total cost risk was the sum of non-recurring cost risk and recurring cost risk, which implies a tacit assumption that the errors in the estimates of non-recurring and recurring costs are perfectly correlated. It is equally plausible that a reduction in non-recurring cost (e.g. for budgetary reasons) could increase recurring cost. We split the difference by assuming they are uncorrelated.

16 In fact, uncertainties in vehicle reliabilities (described above) would also contribute.

Funding could be stretched out by the Administration or Congress in response to mission cancellations or changing national priorities. Logically consistent estimation of total cost risk must account for these possibilities and will require more sophisticated methods than were used here, or in the Space Transportation Architecture Study.

Cancellation of planned missions may cause stretch-outs in production, or vice versa. Stretch-outs in production have been a major contributor to cost growth of weapon systems,[17] and are probably the leading contributor in the 1980s.[18]

Only about 70 percent of DoD missions projected one to five years in advance by the Air Force have actually been launched.[19] Even fewer missions projected by NASA have been launched. The baseline mission model assumed in a 1971 economic analysis of the (then) proposed Space Shuttle postulated 736 flights during 1978-1990; the next year, the baseline was reduced to 514 flights during 1979-1990.[20] This will prove to be a tenfold overestimate if 20 more Shuttle flights are flown before 1991 as now planned.[21] In 1979, NASA projected total U.S. launch activity[22] in 1985 would be 44 equivalent Shuttle flights.[23] This estimate was revised downward as 1985 approached; About 12 equivalent Shuttle flights were actually flown.[24]

17 H.Rep. 96-6S6, op. cit., and U.S. Congress, Congressional Budget Office, Effects of Weapons Procurement Stretch-Outs on Costs and Schedules (Washington, DC: U.S. Congress, Congressional Budget Office, November 1987).

18 M. Rich and 1Improving the Military Acquisition Process R-3373 (Santa Monica, CA: The Rand Corporation, Feb. 1986).

19 DoD/NASA Space Transportation Joint Task Tn, National Space Transportation and Support Study 1995-2010, Annex A (Washington, DC: NASA I headquarters, Code M, May 1986), pp. 14-18.

20 K.P. Heiss and O. MEconomic Analysis of the Space Shuttle System, Executive Summary, (Washington, DC: NASA, 1972).

21 NASA, Payload Flight Assignments – NASA Mixed Fleet, March 1988.

22 For DoD, NASA, other government agencies, and domestic and foreign commercial customers.

23 U.S. Congress, Congressional Budget Office, Setting Space Transportation Policy for the 1990s (Washington, DC: Congressional Budget Office, October 1986).

24 Ibid.

Alternative Cost Estimates

Alternative Assumptions by Reviewer One and Results

Table A-5 summarizes the cost-estimating formulas developed by Boeing as modified in accordance with the recommendations of one reviewer. This reviewer had not estimated the costs of the Improved Titan IV, Titan V, and Transition launch vehicles, and suggested no change in OTA's cost-estimating formulae for these proposed vehicles.

OTA produced alternative estimates of the life-cycle cost of each option in each mission model using the alternative cost-estimating formulae proposed by this reviewer, Boeing's cost-estimating formulae for the Improved Titan IV, Titan V, and Transition launch vehicles, and OTA's estimates of failure cost and cost risk. These option life-cycle cost estimates are tabulatcd in Table A-6.

Table A-5.–Alternate Cost-Estimating Relationships #1

Costs in Fiscal Year 1988 Dollars

Fleet	Dev.	Fac.	Limit	Prod	Operations[a] per year	Operations[a] per launch
Shuttle	0	x	14/yr	0	$2,162M	$43M
Improved Shuttle	$0.6B	x	14/yr	0	$2,162M	$43M
Shuttle 11	$12B	$lB + X	14/yr	3 x $1,500M	$99M	$48M
Shuttle-C	$0.75B	$0.02-0f5:	14- STS	0	0	$163M - C
MLV	o	x	12+ /yr	o	$35M	$33M
Titan IV	o	x	12/yr	0	$162M	$146M
Improved Titan IV	$0.4B	$0.5B + X	12/yr	o	$200M	$95M
Titan V	$1.2B	$0.5B + X	12/yr	0	$267M	$157M
Transition Vehicle	$3.9B	x	0	3 x $110M	$228M	$54M
ALS	$9.5B	x	o	4 x $425M	$230M	$75M

Dev,: development cost.
Fac.: launch facility conversion or construction cost.
Limit: maximum annual launch rate attainable without new facilities.
Prod.: cost of producing reusable elements.
X: $0.15B per unit increase in annual launch rate limit (OTA's nominal estimate). This reviewer did not estimate the cost of increasing the annual launch rate limit by large increments,
C: SSME credit: $80M if both SSMEs have flown on Shuttles until fully depreciated (10 flights); pro-rated otherwise. This reviewer expressed the annual cost as $.412M per year plus $119M per flight at 3 Shuttle-C flights per year and 11 Shuttle flights per year.
[a] Includes cost of producing expendable elements.

Table A-6.–Alternative Cost Estimate #1

in Fiscal Year 1988 Dollars

	Life-cycle cost			Cost risk		
Option	Nonrec.	Operations	Failures	Nonrec.	Recur.	Total[a]
	Low-Growth					
Enhanced Baseline	$1.2B	$54B	$40B	0	$25B	$12OB
TitanIV	$0.4B	$60B	$42B	0	$27B	$129B
TitanV	$1.7B	$57B	$38B	$0.03B	$25B	$121B
Shuttle-C	$0.9B	$60B	$37B	$0.04B	$27B	$125B
Transition Vehicle	$8.0B	$49B	$35B	$1.1B	$26B	$118B
Advanced Launch SysteB	$13.9B	$51B	$37B	$1.9B	$27B	$128B
Shuttle II	$16.7B	$49B	$27B	$4.8B	$22B	$114B
	Growth					
TitanIV	*$2.0B*	*$69B*	*$47B*	0	$28B	$147B
TitanV	$3.OB	$65B	$41B	$0.06B	$26B	$136B
Shuttle-C	$2.2B	$68B	$41B	$0.09B	$29B	$14013
Transition Vehicle	$9.3B	$52B	$37B	$1.3B	$26B	$125B
Advanced LaunchSystem	$15B	$54B	$39B	$2.1B	$27B	$136B
Shuttle II	$18.3B	$58B	$32B	$5.3B	$24B	$133B
	Expanded					
TitanIV	$6.4B	$104B	$65B	0	$34B	$209B
TitanV	$6.5B	$95B	$54B	$0.1B	$30B	$186B
Shuttle-C	$5.8B	$99B	$54B	$0.2B	$35B	$194B
Transition Vehicle	$12.7B	$63B	$44B	$1.8B	$29B	$148B
Advanced Launch System	$17.8B	$66B	$48B	$2.5B	$30B	$162B
Shuttle II	$22.7B	$93B	$49B	6.6B	$32B	$197B

Nonrec; nonrecurring.
Rec~recurring.
[a]Total cost includcs total cost risk, which is the square root of the sum of the squared components of cost risk (nonrecurring and recurring).
SOURCE: OTA.

Alternative Assumptions by Reviewer Two and Results

Table A-7 summarizes the cost-estimating formulas developed by Boeing as modified in accordance with the recommendations of a different reviewer. This reviewer suggested changes only in the cost-estimating formulae for the Shuttle-C, Shuttle II, and Advanced Launch System vehicles, and in facility costs for expendable vehicles. The reviewer also proposed a cost-estimating formula for an expendable Advanced Launch System launch vehicle.

OTA produced alternative estimates of the life-cycle cost of each option in each mission model using the alternative cost-estimating formulae proposed by this reviewer for Shuttle-C, Shuttle II, and Advanced Launch System vehicles, and facilities, Boeing's cost-estimating formulae for the other launch vehicles, and OTA's estimates of failure cost and cost risk. These option life-cycle cost estimates arc tabulated in Table A-8. For these estimates, OTA assumed that the Advanced Launch System launch vehicle would be expendable and would have a potential reliability of 98.9 percent and an actual reliability of 97.9 percent.

Table A-7. – Alternative Cost-Estimating Relationships #2

Costs in Fiscal Year 1988 Dollars

Fleet	Dev.	Fac.	Limi	Prod.	----Operations[a]---- per year	per launch
Shuttle	0	x	16/yr	0	$I,336M	$53M
Improved Shuttle	$0.6B	x	16/yr	0	$1,336M	$43M
shuttle II	$24B	$lB + X	16/yr	3 x $3,000M	$59M	$33M
Shuttle-C	$1.2B	X	16- STS	0	$480M[b]	$80M[b]
MLV	0	0	12 + /yr	o	0	$35M
Titan IV	0	x	12/yr	0	$200M	$100M
Improved Titan IV	$0.4B	x	12/yr	o	$200M	$95M
Titan V	$1.2B	$0.5B + X	12/yr	0	$267M	$157M
Transition Vehicle	$3.9B	x	o	3 x $11OM	$228M	$54M
ALS (flyback)	$12.3B	x	o	4x $425M	$630M[c]	$31M[c]
ALS (ELV)	$2.8B	x	o	4 x $425M	$240M[d]	$40M[d]

Dev.: development cost.
Fac.: launch facility conversion or construction cost.
Limit: maximum annual launch rate attainable without new facilities.
Prod.: cost of producing reusable elements.
X: $0.15B per unit increase in annual launch rate limit,
C: SSME credit: $80M if both SSMEs have flown on Shuttles until fully depreciated; pro-rated otherwise. A new SSME is assumed to cost $40M; its allowed lifetime on the Shuttle is assumed to be 10 flights until 1989, 20 flights from 1989101995, and 40 flights thereafter.
[a]Includes cost of producing expendable elements,
[b]Expressed by this reviewer as an average cost of $140M per launch at 8 per year and $104M per launch at 20 per year expressed in this form by OTA.
[c]Expressed by this reviewer as an average cost of $110.25M per launch at 8 per year and $63M per launch at 20 per year; expressed in this form by OTA,
[d]Express, ed by this reviewer as an average cost of $70M per launch at 8 per year and $52M per launch at 20 per year; expressed in this form by O IA.

Table A-8. –Alternative Cost Estimate #2

in Fiscal Year 1988 Dollars

Option	Life-cycle cost: Nonrec.	Life-cycle cost: Operations	Life-cycle cost: Failures	Cost risk: Nonrec.	Cost risk: Recur.	Total[a]
			Low-Growth			
Enhanced Baseline	$0.9B	$42B	$40B	00	$25B	$108B
Titan IV	$0.lB	$44B	$43B	0	$26B	$112B
Titan V	$1.4B	$45B	$38B	$0.03B	$24B	$109B
Shuttle-C	$1.lB	$42B	$37B	$0.04B	$26B	$1O6B
Transition Vehicle	$4.2B	$38B	$35B	$0.lB	$24B	$102B
Advanced Launch System	$4.9B	$37B	$35B	$0.7B	$25B	$102B
Shuttle II	$32.OB	$36B	$36B	$9B	$25B	$132B
			Growth			
Titan IV	$0.5B	$50B	$47B	0	$27B	$126B
Titan V	$1.8B	$54B	$41B	$0.04B	$25B	$122B
Shuttle-C	$1.4B	$46B	$41B	$0.06B	$27B	$115B
Transition Vehicle	$6.2B	$41B	$37B	$0.lB	$24B	$108
Advanced Launch System	$5.3B	$39B	$37B	$0.7B	$25B	$107B
Shuttle 11	$32.5B	$43B	$41B	$9.4B	$27B	$145B
			Expanded			
Titan IV	*$1.7B*	*$74B*	*$65B*	0	$31B	$172M
Titan V	$2.7B	$83B	$54B	$0.05B	$29B	$170B
Shuttle-C	$24B	$61B	$54B	$0.09B	$30B	$148B
Transition Vehicle	$6.2B	$46B	$45B	$0.lB	$25B	$126B
Advanced Launch System	$6.2B	$46B	$50B	$0.9B	$27B	$125B
Shuttle II	$33.7B	$70B	$58B	$9.8B	$32B	$192B

Nonrec.: nonrecurring.
Recur.: recurring.
'Total cost includcs total cost risk, which is the square root of the sum of the squared components of cost risk (nonrecurring and recurring).
SOURCE: OTA.