Space Policy Alternatives

edited by
Radford Byerly, Jr.

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Chapter 14

THE SPACE SHUTTLE PROGRAM: PERFORMANCE VERSUS PROMISE

Roger A. Pielke, Jr., and Radford Byerly, Jr.

THE WHOLE AIM OF THE SCIENTIFIC STUDENT OF SOCIETY IS TO MAKE THE OBVIOUS UNESCAPABLE . . . THAT WHICH IS KNOWN IMPLICITLY AND BASED UPON DIFFUSED, UNVERBALIZED EXPERIENCE MUST BE MADE EXPLICIT IF NEW WAYS OF DEALING WITH THE WORLD ARE TO BE INVENTED.

—H. D. LASSWELL

NEVER PROMISE MORE THAN YOU CAN PERFORM.

—LIVY

Introduction

On February 2, 1989 James Fletcher, then NASA Administrator, testified before a Congressional committee that "the [Space] Shuttle is the fundamental link in a space transportation infrastructure which will carry this nation into the 21st century. It is our means to place human beings into orbit and it makes Space Station Freedom possible and practical".[1] More recently, in an official NASA publication a similar view of the Shuttle program was given: "Any spacefaring nation would characterize an optimum transportation system as being a reliable, reusable, man-rated, heavy-lift booster, carrying crews and significant cargos to and from space – the very definition of the Space Shuttle program".[2] NASA officials have regularly characterized the Shuttle as a "fundamental link" in the United States civilian space program.[3] However, a well-respected committee of experts, who were asked to examine NASA, recently suggested in a highly publicized report that the United States should "defer or eliminate the planned purchase of another orbiter" based on the committee's concern that "the space shuttle would seem to be the weak link of the civil space program -- unpleasant to recognize, involving all the uncertainties of statistics, and difficult to resolve".[4] This viewpoint is very different from that espoused by NASA.

While it is not logically inconsistent for a "weak link" to also be a "fundamental link", certainly it would defy logic to make a weak link fundamental to our space program. This paper provides performance information on the Shuttle relevant to whether or not it is a weak link. The information can also illuminate decisions on other programs -- Space Station, Human Exploration, a new launch system -- which depend on evaluation of Shuttle performance. Better information is the first step toward better policy.

Cost, schedule, and capability are the factors for analysis because upon project approval these factors are established as programmatic goals, thus providing a baseline against which performance may be measured. Perhaps more importantly, the Shuttle program's initial promises were implicitly agreed between NASA and Congress.[5] As will be shown, the difference between initial promise and actual performance suggests that the Shuttle program as originally conceived by NASA and approved by Congress was poor public policy.[6]

As a necessary first step towards better policy this paper documents the performance shortfall. To fully understand the policy shortfall it would be necessary to conduct a full policy appraisal of the Shuttle program; for example expanding the analysis to include examining why the gap between promise and performance exists, assessing likely future scenarios for the Shuttle program, and recommending the most worthwhile policy alternative for the program. A full policy appraisal goes beyond the scope of this paper.

It is hoped that performance that falls well short of program promise is perceived to be a significant policy problem, stimulating future work to examine why this occurs and how we may do better in the future -- in the Space Shuttle program as well as in other space programs.

The factors for analysis are defined as follows:

Cost

The *total cost* of the program, as measured from program inception to termination.[7]

The *average cost* of a Shuttle flight, as measured in several different contexts. A range of future projections of the program's average cost per flight, as well as historical data, will be presented.[8] Furthermore, costs associated with Shuttle *attrition rate* will be considered.

The *annual cost* of the program is relevant as funding decisions are made on a year-by-year basis. Here as well, both historical data and future projections will be considered.[9]

Schedule

An analysis of the *flight rate* is necessary to ascertain what may be expected from, as opposed to planned for, the program in future years.

Capability

The *capability* of the Space Shuttle may be evaluated in many ways, both quantifiable and nonquantifiable, with respect to programmatic goals. Measures of capability include: payload capacity, payload type (e.g., man), etc. Measurements of performance are necessary as decisions are made concerning the future of the civil space program.

The twenty year history of the program and 10 years of Shuttle operations provide data for an examination of the program based on these factors. Because the data are difficult to collect and interpret, the methods of analysis used are purposely simple and transparent. These methods are no substitute for more sophisticated methods, e.g., economic and engineering, but rather are preliminary and complementary. Better data will support more sophisticated analysis of this and other civil space programs.

This paper builds on studies of Shuttle history by examining *how* program performance compares to original goals, and what might be expected for the future.[10] Rather than dismissing program shortfalls we should strive to understand them.
avoid making the same mistakes again. In 1972 NASA predicted the net cost of the Space Shuttle program as shown in Table 14.1.[11]

One must add $8 billion in 1990 dollars to the $42.7 billion NASA estimate to represent civil service salaries which are not accounted for in the table.[12] Thus the total cost estimate for the Shuttle program is $50.7 billion through 1990.

Table 14.1. NASA predictions for the total cost of the Shuttle program through 1990 (dollars in billions).

	Then-year dollars	1990 dollars
1. Investment in Space Shuttle, including initial inventory (details show below)	$6.45	$17.1
(a) Develop, test, and procure 2 orbiters and 2 boosters (1972-1980)	*(5.15)*	*(13.6)*
(b) Refurbish 2 orbiters and procure 3 more, including engines, and initial production boosters (1979-1980)	*(1.0)*	*(2.6)*
(c) Facilities for development, test, launch and landing capability	*(.3)*	*(.8)*
2. Additional investments required to fly mission modes assumed; (includes possible future development of space tug by 1985, expendable injection stages for high orbit satellites and deep space probes prior to tug development, and operational site facilities at Vandenberg AFB, California.)	$1.6	$4.2
3. Total launch costs, including procurement of replacement boosters, 580 flights (1972-1990)	$8.1	$21.4
4. Total 1972-1990 (sum items 1, 2, and 3)	$16.15	$42.7

NASA also made predictions for the total number of flights that were to occur during the same time period. From 1979-1990 the Shuttle was to fly 580 flights, about 48 per year. NASA's planning model suggested that the 580 Shuttle flights would be so much cheaper than 580 equivalent conventional launches (i.e., on expendable launch vehicles or ELVs) that the Shuttle would pay for its development, its operations, and still save over $13 billion ($5 billion in 1972 dollars).

1972: Shuttle Program Promises

Perhaps because there is no dispute over whether the Space Shuttle program achieved the goals set out in 1972 there is not much discussion over how the program fails to meet them. Nevertheless, it is important to remember those goals: Not to lay blame, but rather to illuminate how these goals were not met and to develop strategies to Later there were plans to recoup launch costs by charging for the use of the Shuttle.[13] Other performance goals were mainly payload-based. In order to fill almost 50 payloads per year NASA listed a range of possibilities from getaway specials, i.e., small payloads flown on a space-available basis, to large scale space construction. The goals for the project set out in 1972 are clear and unambiguous, thus providing criteria for program appraisal.

Shuttle Program Costs: 1970-1990

In any public enterprise project cost is important to policymakers, policy analysts, and American citizens as projects often compete on that basis. Project cost, both historical and projected, can provide some of the information necessary for both program appraisal and policy decisions.

The manner which NASA keeps its accounts does not facilitate this type of analysis because costs are not accounted by specific programs, but rather by budget categories. Shuttle costs have been identified in the following four budget categories:[14]

> *Research and Development [R & D]* : This category primarily includes the costs budgeted for the development phase of the project under the line item *Manned Space Flight: Space Shuttle* from fiscal year (FY) 1972 to FY 1984. After 1984 there are additional costs in this category, e.g., in *Engineering and Technical Base, Payload Operations and Support Equipment*, and *Spacelab*, but we have not included them because they are difficult to separate and identify. Expendable launch vehicle costs, budgeted in this category, have been excluded.

> *Space Flight, Control and Data Communications [SFCDC]* : This category primarily includes Shuttle costs budgeted for the operational phase of the project in the following two line items: *Shuttle Production and Operational Capability* and *Space Transportation Operations* from FY 1985 to FY 1990.[15] There are also tracking and communications costs in this category, which

were not included because we know of no way to allocate them to Shuttle.

Construction of Facilities [CoF] : This category includes all costs which are explicitly labeled in the NASA budget for the Shuttle program for the purpose of providing for repair, modification, new construction, and design and planning of facilities.

Research and Program Management [R&PM]: This category includes costs for civil service staff, i.e., salaries, maintenance of facilities, and technical and administrative support. Unfortunately, within this budgetary line item costs are not broken down by program, but rather by NASA center. To arrive at the R&PM costs for the Shuttle program we made use of the available data as follows: Shuttle R&PM costs were taken to be equal to the total R&PM costs at a NASA center multiplied by the fraction of that center's personnel that work on the Shuttle.[16] This calculation was done for the three main centers where Shuttle work is done: Kennedy Space Center, Marshall Space Flight Center, and Johnson Space Center. Additional Shuttle R&PM costs at other centers were not included.

As noted some costs were not included due either to the difficulty of accurately ascertaining the Shuttle-relevant part, or their insignificance. The addition of these categories would increase the estimates, but probably by less than 10%. Also not included is the cost-of-money. Thus, again the estimates are low.

The Department of Defense [DoD] also spent a significant amount of money on the Space Shuttle program which is not included. Through 1980 DoD had spent $1.8 billion on the Shuttle program, and in 1980 it was estimated that an additional $1.2 billion would be spent by 1984. The funding was to cover the development of the Inertial Upper Stage [IUS], construction of the Shuttle launch complex at Vandenberg Air Force Base, DoD launches, and all other DoD Shuttle-related costs.[17]

NASA also receives funds for the Shuttle program when it is reimbursed for a Shuttle flight, e.g., when it flies a DoD, commercial, or foreign payload. These reimbursements represent additional resources available to the program -- they do not go to the Treasury to offset the costs of the program. These funds were also not included in the tabulation. In FY 1990 the Shuttle reimbursables were $82 million, compared to slightly more than $4 billion which were appropriated.[18] In FY 1985 when there was much more reimbursable activity (e.g., DoD and commercial payloads) NASA was reimbursed about $480 million for the Shuttle, compared to appropriations of almost $4 billion.[19]

Total Costs. Figure 14.1 shows that the total cost of the Space Shuttle program through 1990 is approximately $65 billion, compared to the original estimate of $51 billion. While this is a fairly small overrun, about 27%, it must be remembered that the $51 billion was to have paid for 580 flights while only 37 had been flown through 1990. The R & D and SFCDC categories make up most of this amount, about 83%. The Construction of Facilities line item for the Shuttle program is relatively small, on the order of 2% of the total. Research and Program Management accounts for approximately 15% of the total.

Annual Costs. As funding decisions are made on a year-by-year basis in Washington the program's annual cost is important to consider. Figure 14.2 displays this data. Since 1982 the Shuttle program's annual costs have been approximately $4 billion, although costs seem to be rising.[20] Of note here is that annual costs during the "operational" phase, i.e., beginning with the fifth flight, have been higher than during the pre-flight "development" phase. Costs were highest in FY 1982 and FY 1983 when there were still significant orbiter construction costs as well as large flight costs. Budget estimates for the next three years show annual program costs rising to about $5 billion in 1993.

Average-cost-per-flight. The subject of much debate over the lifetime of the Shuttle program has been how much a Shuttle flight actually costs. No attempt is made here to ascertain how much the *next* flight costs, i.e., the marginal cost, but rather to determine how much the average cost of a Shuttle flight will have been over the entire life of the program based on various estimates of when it will be terminated.

If the program had ended with the completion of FY 1990 the average cost per flight would have been about $1.7 billion. Ignoring the costs incurred prior to the "operational" phase - i.e., before 1983 - the average-cost-per-flight would be lowered to about $1.1 billion. For comparison, Macauley and Toman calculate a long run marginal cost ranging from $200-320 million (1990 $) per flight, and the GAO has recently used an "additive" cost of approximately $80 million.[21]

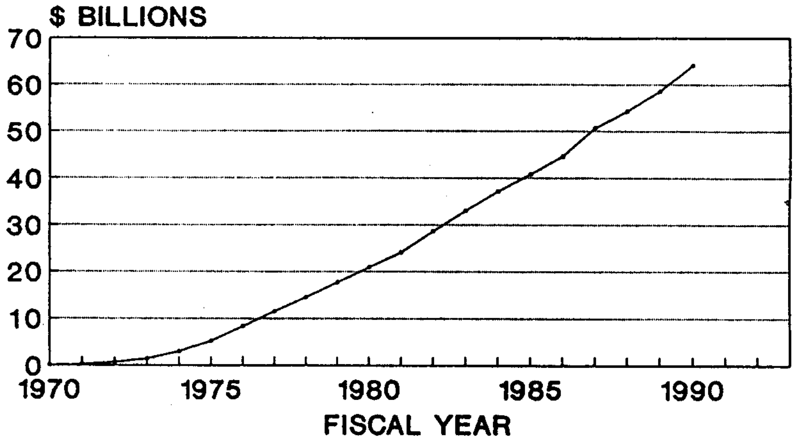


Figure 14.1: Space Shuttle Program Total Costs. Cumulative cost of the Shuttle program in 1990 dollars. Note: Transition quarter not included. Source: NASA.

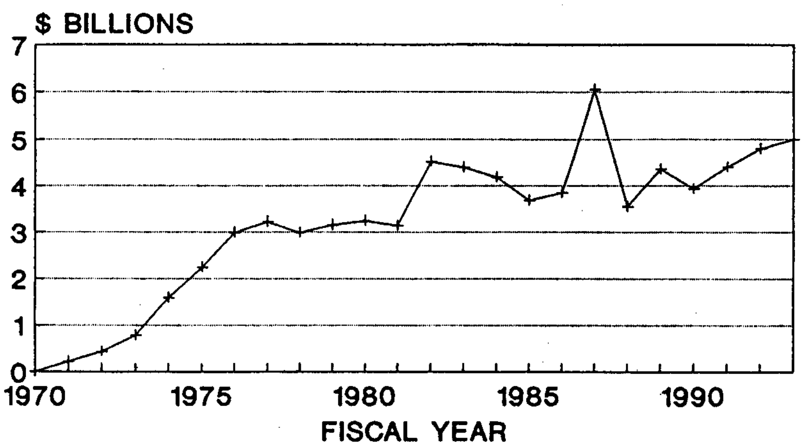


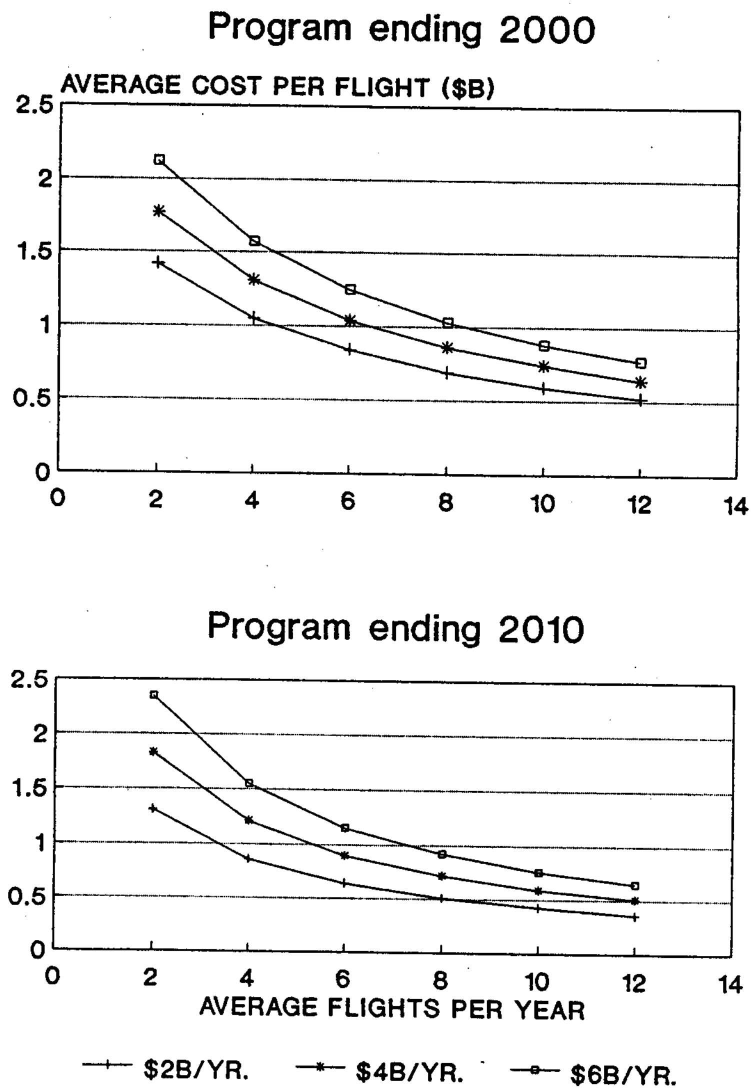
Figure 14.2: Space Shuttle Program Annual Costs. Annual costs of the Shuttle program in 1990 dollars. Note that costs are now higher than during the development phase, 1972-1981. High costs occurred in FY 1982 and 1983 when there were both significant operations costs and orbiter construction costs. the 1987 peak is an anomaly due the one-time replacement for the *Challenger*. Note: FY 1991-93 estimates. Source: NASA.

Figures 14.3a and b show the average cost per flight over the entire history of the program for a range of possible futures.[22] Two program termination years are considered: 2000 and 2010. For each of these scenarios the average cost per flight is calculated at the end of the relevant time period for a range of 2 to 12 flights per year, assuming average annual future appropriations of $2, $4, or $6 billion per year to operate the program.

These figures show that for the reasonable projection of 8 flights per year and a $4 billion average annual appropriation, the average cost per Shuttle flight will be about $800 million for either termination year. This corresponds to an average cost per flight of $500 million for the remainder of the Shuttle program, independent of termination date.[23] This is an important cost number for making decisions about the program, as it does not include sunk costs. More pessimistic projections of annual appropriations and flight rates push the average cost per flight over $1 billion.

Although in principle the average cost of a flight is important for program evaluation, it has much less political importance. Politically the Shuttle is a highly visible, manned space program, a symbol of U.S. leadership. Only secondarily is it a transportation program. Thus, its costs are seen as costs of having the program, not costs of getting payloads to orbit. Thus, it makes sense for policymakers to think "if we have the Shuttle we may well fly it as often as possible". Therefore, from this perspective the Shuttle may be considered "free" transportation, at least for NASA payloads. Furthermore, if the shuttle is (or will be) flying as often as possible, then it makes little sense to speak of marginal costs as there is no margin. However, the marginal cost of one <u>less</u> flight becomes important if the program is to be considered operating at less than maximum capacity.

Not included in the average cost calculations presented above is the cost of replacement orbiters. The Challenger replacement, Endeavor, cost $2.3 billion which was appropriated in a lump sum.[24] If lost orbiters are to be replaced in the future, then the average cost per flight of orbiter attrition can be determined by assessing a predetermined "surcharge" on each flight based on the expected reliability. The Office of Technology Assessment has estimated the Shuttle's reliability to be 0.98. If this is accurate there would be a 50-50 chance of losing at least one orbiter within 34 flights, or in other words, within 3 to 6 years depending on the flight rate.[25] Based on



Figures 14.3a and b: Average Cost per Shuttle Flight at Program Completion. The average cost per Shuttle flight calculated assuming various numbers of flights per year and assuming three different average levels of funding per year, $2 B, $4 B, and $6 B. Figure 14.3a assumes the program will end in the year 2000, while 3b assumes it will end in 2010, i.e., that there will be more flights over which to spread early costs.

this estimated reliability, and assuming lost orbiters will be replaced for $2.3 billion, one estimate of the surcharge per flight to pay for orbiterattrition is $46 million.[26] Since orbiter reliability is not 1.0, policy should reflect the likelihood of losing orbiters.

Shuttle Schedule: 1981-1990

Schedule refers to when capabilities are available. The first manned orbital flight of the Shuttle was originally planned for 1978 and actually occurred in 1981. Flights were planned to occur regularly after that, at an average rate of nearly 50 per year.

For two reasons the best data to analyze the Space Shuttle flight rate are from the pre-Challenger era. First, 25 successive launches occurred forming the longest unbroken stretch of launches in the Shuttle's history. Secondly, since the Challenger accident the Shuttle program has performed less well due to a cautious restart period and numerous down-times, and therefore is not representative of what the Shuttle has done. The pre-Challenger data can now be considered a best-case scenario as NASA no longer intends to pursue such a high flight rate. It should be emphasized that the data presented here are not for planning purposes, but instead are a reasonable estimate as to what policymakers might expect in the future.

Analysis of the Shuttle flight rate is made difficult due to the number of variables involved. Factors which have an impact on the flight rate include:[27]

NASA Budget : The annual appropriation from Congress, which determines overall resources.

Mission Payloads : The payloads carried to orbit, e.g., the Hubble Space Telescope. Some payloads take more time to integrate, some have problems that cause delays.

Vehicle Assembly Building (VAB) : Here the orbiter is mated to the solid rockets and the external tank. Orbiters must pass through the VAB serially, thus, unexpected problems can cause delays on subsequent flights.

Number of Orbiter Processing Facilities [OPF] : Much of the turn-around work on the orbiters is done in the OPFs. When there are fewer OPFs than orbiters, a problem with one orbiter could stall another.

Number of Mobile Launch Platforms [MLP] : These ferry the Shuttle from the VAB to the launch pad.

Landing Site : Orbiters which land at Kennedy can be prepared for launch in less time than ones which land at Edwards Air force Base, due to the time it takes for transfer from Edwards to Kennedy.

Shuttle Transfer Aircraft : Modified 747s that return orbiters from landing sites to Kennedy Space Center.

Mission Duration : This is the time from launch to landing.

Weather : This can be either at Kennedy or transatlantic abort landing sites, potentially delaying launch, or at Edwards, White Sands, or Kennedy, affecting landing.

Payload Launch Window : This is time period within which a payload must be launched in order to meet mission objectives, e.g., planetary alignments.

Crew Training Time : This is the preparation time necessary for the Shuttle crew. It cannot proceed ahead of development of mission software, which in turn depends on payloads, etc.

Logistics : Primarily the availability of spare parts to repair Shuttles.

Hardware Failures : Including wear-out due to cumulative use, as well as accidents.

Ground Crew Time-off : The time periods during which no work is done on Shuttles due to holidays, etc..

Which Orbiters Fly : All orbiters are not equally capable of sustaining the same flight rate. For example, it has been generally recognized that Columbia does not perform as well as the other orbiters.

Shuttle Hardware : These include the orbiter, the Solid Rocket Boosters, the External Tank, the Main Engines, and other hardware necessary for flight.

It is necessary to distinguish between the number of orbiters and the number of "schedulable" orbiters. Because orbiters occasionally have to be removed from their flight rotation for major repairs or factory modifications, the number of schedulable orbiters is less than the actual number of orbiters. In 1986 the National Research Council found that of the three orbiters there existed only "a bit in excess of 2" schedulable orbiters, which gives an estimated schedulability ratio of about 0.7 per orbiter.[28]

Another necessary distinction is between work days and calendar days: Work days are defined as those in which normal orbiter preparation takes place. For example, during the one-year period

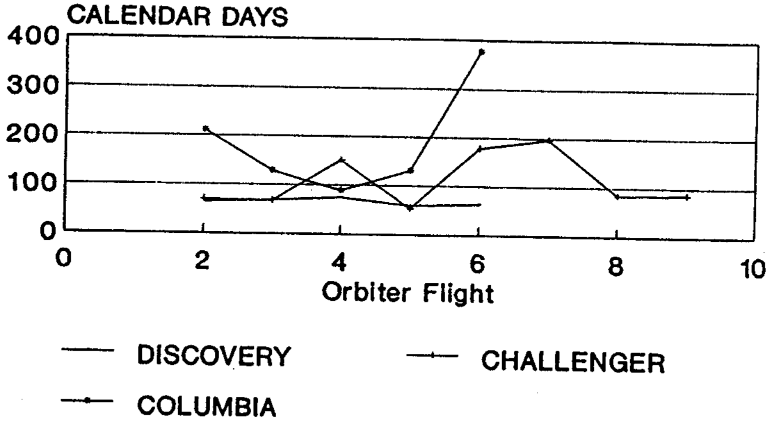


Figure 14.4 Space Shuttle Program Orbiter Turn-Around Time. Orbiter turn-around time (i.e., launch to launch) in calendar days, for flights before the *Challenger* accident.

beginning with the Shuttle flight of August 30, 1984 NASA launched 9 missions using only two orbiters, Challenger and Discovery. The two orbiters were able to achieve an average turn-around of 55 work days. However, this amounted to an average turn-around time of 81 calendar days between flights. The difference of 26 days is accounted for by ground crew time-off, mission duration, transfer to Kennedy from the landing site, weather delays, on-the-pad payload problems, and other such factors and contingencies.

Figure 14.4 shows some data on pre-Challenger turnaround experience for the three orbiters which flew most of the flights.[29] Ground operations for the first flight of each orbiter are ignored.[30] Worth noting is the poor performance record of Columbia, the oldest active orbiter. As long as Columbia is in the fleet overall flight rates may be less than would be possible without it.

After the Challenger accident NASA's goal has been to achieve a turnaround time of 75 work days per flight.[31] Adding 25 days to represent other time factors results in a best-case figure of 100 calendar day orbiter turnaround. Therefore, the post-Challenger best case scenario, assuming 4 orbiters (2.8 schedulable) is 10.2 flights per year. If the fraction of schedulable orbiters were raised to 0.8 (e.g., by decreasing time for factory modifications or avoiding accidents) the annual flight rate could be 11.7 per year, consistent with a 1988 OTA estimate of 12 to 14 flights per year.[32]

Shuttle Capability

The capability of the Shuttle program is difficult to measure. There are three criteria by which capability may be measured: (1) with respect to program's original goals, (2) against similar programs, and (3) with respect to present or future goals.

It is generally accepted that the Shuttle program has not met its original goals. This is not to say that the Shuttle is not a grand technical achievement -- it is. Nor to say that the Shuttle does not serve a useful purpose. However, the specifics of the performance shortfall are as follows.

Through 1990 the program's total costs were about 27% percent more than what was predicted in 1972.[33] The number of flights is one fifteenth the 1972 prediction. The average cost per flight is over 19 times what was promised. It is worth noting that if the Shuttle were to fly an average of 8 flights per year, at $4 billion average annual appropriation, it would take about 68 additional years, and approximately $270 billion, to reach the original goal of 580 flights. In addition, the Shuttle recovered few of its operating costs during the 1980s, and will not recover many in the future due to a policy decision against flying commercial flights and DoD's decision to minimize its Shuttle flights.

Figure 14.5 shows actual Shuttle performance (solid line, with circles showing individual flights) versus various predicted flight plans (dotted lines).[34] It shows that predictions were repeatedly missed. Each delay -- the horizontal distance between prediction and actuality -- represents unaccounted costs and disappointments to payload operators.[35] Data on the costs of delays are not readily available. It now seems that a more achievable flight rate is planned. However, the next major task for the Shuttle is assembling the Space Station, which will require some twenty flights be flown in sequence as scheduled years in advance, which has never occurred.

Typically Shuttle flights are flown in an order and on dates very different from those originally planned. For example, reading from the January, 1984 manifest, the fifteen flights 10 through 24 were scheduled to fly in that order, i.e., 10, 11, 12...24. The next fifteen flights actually flew in the following order: 10, 11, 12, 14, 16, 18, 19, 17, 22, 21, 24, 25, 27, 29, and 30. Table 14.2 shows how the launch dates planned in various published Shuttle manifests for representative payloads become disordered. Mostly the launch dates slip (delay) but occasionally they move ahead, or move to a different orbiter. This is

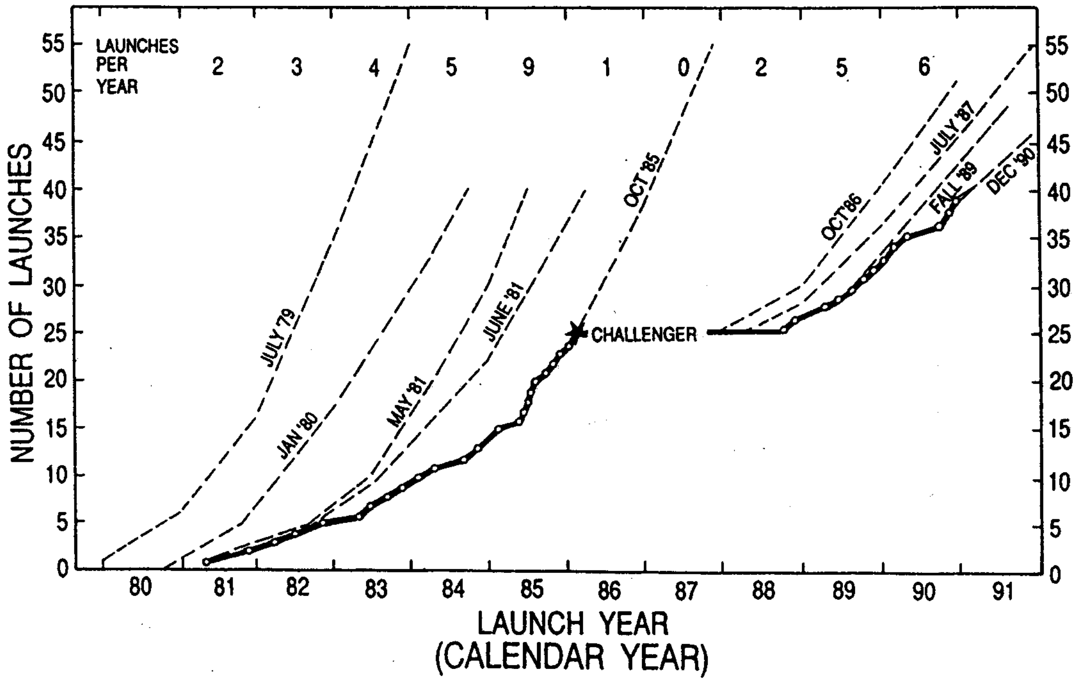


Figure 14.5: Shuttle Schedule vs. Actual Performance. Shuttle manifest plans versus actual launches. Flight delays are shown by the horizontal distance between manifest (dotted line) and actual (solid) for a given flight number. Note that more manifests were planned than could be plotted on this graph.

Table 14.2. Launch date and vehicle for 11 primary payloads as scheduled on 6 different manifest dates. n.a.= Not Available.

LAUNCH SCHEDULE FOR VARIOUS SHUTTLE PAYLOADS
(Payload Manifest Date)

Payload	8/84	6/85	10/86	8/88	1/90	12/90
LDEF RET	3/18/85 Discovery	9/24/86 Challenger	11/15/90 Atlantis	11/13/89 Columbia	1/9/90 Columbia	Launch 1/9/90
HST	8/6/86 Atlantis	8/8/86 Atlantis	11/17/88 Atlantis	2/1/90 Atlantis	4/18/90 Discovery	Launch 4/24/90
ASTRO-01	3/6/86 Columbia	3/6/86 Columbia	1/19/89 Columbia	3/1/90 Columbia	5/9/90 Columbia	Launch 12/12/90
SLS-01	12/22/86 Challenger	n.a. n.a.	12/7/90 Discovery	6/7/90 Columbia	8/29/90 Columbia	5/91 Columbia
ULYSSES	5/15/86 Challenger	5/15/86 Challenger	n.a. n.a.	10/5/90 Atlantis	10/5/90 Discovery	Launch 10/6/90
GRO	5/88 Atlantis	n.a. n.a.	1/18/90 Columbia	4/5/90 Discovery	11/1/90 Atlantis	4/91 Atlantis
IML-01	n.a. n.a.	n.a. n.a.	4/20/90 Discovery	4/11/90 Columbia	12/12/90 Columbia	12/91 Atlantis
TDRS E	n.a. n.a.	n.a. n.a.	n.a. n.a.	11/18/90 Discovery	1/31/91 Discovery	7/91 Discovery
ATLAS-01	n.a. n.a.	n.a. n.a.	1/17/91 Discovery	12/20/90 Columbia	4/4/91 Columbia	4/92 Atlantis
TSS-01	12/22/87 Atlantis	n.a. n.a.	10/25/90 Columbia	1/31/91 Atlantis	5/16/91 Discovery	3/92 Discovery
UARS	n.a. n.a.	n.a. n.a.	n.a. n.a.	9/26/91 Discovery	8/22/91 Discovery	11/91 Discovery

especially important for the Space Station assembly because the orbiters are not equally capable. Thus, station payloads should be designed to go on any orbiter, and perhaps to be assembled in various sequences where possible.

Of course some of the rescheduling shown is due to payload-specific problems and the Challenger accident, but that is the nature of a manned, reusable system: Because it is manned, safety comes first and delays result. Because it is reusable, delays in one mission necessarily delay later missions using the same orbiter. Thus, predicted flight rates are already less than a fourth of those predicted at the program's inception.

Table 14.3. Launch Vehicle Success Rate Through 1988

Vehicle	Average Success Rate
Ariane	77.8%
Atlas E	89.3%
Atlas/Centaur	89.7%
Titan	94.4%
Delta	95.2%
Shuttle	96%
Scout	100%
Saturn V	100%

Table 14.4. Major Manned Space Program Costs

Program	Cost
Apollo	$85 billion[36]
Mercury, Gemini, Apollo, Skylab, and Apollo-Soyez	$100 billion[37]
Shuttle (through 1990)	$65 billion

The performance of the Shuttle may also be measured against other launch vehicle programs. However, this is difficult because of the uniqueness of the Shuttle. Table 14.3 shows launch success rates for various vehicles through 1988, which must be read in recognition that the Shuttle is the only man-rated vehicle launched by the U.S. in the last 15 years.[38] The Shuttle compares well.

Table 14.4 compares the costs of three manned space programs. These comparisons are meaningless without relevance to program achievements. Clearly the goal of exploration is defined broadly enough that the Shuttle program meets it. However, it is not so clear that the Shuttle meets the criteria of being the "next logical step", e.g., towards a mission to Mars. Program goals should be specific enough and achievable in short enough time that progress towards them can be definitively measured. The Apollo program certainly achieved its principal goal -- that of demonstrating U.S. technical preeminence by putting a man on the moon and returning him safely to earth within 8 years of program inception.

Another simple, quantifiable measure of performance is payload mass capability. The original promise for the Space Shuttle was 65,000 pounds to a 180 km, 28 degree orbit.[39] Now, the average capability of the three active orbiters is about 49,000 pounds to the same orbit, a decrease of about 25%.[40] It should be noted here that the Shuttle puts about 250,000 pounds into orbit each launch, but about 200,000 pounds – the weight of the orbiter – comes back to Earth. This is a cost of reusability and of having a manned transportation vehicle. Another such cost arises from the need to make manned flights as safe as possible: Thus even unmanned payloads must also be man-rated. For example, the Shuttle-Centaur upper stage rocket was canceled when, after spending hundreds of millions of dollars, it was decided that the stage could not be made safe enough for deployment from the Shuttle.

The fact that the Shuttle gives us a manned space program is a clear, if non-quantitative measure of performance. Seen in this light much of the cost of the program can be attributed to the symbolic, rather than operational, aspects of the program. In this case it would be in the best interests of the nation to separate from the manned program that which does not have to be included. That is, payloads not needing manned intervention could be flown on ELVs, thus avoiding costly delays. In parallel the U.S. could pursue a vigorous, but independent, manned program where costs could be directly attributed to the symbolic. This separation could be done within NASA.

Given the Shuttle, and that its performance is expected to be in the range outlined above, it is possible to set goals for it and other programs that are consistent with relevant experience. For example, we should not expect the Shuttle to fly more than about 8 times a year, nor for less than about 4 billion dollars per year. While it is possible that the Shuttle may exceed these expectations, it is also possible that it will fail to meet them. We should not plan a space station needing more flights, nor reliable launch dates. Similarly policymakers should not commit our space program to planned capabilities of a new launch system until there is some evidence that performance will approximate promises.

Table 14.5. Summary comparison of goals established at program approval and actual achievements for the Shuttle program through 1990.

GOAL	PROMISE	PERFORMANCE
First Flight	1978	1981
Total cost	$51 billion	$65 billion
Average cost per flight:		
Including development	$88 million	$1.7 billion
Excluding development	$14 million	$1.1 billion
Flight rate:		
Annual average	48	4
Total	580	37
Payload mass	65,000 pounds	49,000 pounds
Manned capability	yes	yes
Reusable	yes	yes

Concluding Remarks

As the nation considers whether to embark on another major space program -- a human visit to Mars -- it is well to review the performance of the Shuttle program:

First, table 14.5 shows that the Shuttle has not achieved its goals. This should be remembered when considering the promises made for current civil space program alternatives.

Second, for useful program appraisal clearly-defined short-term goals are necessary. These can be used as measures of progress before large amounts of resources are committed. Goals should be specific and must include near-term objectives so that performance can be easily measured, and so that the program's political support can be solidified on a basis of cumulative success rather than on the hope of achieving fabulous promises in the distant future. That is, the evaluation of program performance with respect to specific goals should have quick turnaround times so that successes can be fed back for a positive effect on mission justification. Failures provide an opportunity for constructive correction of both policy direction and pace. Currently, many programs are designed with objectives that cannot be measured until a large amount of resources are spent. This complicates the evaluation process until it is too late to redirect monies from poorly-performing or non-performing projects. One possible set of criteria for program evaluation are cost, schedule, and performance as used in this paper.

Third, for the remaining half of its productive life we should operate the Shuttle based on a realistic view of its capabilities. During the 10 years of operations the Shuttle has proven to be neither cheap nor reliable; rather it is expensive, difficult to hold to a schedule, and the only U.S. means to launch humans into space. Acceptance of these facts would allow formulation of realistic launch policy. This, in turn, would allow for a realistic assessment of the Shuttle's role in the Space Station program and in any large scale human exploration program. Furthermore, when the decision to build a new launch system is made, it will be based on a clear picture of what shuttle capabilities allow, giving the new system a better chance of performing as promised.

Finally, for the U.S. to have a vigorous and productive manned space program we need to tailor our engineering, resources, and policy to fit realistic, achievable goals rather than being forced to alter unrealistic goals to fit the unforgiving realities of engineering, resources, and politics.[41]

Notes

1. Statement of James C. Fletcher, NASA Administrator, testimony before the Subcommittee on Space Science, and Applications, Committee on Science, Space, and Technology, House of Representatives, February 2, 1989.

2. J. Lawrence, *NASA Activities*, Vol. 21, #6, p.3 (1990).

3. Proceedings of the *Fourth National Space Symposium*. For example note J. Fletcher, "To be sure, the Shuttle has done what it was meant to do; it remains the most versatile, flexible, and useful flying machine in the world." (U.S. Space Foundation, Colorado Springs, CO) 1988.

4. "Report of the committee on the future of the U.S. space program," Washington, D.C. (1990).

5. The agreement can be defined as follows: All parties involved publicly agree upon goals for the program (in this case cost schedule, and capability), and this is established in Congressional Committee hearings and legislative reports which form the foundation on which public law is based. For comparison, goals which are not formally agreed upon, such as institutional needs or moving dollars to Congressional districts, may be thought of as the effective goals of the program. These goals are generally not part of the formal agreement.

6. The term "promise" has been chosen because it reflects a formal agreement, as described above. Some may assert that initial program promises are not to be taken seriously, i.e., they are overly-optimistic forecasts necessary to gain program approval. If program performance is important then a measure of performance is necessary.

Moreover, unless programs perform comparable to the expectations on which they are bought and sold, there can be little hope for any improvements in the policy process.

7. All cost data in this paper are in 1990 dollars, calculated using GNP price deflators from the Department of Commerce. Also total, annual, and average per-flight costs are calculated using NASA costs only, i.e., DoD costs are not included. Source for NASA budget data: 1970-1992 NASA Budget Estimates. (Actual expenditures used when available).

8. There are several analyses of Shuttle costs. Two representative examples are: Toman, M. A., and Macauley, M. K., No Free Launch: Efficient Space Transportation Pricing, *Land Economics*, Vol. 65, No. 2, May 1989, pp. 91-99 and "Space Shuttle Pricing Options", Congressional Budget Office, (March, 1985).

9. This paper does not attempt or perform an economic analysis of marginal costs for two reasons. First, Toman and Macauley (1989) have already tackled this problem. Their analysis was technical and because Shuttle program costs are not accounted in a way that allows understanding of how costs should be allocated, (i.e., which costs should be amortized over how many flights), they were forced to make several limiting assumptions. Until better data are available, further analysis of this type may not be useful. Second, it may not make sense (beyond what Toman and Macauley have done) to treat the Shuttle program in a standard economic manner: The de facto policy has been to fly the Shuttle as often as possible, and all cost data have originated under this policy. Furthermore, there is no economic "market" for Shuttle flights because most carry captive NASA payloads which fly on the Shuttle without consideration of price. For example, a NASA science payload can be given a "free" launch on the Shuttle or has the alternative of buying an ELV launch on the market. The science program sees its budget choices as: 1) no cost for the Shuttle launch and 2) a significant cost, i.e., market price, for an ELV launch. In this sense the Shuttle launch is "free" to the internal NASA users, although not free to taxpayers. Finally, resources are made available to the program through a political appropriations process not through a process of sales generating revenues.

10. For example see J. Logsdon, Science, Vol. 232, 1099, (1986); S. Pace, "Engineering Design and Political Choice: The Space Shuttle, 1969-1972", M.S. Thesis, MIT May, 1972; A. Roland, "The Shuttle: Triumph or Turkey", *Discover*, November, 1985 pp. 29-49; and R. D. Launius, "The Development of the Space Shuttle, 1967-1972: Technological Innovation and Governmental Politics", unpublished manuscript, NASA History Division, Washington, DC (1991).

11. NASA, Space Shuttle, information booklet, (October, 1972), p. 14.

12. As will be seen below, civil service salaries make up about 15% of the shuttle program's total cost. $8 billion errs on the side of being too large i.e., it makes the comparison more favorable to the original estimate. Adding this here gives a number which can be compared with our tabulation of actual total costs below.

13. NASA, Space Shuttle, information booklet, (October, 1972), p. 14.

14. For a complete description of NASA budget categories see the annual NASA budget requests to Congress.

15. It is beyond the scope of this paper to break down the program's cost into component parts (which would be necessary for a marginal cost calculation). Therefore the R&D /operations distinction is irrelevant, hence it has not been made.

16. All input necessary to compute the algorithm is available in the annual NASA budget request.

17. U.S. House of Representatives, United States Civilian Space Programs: 1958-1978 - Volume I, (January 1981) pp. 603-604.

18. NASA, Budget Estimates, Fiscal Year 1992, Volume 1. NASA, 1991. page 5F SUM 4.

19. U.S. General Accounting Office, *Budget Reimbursements: The National Aeronautics and Space Administration's Reimbursable Work*, GAO/NSIAD-87-171FS, U.S. G.A.O., June 1987, p. 9, and T. Dawson, personal communication.

20. The 1987 NASA budget also included an additional $2.3 billion (1990 $) for the orbiter which was procured to replace the Challenger. This figure is included in the total cost calculation.

21. U.S. General Accounting Office, Testimony presented by C.A. Bowsher, before Subcommittee on Government Activities and Transportation, House Committee on Government Operations, May 1, 1991. Additive costs are the variable costs of consumables associated with each flight, i.e., the costs of fuel, expendable hardware, etc..

22. The average costs per flight displayed in these two figures include shuttle development costs. This is so that projected average costs may be compared with original promises. To calculate an average cost per flight for the remainder of the program, divide average annual appropriation by average flight rate.

23. It should be noted that this number is marginal, as well as average, if annual flight rates and appropriations do not vary a great deal from these numbers.

24. The 1987 budget contained $2.1 billion for the replacement orbiter which would be $2.3 billion in 1990 dollars. To be conservative some additional costs were not counted: Approximately $400 million for structural spares had already been procured and were used in the replacement. Further, about $100 million for main engines was not included in the $2.3 billion.

25. Office of Technology Assessment *Access to Space: The Future of U.S. Space Transportation Systems* (OTA-ISC-415, Washington, DC: U.S. GPO) 1990.

26. This figure is arrived at by multiplying the expected chance of failure on one flight (0.02) by the cost of a replacement orbiter ($2.3 billion). For example, had the cost of Endeavor, the Challenger replacement, been assessed on a per flight "surcharge" basis rather than in a lump sum, it would be paid for after the fiftieth flight. Through 1990 the shuttle launched 38 times with one loss. Due to the fact that shuttle reliability can not be known with a high degree of accuracy, such a method of determining the surcharge amount might or might not recover the full cost of replacement orbiters. The $2.3 billion cost for replacement orbiters is conservative because it does not include costs of "structural spares" and shuttle main engines which were paid for elsewhere. See note 24.

27. For more information on Space Shuttle launch rates consult: Committee on NASA Scientific and Technical Program Reviews, Commission on Engineering and Technical Systems: *Assessment of Constraints on Space Shuttle Launch Rates* (1983) and National Research Council *Post-Challenger Assessment of Space Shuttle Flight Rates and Utilization* (National Academy Press, Washington, DC. 1986).

28. National Research Council (1986), pp. 4-5 (see note 27).

29. Atlantis flew twice before the Challenger accident and gave indications that it could be expected to perform as well as Discovery.

30. Not surprisingly, many small problems are discovered in preparation for a first flight. Similarly, the seventh flight of Columbia is ignored as it had been out of service while at the factory for several years for modifications.

31. However a 1988 OTA report has expressed concerns that the 75 workday turn-around is too ambitious. See *Reducing Launch Operations Costs: New Technologies and Practices*, OTA-TM-ISC-28 (Washington, DC: U.S. GPO, 1988).

32. U.S. Congress, Office of Technology Assessment, Reducing Launch Operations Costs: New Technologies and Practices, OTA-TM-ISC-28 (Washington, DC: U.S. GPO, September, 1988). p. 41.

33. Additionally, in an unpublished 1986 white paper prepared for the Rogers' Commission NASA determined that costs per flight were underestimated by 475%.

34. Even more schedule predictions were made than could be presented on the graph. This graph has been provided by Bruce Murray.

35. For example, flight 20 was predicted (in July, 1979) to occur early in 1982. Given satellite lead times, construction of the payload had to be occurring by July, 1979, i.e., costs incurred. The chart shows that flight 20 actually launched in mid-1985, three years late. If it were a communications satellite the builder would have paid three years interest on the investment -- some millions of dollars.

36. This number is probably underestimated. The Augustine committee cites $95 billion for the cost of Apollo, source: NASA Historical Data Book, Volume II: Programs and Projects 1958-1968, (NASA SP 4012,) (1988). NASA, Washington, D.C.

37. NASA (1988) p. 121 (see note 37).

38. Chart reproduced from *Reducing Launch Operations Costs*, Office of Technology Assessment (1988). Data on Saturn V from *U. S. Civilian Space Programs 1958-1978*, Committee on Science and Technology, U.S. House of Representatives (1981).

39. NASA, Space Shuttle, information booklet. (October, 1972), p.1.

40. *Access to Space: The Future of U.S. Space Transportation Systems*. p.41, and T. Dawson personal communication. It should be noted that some NASA payload weights include items such as the space suits, the robot arm, and the galley, all of which return to Earth with the orbiter.

41. We would like to acknowledge the useful comments made by Ronald Brunner, Terry Dawson, Pete Didisheim, Millard J. Habegger, Donald Hearth, Molly Macauley, Richard McCray, David Moore, Richard Obermann, Michael Rodemeyer, William Smith, Alan Stern, Skip Stiles and Albert Wheelon on earlier drafts of this paper. We would also like to thank Patricia Duensing for her efforts in the preparation of this paper. However, as usual, all responsibility for the content lies solely with the authors.