A Presentation Paper

The Joint Confidence Level Paradox:

- A History of Denial -

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NASA's Joint Confidence Level Paradox: A History of Denial

Introducing the Joint Confidence Level - Probabilistic Calculator (JCL-PC)

(The authors provide Historical Evaluation of Cost and Schedule Estimating Performance During NASA's Tenure as an Agency - Following which they introduce an optimum Hybrid model for more accurately calculating Cost and Schedule estimates in NASA's Complex systems engineering environment.)

The authors have endeavored to make objective determinations in selecting historical information that seemed most appropriate toward achieving a fair and equitable treatment of the subject matter presented herein. Although some data is in conflict with others, every effort has been made to validate content integrity by citing sources within footnotes and carefully inputting the referenced data, thus preserving original accuracy, correctness, value, sufficiency, and completeness of the information. While no error was knowingly permitted to remain in this presentation, the authors shall have no liability to any customer or other using party for any loss, expense, or damages (direct or indirect) including consequential, incidental, special, or punitive damages, lost profits or lost revenue arising out of or caused by any inadvertent error or omission in connection with the information contained herein.

Foreword

Cost Estimating and NASA's Changing Culture

This paper is intended to provide a reliable methodology for those tasked with generating price tags on construction (CoF) and research and development (R&D) activities in the NASA performance world. This document consists of a collection of cost-related engineering detail and project fulfillment information from early agency days to the present. Accurate historical detail is the first place to start when determining improved methodologies for future cost and schedule estimating. This paper contains a beneficial proposed cost estimating method for arriving at more reliable numbers for future submits.

When comparing current cost and schedule methods with earlier cost and schedule approaches, it became apparent that NASA's organizational performance paradigm has morphed. Mission fulfillment speed has slowed and cost calculating factors have increased in 21st Century space exploration. Two reasons stand out:

1) The rapid development mindset in the "space race" territory of yesteryear was supported by "frontier risk" thinking. Risk aversion at all costs was not yet a NASA moniker. Back then, an "acceptable risk level" was supported as a defensible reality. This "allowable hazard" paradigm is not accepted as a mission philosophy today. Slower development schedules have replaced earlier more aggressive performance timelines. Expanded regulatory constraints in the area of safety and mission assurance have increased engineering redundancy processes which, in turn, push fulfillment schedules to the right. The previous "can do" bravado has been supplanted by a "can do with caveats" culture. The "zero failure" standard has resulted in a far more complex mission readiness protocol when standing up a new space program.

2) NASA of today has multiple contracting tentacles under its current business umbrella. Contracting requirements in today's CoF and R&D worlds are more complex which inevitably slows procurement and sub-development efforts. Regulatory constraints further complicate the systems engineering world. Streamlined development in former times meant beating the calendar. Streamlined development today usually means complying with a myriad of checklists and trying to tie down highly volatile baselines while still demonstrating visible progress toward project end-goals. Concurrent development of back-up scenarios that can, if necessary, be brought on line with minimal cost and schedule impact inevitably slows the overall timeline. Calendar targets (though still acknowledged as important in the NASA planning world) have become subordinate to an expanded landscape of engineering, organizational, and regulatory constraints, protocols and procedures.

We leave the efficacy of the "old" and "new" development paradigms within NASA to the judgment of the reader.

NASA Credibility Hangs in the Balance

GAO
Accountability ★ Integrity ★ Reliability

United States General Accounting Office
Washington, D.C. 20548

"NASA has yet to implement a well-defined process for estimating the cost of its programs—a weakness we and NASA's Inspector General have repeatedly reported."

See, for example, GAO-04-118; GAO-04-255; GAO-03 114; U.S. General Accounting Office, *Space Station: Actions Under Way to Manage Cost, but Significant Challenges Remain*, GAO-02-735 (Washington, D.C.: July 17, 2002); *NASA Program Costs: Space Missions Require Substantially More Funding Than Initially Estimated*, GAO/NSIAD-93-97 (Washington, D.C.: Dec. 31, 1992); and NASA Office of Inspector General, *Final Management Letter on Failures in Cost Estimating and Risk Management Weaknesses in Prior Space Launch Initiative Assignment Numbers A-01-049-01and A-01-049-02*, IG-03-023 (Washington, D.C.: Sept. 29, 2003).

May 28, 2004

The Honorable Sherwood L. Boehlert
Chairman
The Honorable Bart Gordon
Ranking Minority Member
Committee on Science
House of Representatives

The lack of reliable financial and performance information has posed significant challenges to the National Aeronautics and Space Administration's (NASA) ability to manage its largest and most costly programs effectively. For nearly 15 years, NASA contract management has been on GAO's high-risk list—due in part to NASA's inability to collect, maintain, and report the full cost of its programs and projects.[1] Without such information, NASA has consistently developed unrealistic cost and schedule estimates, which, at least in part, are reflected in the cost growth and schedule increases in many of its programs.

NASA's Joint Confidence Level Paradox: A History of Denial

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Abstract:

NASA purports to seek joint probable cost and schedule reality for our programs - yet we intentionally omit discernable risks from our comprehensive analyses studies. Underestimating risk vicissitudes (and consequently under-shooting cost and schedule projections) is a well verified NASA phenomenon. However, NASA rarely acknowledges publicly this pattern of aiming high and shooting low. Cost and schedule estimating candidness has proven difficult to come by. NASA should actively pursue a course that will change our prevailing reluctance to "tell it like it is in the cost and schedule world." The goal of this paper is to be a catalyst in facilitating that change.

In this publication, we will examine historical evidence relative to underestimating both costs and schedules for long-term NASA programs and other large scale projects. We will also look at how skewed confidence levels resulting from ultra-optimistic estimates can jeopardize program continuance. Furthermore, this study will examine detail accuracies and discuss methods of risk quantification. If the presentation seems to become too hard hitting at times, it is because we have followed the advice of Winston Churchill when he counseled: *"If you have an important point to make, don't try to be subtle or clever. Use a pile driver. Hit the point once. Then come back and hit it again. Then hit it a third time - a tremendous whack."*

The presentation approach we have chosen for this paper was calculated to win support for the recommendations presented herein and is ultimately aimed at achieving endorsement from NASA's top decision makers in an effort to reverse the practice of submitting historically low cost projections and overly optimistic schedule milestones. Every effort has been made to reflect NASA's actual business reality - i.e. the way NASA builds programs, fulfills its objectives, and achieves its goals. Relevant case studies and examples will be provided going back in history even before NASA's organizational genesis. These examples reveal that the cost-schedule paradox is a morass that has chronically plagued the financial estimating community and construction schedulers throughout a variety of work venues for the past 200 years.

The primary objective of this presentation is to introduce to the NASA business community what the author's feel is the optimum hybrid model for accurately estimating cost and schedule reality in complex science and engineering environments where maturing technologies are present. We refer to this heuristic model as the ***Joint Confidence Level - Probabilistic Calculator (JCL-PC)***. The JCL-PC approach merges years of professional analysis into a tool which compensates mathematically for what human monitoring cannot determine, foreshadowing the need for illusive fiscal requirements and schedule realities so essential to reliable cost estimating output.

Key Words: Joint Confidence Level (JCL), Cost Overrun, Cost Growth, Schedule Slip, Estimate Confidence Level, JCL-PC, Boondoggle, Monte Carlo, Probabilistic Estimates, Risk

A Paradox at NASA

A paradox is a statement that contradicts itself. We at NASA purport to seek the *joint probable cost and schedule* for our programs yet we exclude many credible risks from our analyses. To paraphrase Occam's razor: "The simplest explanation is often the correct one" leads us to two possible conclusions:

- Conclusion 1: We really are not seeking probable cost and schedule accuracy, but are primarily concerned with keeping programs viable and fundable as long as possible.
- Conclusion 2: The variables are too complex, unquantifiable, and incalculable.

With respect to conclusion #1, an unidentified European civil servant has observed:

> **"You will (as a planner) know the real costs. You will realize that the budget is too low but it is difficult to pass such a message to the managers and the private actors. They know that high costs reduce the chances of funding."**
>
> *Author Unknown*

If this form of malfeasance is real - though never spoken - then we must all sadly confess that ethics training has failed us at the very foundation of our professional identity. We would hope that expediency would never cloak our responsibility to tell it like it is. If, however, staying afloat in this "half truth" way has been done in the past, we can certainly resolve that it will NOT be resorted to in the future. We owe this to ourselves and to the worthy reputation that NASA has won during its matchless career as an agency.

With respect to conclusion #2, we submit that although the science/art of cost and schedule estimating is multi-layered and multi-dimensional, outcomes ARE more discernable than current cost and schedule methodologies will allow. Joint Confidence Level (JCL) analysis is being sold as a panacea for solving the ills that have dogged the cost estimating community. We hold that JCL, as it is currently being implemented, will not deliver reliable results currently being advertised. Something more is needed!

This paper presents a case for what that additional "something more" is. We acknowledge that probability analysis IS indeed complex, but it does have bounds and dimensions that are quantifiable and which will give up steering secrets when probed with the right tools. Our approach engages additional types of assessment techniques. Starting with the best estimates that our subject experts can provide, we 1) *perform distributive curve statistical analysis*, together with 2) *project phase evaluation* in such a way as to predict with substantially greater precision the final cost and schedule outcomes of new engineering efforts. We refer to our tool as the **Joint Confidence Level - Probabilistic Calculator or JCL-PC**. We are confident that implementing the JCL-PC will assist NASA in achieving the long sought for accuracy in its budget creation process and funding profile submissions. The need for the JCL-PC will be defended in the following pages of this paper which assembles evidence and statistics compiled from many decades of historical recordkeeping.

What is a JCL?

Simply stated, Joint Confidence Level (JCL) is the output data provided by a probabilistic Monte Carlo calculation, expressed as a percentage. Example, we are 50% confident that we can achieve our stated goal(s) by our stated completion date, given our current estimated funding level. This is a confidence level declaration that only looked at cost probabilities. Much has been written and is readily available on the subject of estimate confidence levels for those desiring to enhance their understanding.

Biases Defined

"Bias" refers to any consistent tendency based on human perspective for estimates to be lower or higher than actual cost outcomes. "Dispersion" relates to the probability (likelihood) that an individual estimate may differ from its actual cost, even after the bias is taken into account.

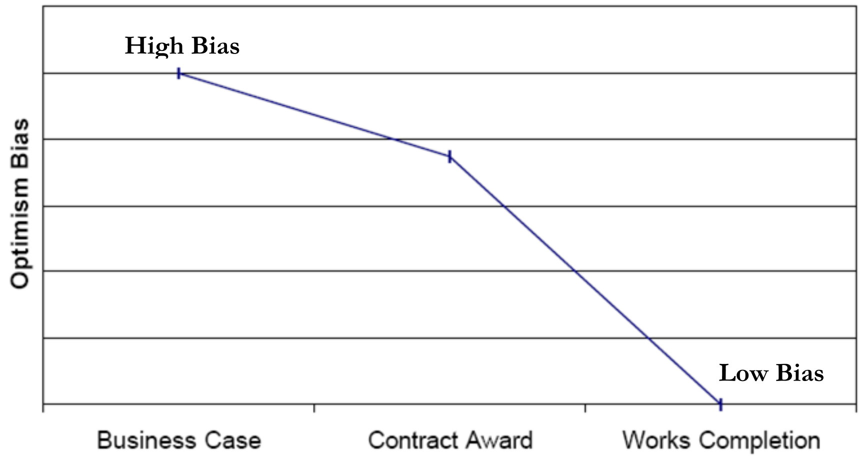


Figure 1: *Optimism Bias Chart*

Optimism bias is defined as a measure of the extent to which actual project costs *(both capital and operating)* and actual project duration, or the time it takes from contract award to benefit delivery, exceed the *estimated* cost and time data. *Optimism bias* is a measure of the degree by which the actual benefits delivered by a project fall short of the benefits that were estimated. Optimism bias means project achievements fall short of expectations. If a cost estimator has an optimism bias, they will underestimate project costs and completion schedules. Possessing an *anti-optimism bias* means having the ability to determine (in advance) with a meaningful measure of accuracy how events and costs will actually come to pass. Through the use of various tools (e.g. deductive reasoning, mathematical analysis and other outcome adjustment techniques) estimates can be made to turn out close to actuals when all is said and done. To a cost estimator or budget analyst this is nirvana.

Early estimates of important parameters are generally inaccurate in two respects. Such estimates are almost always *biased* toward optimistic outcomes. Second, in addition to this natural positive bias, subjective errors in estimating cost calculations reveal large variations or dispersions.[1]

This paper will examine historical program cost and schedule accuracies (or lack thereof) and discuss several methods of risk quantification (noting limitations of each) and then introduce a methodology that will place the estimator on much more credible ground in providing trustworthy estimates. It must be stated that historical perspective is essential to understanding the nature of our challenge. NASA's way of doing its cost and schedule analysis in the past must give way to a new frontier. That frontier includes a hybrid model for NASA to use in calculating with greater precision its joint cost and schedule confidence levels and estimates.

> **"Scientists tend to downplay costs early to convince NASA that their project is cheaper than someone else's. Later, once NASA commits and the money is being spent, more bucks are needed - so NASA spends more instead of canceling the project."**
>
> *Mike Griffin – NASA Administrator*

[1] RAND Predictability of the Costs, Time, and Success of Development, 1959

The Importance of Determining "Project Phase"

In addition to resolving the problematic estimating factor of *optimism bias*, there is one more variable that must be dealt with in order to achieve reliable estimates. Determining where the "program/project" sits on the completion timeline is tantamount. Put another way; accurately identifying what stage the project is in is essential to providing reliable estimates. When estimates are created early in the process, the estimator can only be guided by existing design plans and schedules. As development proceeds, initial designs and plans are often changed. This happens because of unforeseen technical difficulties that will prevent meeting performance requirements or to opt for tradeoffs where the net effect is to increase end-product performance.

For example, on the Delta V program, the operational facilities were being constructed concurrently with the rocket. When the new RS68 engine was finally tested, it did not meet the expected performance criteria, possibly due to optimism bias. The solution meant obtaining additional fuel capacity which required an increase in the diameter of the propellant tanks. This single change reverberated down through the program and drove "cause and effect" impacts on the rocket, facilities, and ground support equipment. Taken together, there was serious program cost and schedule impact.

This type of error is not the exception - but the rule. The paradox that remains to be solved can be framed into the following question: *How do we estimate something we don't yet know we need?* A variation of this question is: *How do we estimate requirements which management is not yet prepared to acknowledge?* When "deferred or unrecognized requirements" are finally clear enough to deal with, the Change Requests (CR's) initiated inevitably affect cost and schedule in a problematic way. Too often (by the end of the project) final costs incurred were not based on the initial BOE, thus making it impossible to reconcile final costs with initial estimates. When the real costs eventually come home to roost and the full extent of project growth can be clearly seen, the estimator rightfully states that what was actually built - was NOT what was originally estimated.

The phenomenon of "underestimating" risk and consequently cost and schedule is not new or unique to NASA. This cost-schedule morass has existed for at least 200 years of recorded history. In 1869, the Suez Canal's cost overrun was 1,900%. Claire Brown[2] observed that prior to World War II, "virtually no government agency had to account for its costs or budgets." A plethora of studies have sought the reasons for the occurrence of such sizeable fiscal cost differentials. Understanding cost estimating infidelity has been an illusive pursuit due to the challenge of obtaining valid information. Nevertheless, it is meaningful that many experts still find agreement on the causes. To date, despite numerous attempts to eliminate cost and schedule over-runs, the trend of cost/schedule unreliability continues.

"The further backward you look, the further forward you can see."

Winston Churchill

"Enough material has been written on the subject of cost growth during the last ten years to fill a minuteman silo. Unfortunately, cost growth is STILL with us."

Witness to House Armed Services Committee (HASC) 1982

[2] An Overview of the Cost Accounting Practices Used for U.S. Defense Weapon Systems 1982

In many cases, project leaders or senior decision makers do not want a rigorous objective cost risk analysis because of the possibility that candid findings could cause a favored project to be canceled.[3] The thinking is that if true costs are known beforehand, many projects would not be undertaken at all since they will not clear cost benefit analysis hurdles. The "play-it-safe-notion" often prevails - meaning that even if high overruns occur down the road, many project/program owners will be trapped into "program continuance" by the sunk cost principle. That is to say that during project execution, when cost overrun becomes visible, termination becomes unacceptable - and even though continuation will not prove to be economical, the logical decision will still be to proceed forward to completion.

Large Program History

Although there are volumes of information on the cost and schedule of various NASA projects, we will cite a few of the credible studies to date and briefly examine the best available data in an effort to ground our discussion and place any extrapolated conclusions on solid footing. NASA and DoD projects explore achievements at or near the margin of technical feasibility and often employ cost plus contracts which carry very little penalty for under-stating costs. Hence, contractor firms have a decided incentive to choose the way of under-estimation in order to get the contracts.

We can predict with high likelihood that program costs will increase and schedules will slip as projects go forward. The performance equation reveals that both the cost of completion and the time estimated for completion will increase. Cost escalations of 100% and more are not uncommon - even increases of up to 200% occur more commonly than realized. Schedule growth is also common, the amount seems closely correlated to project type.

> **"Those who do not learn from the past are condemned to repeat it."**
>
> *George Santayana*

> **"There's an unwillingness to recognize that there has to be a real contingency, a large contingency, built into any experimental program."**
>
> *W. M Allen - President Boeing - 1964*

Assembling reliable historical data containing adequate detail has been more difficult than might be expected. Apparently, the majority of the researchers on the cost-schedule landscape have faced the barrier of insufficient apples to apples detail. Some projects show contingencies - some don't. Still other projects hide contingency for fear of being removed by the budget axe. Also, many projects bury their initial estimates and publish revisionist history as though it were pristine original data so they don't look so bad in retrospect.

Another key area of concern is the moving target of yearly inflation and cost escalation. Do the historical budget numbers show base year prices or were the out-years adjusted by some inflation rate tied to then current year dollars? Are the available numbers static with base year rates projected out over the life of the program? These are often unknown - making precision comparisons difficult. Perhaps it was the NASA environment that gave rise to the tongue-in-cheek humor that spawned the following quote:

[3] RAND Impossible certainty : cost risk analysis for Air Force systems / Mark V. Arena 2006

"It's tough to make predictions, especially about the future."

Niels Bohr & later Yogi Berra

Anticipating the Improbable

Las Vegas casinos spend hundreds of millions of dollars on risk management, including high tech surveillance systems, and Monte Carlo analysis. Yet the four largest losses casinos have incurred or narrowly avoided fell completely outside their sophisticated models[4].

- They lost $100 million when Roy Horn was mauled by a tiger at MGM Mirage. The tiger was raised by the performer and even slept in his bedroom. The casino had considered that the tiger may jump into the crowd, but they never thought to insure against what happened.
- A construction worker was injured during the construction of a hotel annex. He was so offended at the settlement offer that he attempted to dynamite the casino.
- Casinos are required to file a special form with the IRS documenting a gamblers profit if it exceeds a certain amount. The employee who was supposed to mail the forms hid them (for unexplainable reasons) in boxes under his desk. This went unnoticed for years before being discovered. The casino nearly lost their gambling license, and had to pay a huge fine.
- In 1993, Steve Wynn's daughter was kidnapped. He raided the casino coffers to obtain the ransom, at the risk of losing their gambling license.

The dollar value of these unknown improbable events exceeds the value of the known & modeled risks by 1,000 to 1, yet there was no allowance for any kind of unexpected impact in analysis.

America's First Aircraft Program

In 1898, in spite of the "conventional wisdom" of the day that heavier-than-air flying machines were impossible to construct, Dr. Samuel P. Langley was actively engaged in developing the first human airplane.

By all reasonable criteria, Dr. Langley was the best and brightest program manager we had. In public stature and prestige, Langley was the most prominent scientist in the United States. Dr. Langley was a brilliant visionary who dedicated the later years of his life to the pursuit of inventing the airplane. After becoming Secretary of the Smithsonian in 1886, he immediately instituted a flight research program using Smithsonian's resources. In 1896, following ten years of sustained experimentation, Langley finally proved that human flight was achievable when his 16-foot unmanned flying machine (powered by a steam engine) flew nearly a mile.[5]

Then in 1898, Langley succeeded in convincing the Department of War to fund a $50,000 program to take his experimental research to the next level. He hired a full-time staff of 10. Langley told the War Department[6] with "confidence" that "the machine will be completely built and ready for trial within a year" - meaning by 1899. As it played out, Langley would spend the entire $50,000 provided by the War Department, run out of money, and then raise another estimated $20,000 from other sources and work for five more years before attempting his first test flight.

[4] The Black Swan: The Impact of the Highly Improbable Nassim Nicholas Taleb 2007
[5] To Conquer the Air, James Tobin
[6] Langley Scrapbook, 1897-98, RU 7003, Smithsonian Institution Archives, "Extract from Proceeding of Board of Ordnance and Fortification"

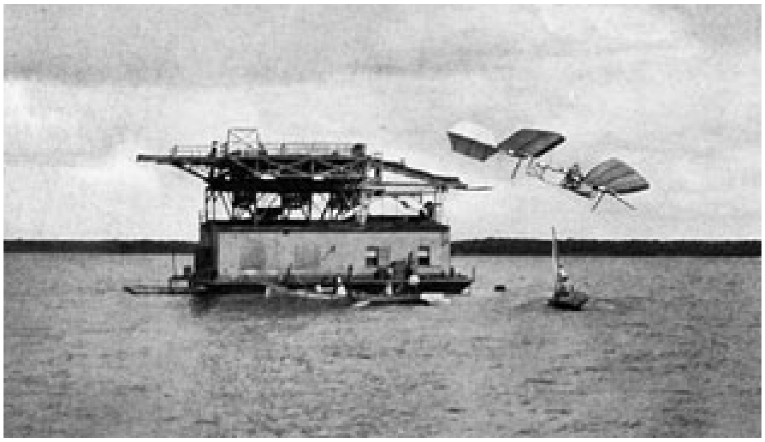


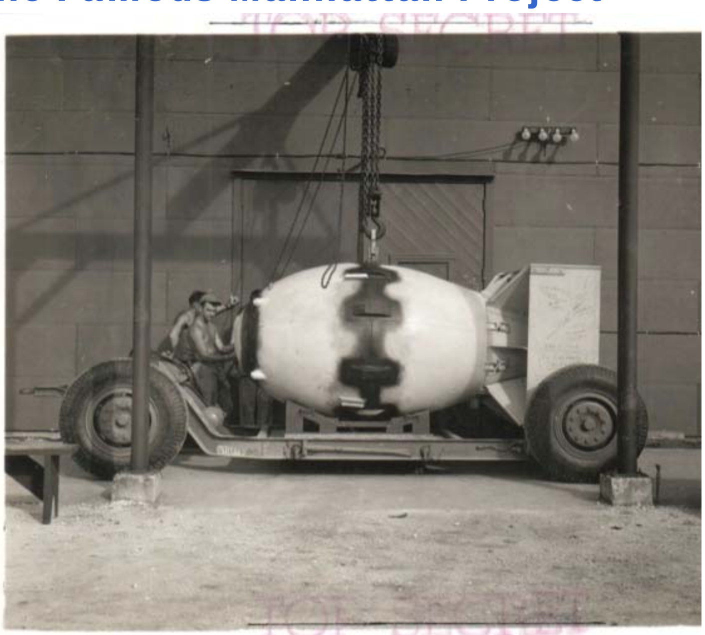
Figure 2: *- Langley's airplane - 1903*

Langley made two attempts. The first attempt failed on October 7, 1903 but the plane incurred only minor damage. The second attempt failed on December 8, 1903 and altogether destroyed the plane. After the second failure, the project was lampooned. Both the media and Congress harshly attacked "Langley's Folly." It was evident the masses still believed practical human flight was impossible and was a waste of public funds.

For over 17 years Dr. Samuel Langley had spent more than $70,000 trying to invent a powered airplane but had subsequently failed. The Department of War canceled the program. The Smithsonian's regents forbid Langley from continuing his research. A statement from the Department of War officially concluded: "We are still far from the ultimate goal of human flight."

Yet ironically, nine days later on December 17, 1903, a brother team from Ohio, Orville & Wilbur Wright, (neither of whom had graduated from high school) demonstrated what most thought was impossible - a manned flight on a flying machine. They had invented the first airplane. What made this more remarkable was the fact that they had accomplished this in their spare time - as a hobby. Though it could rightly be considered an "obsession" with them, by working part-time over four years, the Wright Brothers had succeeded, spending an estimated $1,000.[7] Some lessons learned from this early example include the glaringly obvious point that largess ($70,000 and a staff of helpers) was not able to accomplish what streamlined private initiative was able to do at 1/70th the cost.

The Famous Manhattan Project



The original estimate for the Manhattan Project was $148 Million. The program started in 1942, and was expected to conclude in 1944. The final cost was $2.2 Billion (15 times the original projected cost). It did not finish up until 1946[8] - a 200% schedule overrun. The geo-political need drove the pursuit almost totally back then and budget accuracy did not have its feet held to the fire as it does today. Nevertheless, the specter of cost and schedule was proving to be a formidable foe even then.

Figure 3: *– FAT MAN - The Manhattan Project's first atomic device cost nearly 15 times more than the original estimate.*

[7] The Vision for Space Exploration and the Retirement of the Baby Boomers, The Space Review

[8] Richard G. Hewlett and Oscar E. Anderson, Jr., A History of the United States Atomic Energy Commission: The New World, 1939/1946, Volume I, (University Park, PA: The Pennsylvania State University Press, 1962

Eurofighter

The Eurofighter started in the early 1980s, funded by United Kingdom, Germany, Italy, and Spain. The total program costs were projected to be $20 billion and the date of first service was to occur in 1997. Today, after two decades of technical problems and unforeseen expenses, the Eurofighter is yet to be deployed, and the total costs are in the $45 billion range[9].

RAND Corporation Studies and the DoD

The following excerpts from an Air Force study done 50 years ago titled: *"Predictability of the Costs, Time, and Success of Development"* are revealing:

> "To a large extent, the differences which arise do so over the question of the "extent" of the uncertainty in development - over questions like, "Are estimates of cost of production likely to be off by 25 percent or 300 percent?" . . . In this paper, we present the results of some recent research into the extent and nature of the uncertainty in new developments.
>
> 1) "Early estimates of important parameters are usually quite inaccurate . . . such estimates are strongly "biased" toward over-optimism . . .
>
> 2) "The accuracy of estimates is a function of the stage of development, i.e. estimates improve as development of the item progresses . . .

The vehicle types included in the study referred to above were fighters, bombers, tankers, and missiles of each of the following types: air-to-air missiles, surface-to-air missiles, air-to surface missiles, and surface-to-surface missiles.

Fighters	Factor	Bombers	Factor	Cargoes and Tankers	Factor	Missiles	Factor
1	5.6	1	8.7	1	1.7	1	57.6
2	3.6	2	3.5	2	1.6	2	20.7
3	3.1	3	1.5	3	1.0	3	11.1
4	2.1			4	1.0	4	10.3
5	1.9					5	1.5
6	1.5					6	1.3
7	1.4						
8	1.2						
9	1.2						
Mean	2.4		4.5		1.3		17.1 (9.0)*

Mean -- all classes 6.5 (4.1)*

*Excluding missile case No. 1.

Figure 4: *- Total* *unadjusted* *1959 cost factor increase in average cumulative cost of production[10] - Factors are ratio of latest available estimate, or actual costs where available, compared to earliest available estimates. In some cases the earliest estimate was not really an "early" estimate but was made later in the development process.*

[9] Harvard Business Review Delusions of Success: How Optimism Undermines Executives' Decisions Dan Lovallo, Daniel Kahneman
[10] RAND Predictability of Costs, Time and Success of Development 1959

It will be seen from the above chart, that the mean error factor for missiles is far greater (17.1) than for any of the different models of aircraft. Missiles fall within that category mentioned above as requiring more "technological advance" and hence are subject to a more aggressive estimating error. It's logical therefore; that NASA's space exploration mission pushes the highest limits of cost/schedule uncertainty.

Fighters	Factors A	Factors B	Bombers	Factors A	Factors B	Cargos and Tankers	Factors A	Factors B	Missles	Factors A	Factors B
1	3.9	4	1	6.2	4.0	1	1.4	1.6	1	14.7	6.4
2	2.6	2.5	2	2.8	2.8	2	1.5	1.5	2	9.4	6.0
3	2.0	2	3	1.1	1.2	3	1.0	0.9	3	4.4	2.7
4	1.5	1.5				4	1.0	0.8	4	7.2	7.1
5	1.7	2.1							5	1.5	1.3
6	1.2	1.2							6	1.1	0.8
7	1.0	0.8									
8	1.0	1									
9	1.1	0.6									
Mean	1.8	1.7		3.4	2.7		1.2	1.2		6.4	4.1
Means -- all classes				A: 3.2	B: 2.4						

Figure 5: *- Total <u>adjusted</u> 1959 Factor increase in average cumulative cost of production*[11] *-Adjustments were made for escalation, disparities between actual quantities, and planned quantities. Two sets of adjustments, by two estimators are included, since discretion and judgment is required for adjustments.*

Even with an "adjusted" look at the numbers, the difference in the average error factor value among the different classes of equipment is revealing. The smallest cost increases occurred in the *Cargo* and *Tanker* Class 1.2 times original estimate, with the largest increases still showing up in the *Missile* Class with the final costs 6.4 times the initial estimate.

The explanation is that the size of the error in estimate is 1) a function of the stage of development of the subject article and/or 2) the magnitude of the advance being sought in that subject area. Performance gains for new cargo and tanker aircraft (such as range, speed, and even payload) are usually less dramatic when compared to what has already been achieved in other air-craft, particularly bombers. During the period covered by most of these estimates, missile development encompassed what was in many respects a new and radically different technology. Outcome was expected to show an order of magnitude in improvement over anything previously achieved. The large optimism bias and the resulting variance mirror the study's conclusions (i.e. large technological jumps vs smaller evolutionary efforts translate into greater cost.)

	Small		Medium		Large	
	Factor A	Factor B	Factor A	Factor B	Factor A	Factor B
	1.5	1.5	2.8	2.8	1.1	1.2
	1.7	2	2.6	2.5	1.0	1.0
	1.0	0.8	2.0	2.0	1.0	0.8
	1.4	1.6	1.2	1.2	6.2	4.0
	1.0	0.9	1.1	0.6	1.1	0.8
	1.5	1.5	1.5	1.1	14.7	6.4
					3.9	4.0
					4.4	2.7
					7.2	7.0
					9.4	6.0
Mean	1.3	1.4	1.8	1.7	5.0	3.4

Figure 6: *– Schedule Slip Factor accordingly ranked by the gauge of technological advance from previous generation – Technological advance determination was subjectively categorized by technical experts.*

[11] RAND Predictability of Costs, Time and Success of Development 1959

Among the systems that were pioneering large technological advances, the first estimates became available relatively late in the program. These later estimates contain better information than was generally the case with "early" estimates based only on incremental evolution production-type projects.

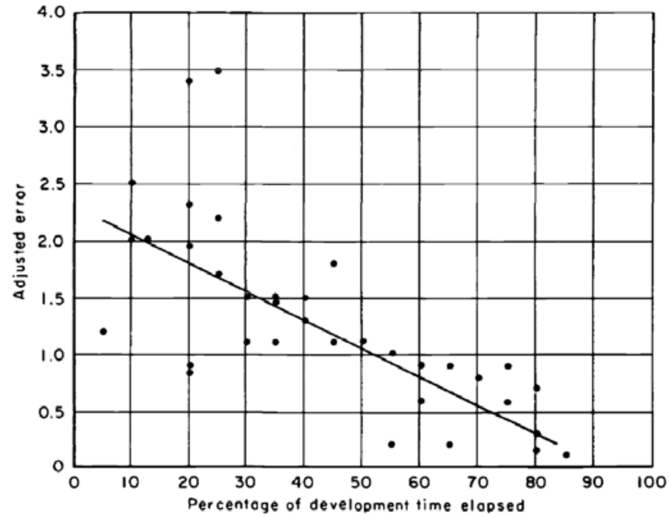


Figure 7: *– Comparison of schedule slip factor vs. project phase status for 22 aircraft and missile projects.*[12]

This data also correlates with a 1962 Harvard Weapons Acquisition Research Project by Dr. Frederic M. Scherer that examined 12 major defense projects with a strong emphasis on performance at the expense of cost and schedule. *Real final costs averaged seven times the initial estimate and schedules took 36% longer than originally planned. The last 10 percent of performance generated one-third of the total cost and two-thirds of the documented problems.*

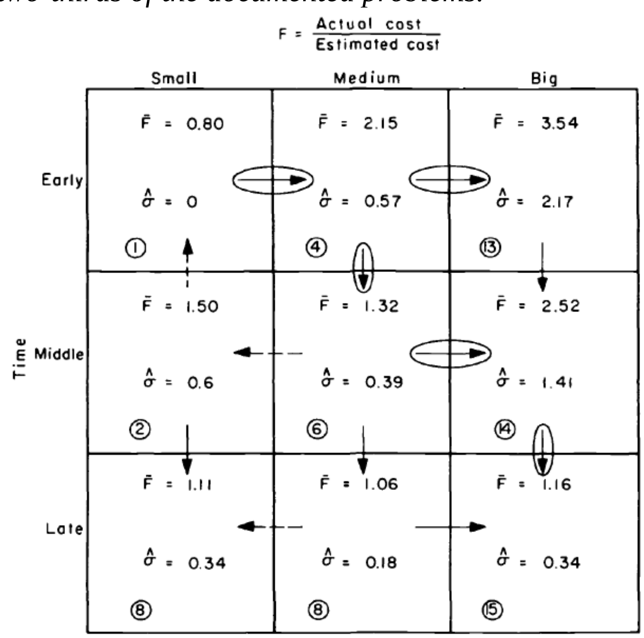


Figure 8: *- The cost growth factor vs technological development from a prior system.*[13] *Arrows indicate direction of changes observed in average errors and standard deviations, in looking across the rows and down the columns, is consistent or at variance with the double hypothesis. Solid arrows run in direction predicted by hypothesis; dashed arrows do not. It can be seen that 9 out of 12 arrows point in "correct" direction and 3 do not. However, only the encircled arrows indicate statistically significant changes - and each of these 5 statistically significant arrows consistently point in the right direction. Time represents project phase.*

[12] RAND The Decision Making Problem in Development
[13] RAND The Decision Making Problem in Development

The "Predictability of the Costs, Time, and Success of Development" Study concludes with the following:

> *"The data presented above is neither as comprehensive nor as unambiguous as one would like . . . Cost increases on the order of 200 to 300 per cent and extensions of development time by 1/3 to 1/2 are not the exception - but the rule . . . The optimistic bias is not hard to understand. Contractors are anxious to have their proposals accepted by the military, and the military itself is anxious to have proposals supported by the Department of Defense and Congress. The incentive to make optimistic estimates is thus very strong. On the other hand, the contractual penalties for having been overoptimistic are generally small. Therefore there have been great uncertainties involved in all of their planning and perhaps especially in the R&D area. Errors were bound to be large on the average. The real problem is to explain why so large a portion of the error shows up statistically as bias rather than variance."*

> *"The variability in size of the errors observed in individual cases stems from two sources. One is just the basic uncertainty that characterizes all development work. The other is the difference in technological advance sought in different systems . . .the business of making decisions is one that calls for shrewd judgments, a large measure of skepticism, and a real appreciation (for) the nature of the problem. Steps can and should be taken to improve the estimates, especially to remove the bias. But even if this is done, significant uncertainties remain to harass the analyst and the decision maker""*[14]

In another RAND study, *cost trends* for 285 different models of aircraft were examined. For every type of aircraft (patrol, cargo, trainer, bomber, attack, fighter, and electronic warfare) annual unit cost escalation rates in the past quarter century have exceeded common inflation indices. These include the Consumer Price Index, the Department of Defense procurement deflator, and the Gross Domestic Product deflator. This trend is true whether cost escalation is measured using either procurement cost or flyaway cost. Patterns of cost escalation differed by aircraft - some showed cost improvement over time, while others steadily increased. It is important to note that RAND recognizes a 2.2% annual productivity increase, but has found other factors that far exceed this [15]

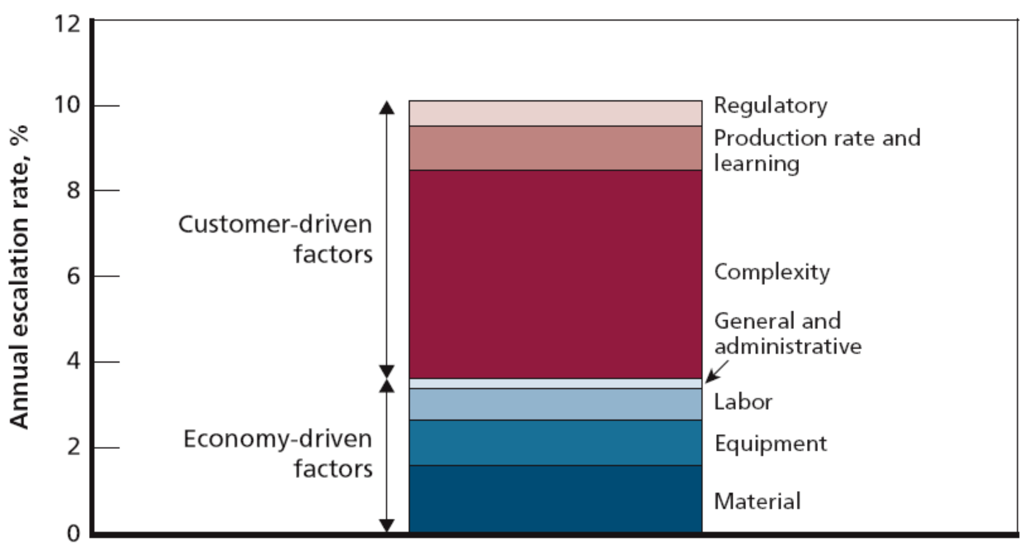


Figure 9: *– RAND Derived Contributors to Price Escalation from the F-15A 1975- to the F22A (2005)*

[14] RAND Predictability of Costs, Time and Success of Development 1959

[15] RAND Why has the cost of fixed-wing aircraft risen? : a macroscopic examination of the trends in U.S. military aircraft costs over the past several decades / Mark V. Arena .2008

In the year 2054, the entire defense budget will purchase just one aircraft. The aircraft will have to be shared by the Air Force and Navy 3½ days per week except for leap year, when it will be made available to the Marines for the extra day."

Norman Augustine - Aircraft Industry Executive

Norman Augustine made this facetious prediction based on costs for individual aircraft which have grown by a factor of four every decade, with increases more closely related to time than capabilities. Trends persist across time and weapon systems. Aircraft unit costs have typically increased from 7 to 12 percent annually. The unit costs for the F-15 increased from $11.9 million in 1974 (as measured in then year dollars) to $54.0 million in 2000.

DOD Programs Cost Growth Analysis

A RAND review of Department of Defense (DoD) programs examines their history of cost growth[16]. Analysis of the data contained in Selected Acquisition Reports (SARs) from the late 1960s to 2004 shows the average total cost growth factor for Major Defense Acquisition Programs (MDAPs) completed was 46% for all program types. This percentage was calculated by comparing program final costs to estimates published at Milestone phase B (MS-B) when the *program was approved*. It is important to note that most other historical cost growth comparisons listed in this section were at MS-A (*initial program estimates*). The same comparison at MS-C (when the *program was approved for production*) reveals that cost growth even in later stages had not been eliminated. In fact, it averaged about 16% from the MS-C decision point when the final estimate was compared to respective estimates at each milestone. This study revealed a systematic bias toward underestimating space systems cost, which was higher than cost growth for other weapons system types included in the full analysis. Further, the cost growth bias doesn't disappear until ¾ of the way between MS B and the end of production. The highest cost growth always occurred in the *development* phase, with average increases approaching 60% across all project types.

The DoD study used two primary cost growth categories:

- ERRORS - defined as inaccurate initial estimates of overall cost and schedule reflecting technology development to accomplish the original work scope and to meet original capabilities as defined at MS-B.

- DECISIONS - defined as program changes within the control of an entity of authority such as the program office, SMC, Air Force, OSD, Congress, or the President.

A companion study on the trend of cost growth during the past three decades also showed that development cost growth for just the past 30 year period had not improved. In fact, variability had actually increased, despite many attempts to reform the acquisition process[17]. The RAND study also showed no correlation with total program cost and cost growth. But it did reveal a substantial correlation to program duration - with twenty year programs experiencing almost twice the cost growth of ten year programs.

[16] RAND Improving the cost estimation of space systems : past lessons and future recommendations / Obaid Younossi . 2008

[17] RAND Is weapon system cost growth increasing? : a quantitative assessment of completed and ongoing programs / Obaid Younossi .2007

Review Status	N	Mean (Standard Deviation)	Median
All programs	76	1.45 (0.80)	1.22
Aircraft	15	1.16 (0.16)	1.13
Cruise missiles	5	1.75 (0.95)	1.43
Electronic aircraft	5	1.59 (0.31)	1.65
Electronics	19	1.20 (0.22)	1.22
Helicopters	8	1.92 (1.48)	1.58
Launch vehicles	3	1.91 (1.53)	1.15
Missiles	14	1.50 (1.04)	1.30
Other	1	1.25	1.25
Satellite	3	1.64 (0.50)	1.88
Vehicles	3	1.81 (1.06)	1.21

Figure 10 *– RAND Average Development Cost Growth Factor Five Years After Milestone B, by Program Type.*

The values of 1.64 and 1.91 correspond to satellites and launch vehicles respectively. Similarly, median values are between 1.13 and 1.88, and the highest value of 1.88 corresponds to the DCGF of satellites. A 2005 RAND study[18] on the same subject indicates the best fit for DoD historical growth is a lognormal distribution - which means there is rarely if ever an occurrence of cost under-run and almost always an occurrence of cost overrun with the potential of having some very high cost overruns.

Recent Trends Affecting Cost Escalation in DoD

The real cost escalation, ***beyond inflation and performance growth***, for military aircraft is about 3 percent per year. Although design improvements may explain some increases, it is remarkable that other advances like 1) more efficient production methods, including computer aided design and manufacturing, 2) microminiaturization of components, and 3) the employment of greater computing power, have not reduced costs nor even held things level.

Aircraft Type	Average Annual Rate, %
Patrol	11.6
Cargo	10.80
Trainer	9.10
Bomber	8.40
Attach	8.30
Fighter	7.60
Electronic	6.70

Inflation Index	Average Annual Rate, %
CPI	4.3
DOD procurement deflator	3.8
GDP deflator	3.7

Figure 11: *– RAND Average annual cost escalation for aircraft and inflation indices 1974-2005 –Excludes 2005-2008 Commodity Price Spikes.* [19]

[18] RAND Toward a Cost Rick Estimating Policy 3-16-05

[19] RAND Why has the cost of fixed-wing aircraft risen? : a macroscopic examination of the trends in U.S. military aircraft costs over the past several decades / Mark V. Arena .2008

There appears to be a number of reasons for this including 1) steadily increasing requirements, 2) using escalation indexes that do not reflect reality, 3) consolidation in the aircraft industry which reduced competition and increased profits & G&A percentages, 4) increased material and parts cost, 5) the utilization of more expensive equipment for manufacturing, and 6) more composite materials being used in the manufacturing process. In the 1940's there were 16 prime military contractors. Today there are two to five depending on the specific technological area in question. As a result of the consolidation in the defense and aerospace industries, debt to equity ratios increased for many firms and this in turn impacts credit ratings. The same factors affect subcontractors also. Some prime contractors are down to sole source suppliers. Because the ability to use foreign suppliers is limited by ITAR and buy American regulations are more prevalent, low cost acquisition options are disappearing. This all tends to inhibit competition and increases costs.

Aggravating the situation still further is the fact that from the mid-1980s through 2007, a number of major American companies have chosen to leave the defense industry - but no major non-defense firms have chosen to enter the industry and fill the void. Some of the reasons cited is 1) the statutory and regulatory constraints required by the government. and 2) the political and bureaucratic complexity of working with the government as both a regulator and a buyer.

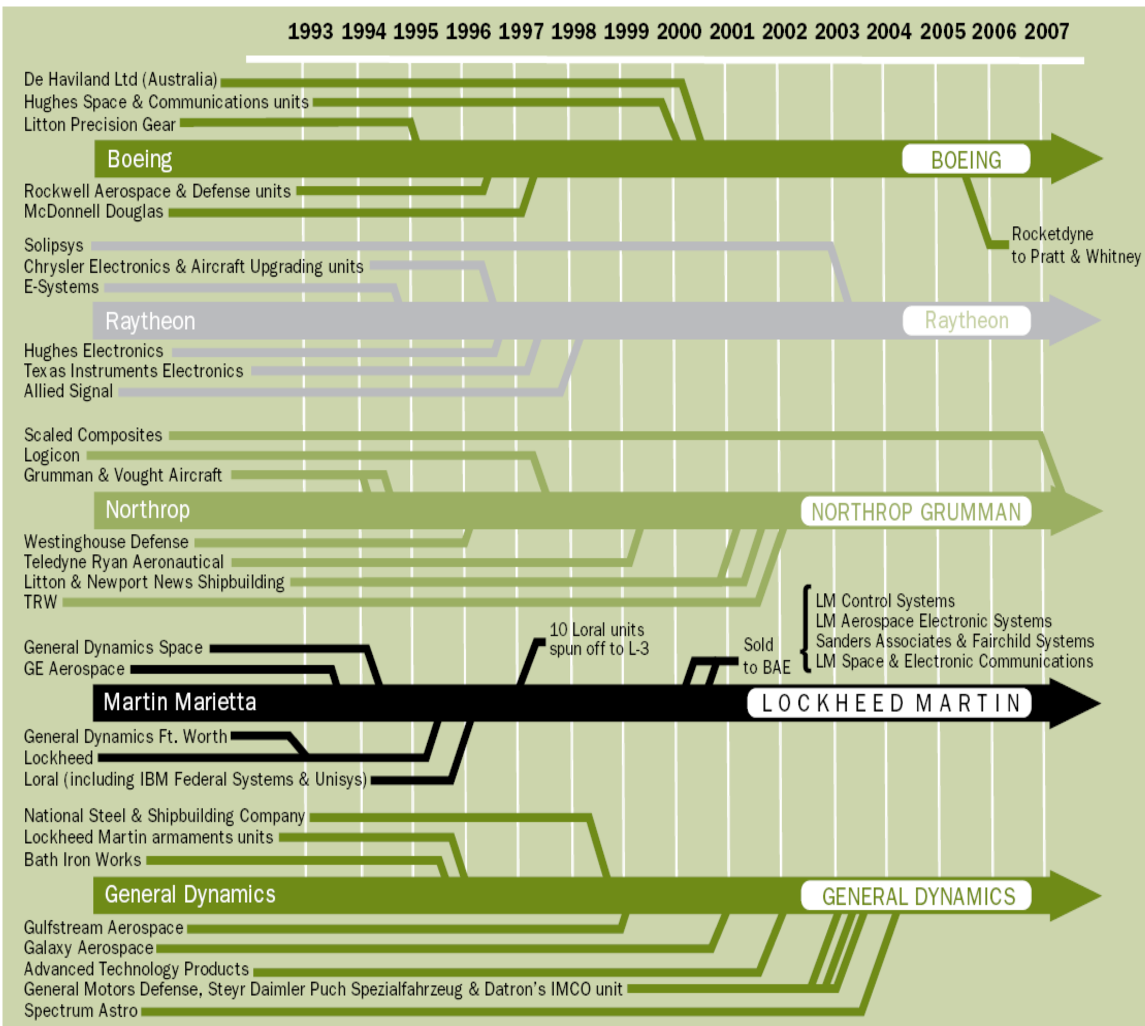


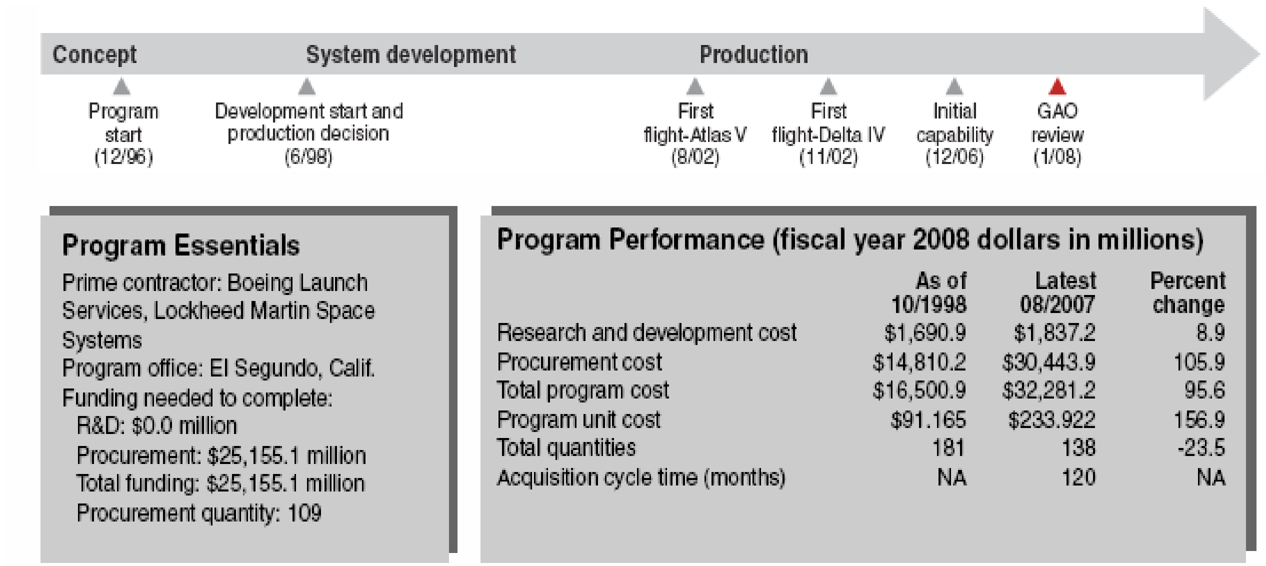
Figure 12: *– A Visual Overview of the Consolidation of US Defense & Aerospace Companies from 1993-2007*[20]

[20] The US Defense Industrial Base: Past , Present and Future, Barry D. Watts

One study[21] correlates as much as 40 percent of DOD program cost overruns to reductions in allowable annual purchase quantities imposed by top-level members of the DoD/Executive branch or Congress (e.g. an order for "X" units was originally placed but afterwards the total order was reduced to "X-n" resulting in a higher per/each cost). These factors are often beyond the control of government or industry program managers. The net result, however, increases costs for a number of reasons including: 1) spreading fixed costs across fewer units; 2) ordering parts that cannot be installed; 3) constraining the ability to buy components in large quantities at lower prices; and 4) buying more in later years after inflation has discounted program dollars. Moreover, cutting funding may negate contractual provisions and enable companies the opportunities to negotiate their way out of being charged for overruns. More than half the costs of a program can be "fixed costs." For example, the cost of a design facility and the salaries of a design team are fixed. When the government stretches a program from two years to three years, such costs are extended and incurred for an additional twelve months.

In 1983, the Air Force originally planned to procure 132 B-2 bombers; then, Defense Secretary Richard Cheney reduced the buy to 75 stealth bombers in 1990 and less than two years later President Bush ended production with a further reduced 20 aircraft purchase. In like manner, as of 2008 it appears that the Air Force will only take delivery of 175 operational F22 fighters whereas the number advertised to the industry in the late 1980s was 880 planes. [22]

The following table summarizes the burgeoning history of another DoD Program, the Evolved Expendable Launch Vehicle (EELV).



Program Essentials

Prime contractor: Boeing Launch Services, Lockheed Martin Space Systems
Program office: El Segundo, Calif.
Funding needed to complete:
R&D: $0.0 million
Procurement: $25,155.1 million
Total funding: $25,155.1 million
Procurement quantity: 109

Program Performance (fiscal year 2008 dollars in millions)

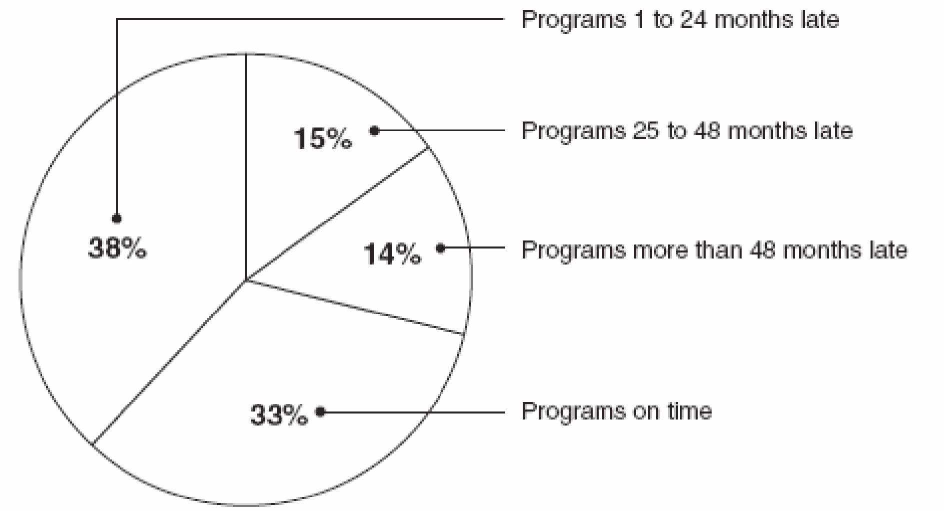
	As of 10/1998	Latest 08/2007	Percent change
Research and development cost	$1,690.9	$1,837.2	8.9
Procurement cost	$14,810.2	$30,443.9	105.9
Total program cost	$16,500.9	$32,281.2	95.6
Program unit cost	$91.165	$233.922	156.9
Total quantities	181	138	-23.5
Acquisition cycle time (months)	NA	120	NA

***Figure 13:** – EELV Project performance*[23]

Another problem has been overestimating the transfer of learning from one unit to the next. Learning-curve theory, originally based on aircraft production experience during the 1930s and late 1940s, holds that as the number of units produced doubles, the recurring cost per unit decreases at a fixed rate or constant percentage. In reality, this becomes a law of diminishing returns scenario and breaks down when production numbers reach some level of output. However, optimistic assumptions about manufacturing and the notional learning curve idea of the past present an obvious temptation to low-ball production costs when bidding the work. Especially given the DOD recent trend to decrease number of units ordered.

[21] The US Defense Industrial Base: Past , Present and Future, Barry D. Watts
[22] The US Defense Industrial Base: Past , Present and Future, Barry D. Watts
[23] GAO-08-467SP Assessments of Selected Weapon Programs

Unsettled requirements in acquisition programs can create significant turbulence. Sixty-three percent of the programs we received data from had requirement changes after system development began. These programs encountered cost increases of 72 percent, while costs grew by 11 percent among those programs that did not change requirements.[24]



Source: GAO analysis of DOD data.

Note: This reflects planned or actual delivery of initial capabilities for programs with comparable schedule data.

***Figure 14:** – DoD Schedule Slip is 21 months on average*[25]

Fiscal year 2008 dollars

	Fiscal year		
	2000 portfolio	**2005 portfolio**	**2007 portfolio**
Portfolio size			
Number of programs	75	91	95
Total planned commitments	$790 Billion	$1.5 Trillion	$1.6 Trillion
Commitments outstanding	$380 Billion	$887 Billion	$858 Billion
Portfolio performance			
Change to total RDT&E costs from first estimate	27 percent	33 percent	40 percent
Change in total acquisition cost from first estimate	6 percent	18 percent	26 percent
Estimated total acquisition cost growth	$42 Billion	$202 Billion	$295 Billion
Share of programs with 25 percent or more increase in program acquisition unit cost	37 percent	44 percent	44 percent
Average schedule delay in delivering initial capabilities	16 months	17 months	21 months

Source: GAO analysis of DOD data.

Note: Data were obtained from DOD's Selected Acquisition Reports (dated December 1999, 2004, and 2006) or, in a few cases, data were obtained directly from program offices. Number of programs reflects the programs with Selected Acquisition Reports. In our analysis we have broken a few

***Figure 15:** – DoD Cost and Schedule Growth*[26]

[24] GAO-08-467SP Assessments of Selected Weapon Programs
[25] GAO-08-467SP Assessments of Selected Weapon Programs
[26] GAO-08-467SP Assessments of Selected Weapon Programs

One major difficulty in determining project cost growth is the fact that government agencies try to put the best positive spin on their projects, even if it means twisting the truth. For example the GAO reported[27] in 2005 "The DOD does present Congress with valuable information about a program's performance by comparing the latest unit cost estimate against the most recently approved baseline. However, this provides only one perspective on performance because re-baselining shortens the period of performance reported and resets the measurement of cost growth to zero. Other meaningful perspectives are not reported. For example, DOD reported in the 2003 SAR, the most recent available, that the F/A-22 Raptor program's unit cost decreased by 0.33 percent in the previous 4 months—since the latest rebaselining (project rebaselined 14 times between 1992 & 2004). DOD did not report that the program's unit cost had cumulatively increased by 72 percent in the last 143 months. Second, the change in unit cost between one budget request to Congress and the next is not measured or reported. For example, DOD reported in the 2003 SAR that unit cost for the Stryker program increased by 1.34 percent in the 2 months since the latest rebaselining; it did not report that unit cost had grown by 21 percent in the previous 12 months. The DOD reported in the December 2003 SAR that the Marine Corps' H-1 helicopter upgrade program's unit cost has shrunk by 1 percent in the last 20 months; however, DOD did not report that the program's unit cost had, in constant dollars, doubled in the last 87 months."

Finally, the DOD has another cost avoidance technique it often uses in an attempt to limit the perception of cost growth. They will alter production standards and accept equipment that may not meet earlier specifications - then ***upgrade*** the equipment at a later date.[28] Taken together, all of the foregoing tend to increase cost growth well beyond the publicly reported statistics.

Award Fees and the DoD

Award Fees should pay for results, not effort. Award fee contracts are not resulting in value for the taxpayer: One of the problems that we have in government, is that if we're paying incentive and award fees, we need to pay for positive results achieved; that people do what they promise or what we need and what they promise, when they promised it, and at the cost that was agreed to. Unfortunately, that's not the case for all too many contracting arrangements in government. They pay for effort and that's it, not results.

Despite the F/A-22 cost overruns unjustified award fees were given. On this contract, Lockheed received $849 million in award fees despite incurring $10.2 billion in cost overruns and delays of over two years. In total, Lockheed received 91% of the available award fee despite the large cost increases and lengthy delays.[29]

The Mercury Program

The3 Mercury Program ran from 1961 to 1963. Its purpose was to demonstrate that humans can travel into space and return to earth safely. There were a total of six flights (two suborbital and four orbital). Alan Shepard was the first American in space (a suborbital flight) on May 5, 1961. John Glenn was the first American in orbit on February 20, 1962. The Mercury program cost $384 Million, almost twice the original estimate.[30] When President Kennedy proposed the Apollo program, the United States had achieved only one human space flight—Alan Shepard's 15-minute suborbital Mercury-Redstone mission.

[27] GAO-05-182 Defense Acquisitions Information for Congress on Performance of Major Programs Can Be More Complete, Timely, and Accessible.
[28] Air Force wants $1.9 Billion Through FY94 to Fix & Improve B-1B, Aerospace Daily, May 3, 1989
[29] GAO-06-66, Defense Acquisitions: DOD Has Paid Billions in Award and Incentive Fees Regardless of Acquisition Outcomes (Dec. 2005) (GAO-06-66).
[30] A Discussion of Space Program Cost, David Novick, RAND February 1964

The Apollo Program

The Apollo Lunar Program (conducted from 1962 to 1973) comprised 17 missions with six successful moon landings between 1969 and 1972. The total program cost (in 2005 dollars) was roughly $170 billion.[31] That total included all research and development (R&D) costs; the expense of procuring 15 Saturn V rockets, 16 command/service modules (C/SMs), 12 lunar modules, program support and management costs; construction expenses for facilities and their upgrading, and costs for flight operations .

> On April 25, 1958 the Air Force Ballistic Missile Division published the first development plan to "achieve capability to land a man on the moon and return him safely to earth." The complete program would be carried out in four phases: first, "Man-in-Space Soonest"; second, "Man-in-Space Sophisticated"; third, "Lunar Reconnaissance," exploring the moon by television camera and a soft landing of an instrumented package on the moon's surface; and finally, "Manned Lunar Landing and Return," which would first test equipment by circumlunar flights returning to earth with instrumented capsules containing animals. At this stage of project development, the payload capacity would be increased to 9000 pounds. The spacecraft would then undertake a full-scale flight to the moon and safe return with an animal passenger. The climax would be a manned lunar landing, brief surface exploration, and return. This would be followed by other flights to explore the lunar surface thoroughly and gather additional data. The program was scheduled for completion in December 1965 at a cost of $1.5 billion.[32]

> **"We can give you estimates all the way to the end of the Saturn-IVB, but do you really want to know it?"**
>
> *Donald W Douglas - President Douglas Aircraft - 1964*

Apollo is often painted as a successful program that came close to its initial 1961 estimate for a 1967 moon landing. As can be seen from the foregoing 1958 Air Force estimate, the original cost was 1.5 billion with completion targeted in 1965. The "actual" historical events went something like this. The NASA cost estimating gurus in 1961 projected an amount close to $7 Billion to do the entire program.[33] [34] This figure was apparently padded to $10-$12 Billion by management prior to giving that estimate to James Webb, the NASA Administrator. Mr. Webb (within hours of receiving the $10-$12 Billion figure) placed an "administrator's discount" on NASA's ability to predict costs with due precision and by the stroke of his own pen, changed the estimate to $20 billion and submitted it to Vice President Linden B. Johnson. In the words of Robert Seamans Jr., (the Associate Administrator at the time) "We were aghast!"[35] This cavalier beginning describes how Apollo's original fiscal requirements arrived at the steps of the Capitol and was subsequently blessed by Congress.

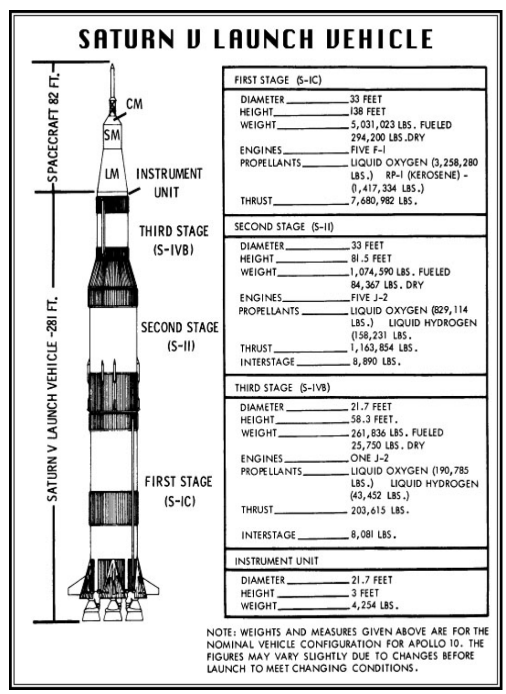


Figure 16: – *Saturn V Overall Dimensions.*

[31] CBO A Budgetary Analysis of NASA's New Vision for Space, Sept 2004
[32] Chronology of Early USAF Man-in-Space Activity, 1945-1958 (U.S. Air Force, 1965), unpublished, pp. 21-22
[33] Apollo Executives' Meeting Proceedings Ashville, NC June 18-19 1964
[34] A Discussion of Space Program Cost, David Novick, RAND February 1964
[35] Aiming at Targets - The Autobiography of Robert C. Seamons Jr. - The NASA History Series 1996, pp. 91

Ironically, the $20 billion amount submitted by Mr. Webb to the Vice president appeared to be a completely arbitrary and highly irregular move. In anyone's book it was a radical cost estimating maneuver to be sure. But in the end, Mr. Webb's innate business sense and the courage to follow what that sense told him validated his action. It turned out to be a leadership demonstration of profound foresight. In the end the "real cost" of Apollo ultimately surpassed Mr. Webb's $20 billion estimate with a price tag of $25.4 billion as was reported to congress in 1973. The final program cost varies depending on what we include or exclude in the calculations,[36] [37] [38] but in all instances exceeds $20 billion.

Officially, Apollo met President Kennedy's publicly declared goal of putting a man on the moon by the end of the 1960s.[39] To achieve this tremendous exploit, the original cost estimate from NASA experts ($7 billion), was increased by nearly 3 times that amount when it became the "official" agency submission for the Apollo Program.

> **"The fellow who proposed to do the job at the lowest estimate normally ends up by doing the job for twice the estimate."**
>
> R. R. Hough - Vice President AT&T - 1964

The greatest cost items were the Saturn V rockets @ $6.4 billion, followed by Command and Service Modules @ $3.7 billion, Lunar Modules @ $2.2 billion, and Manned Space Flight Operations @$1.6 billion.

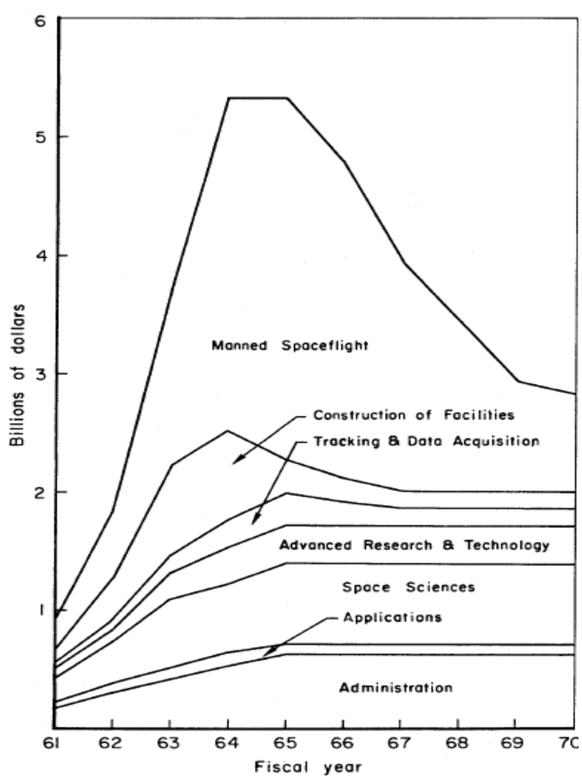


***Figure 17:** – 1964 Projection of NASA Funding*

- ***Schedule Performance***
  - Assuming 1962 official program start
  - Scheduled date of 1st moon landing 1967
  - Actual date 1st moon landing was July 1969
  - 1962 – 1967 = 5 years
  - 1962 – 1969 = 7 years
  - (7 / 5) - 1 or (5 / 2) = 40% schedule slip

- ***Cost Performance***
  - Original Estimate $7 Billion
  - Final Costs $25.4
  - (7/25.4) – 1 = 263%

[36] NASA Budget http://en.wikipedia.org/wiki/NASA_Budget
[37] Ezell, NASA Historical Data Book, Vol II, 2:122-32
[38] House, Subcommittee on Manned Space Flight of the Committee on Science and Astronautics, 1974 NASA Authorization, Hearings on H.R. 4567, 93/2, Part 2, Page 1271.
[39] CBO A Budgetary Analysis of NASA's New Vision for Space, Sept 2004

The Space Shuttle

The Space Shuttle reportedly was given initial approval with a 1 vote margin. There was much concern regarding estimate accuracy. Shuttle planning began in 1968[40] and the initial 1971 estimate was $10 Billion[41] for a more complex vehicle than ultimately was built that included fly-back capability using a liquid booster. As a result of prevailing budget pressures the scope was cut. The 1972 final estimate was for the development portion of shuttle's current configuration using solid rocket boosters. The figure for five orbiters was near $5.5 Billion plus a 20% contingency for reserves[42] totaling 6.6 Billion. The Shuttle was scheduled for first horizontal flight in 1975, first vertical flight 1977, first manned flight by the end of 1977, and initial operating capability in 1978/1979.[43]

The January 5, l972 estimate for the Shuttle Program called for an expenditure of $5.5 billion for research, development, test and engineering, together with a 20 percent overrun allowance, and $0.3 billion price tag for launch facilities. This Shuttle would be a two-stage vehicle—consisting of a booster and an orbiter. Each booster would cost $50 million. At this point in time, the booster reuse capability was not defined. Each orbiter (which NASA claimed could be used 100 times) will cost an estimated $350 million. NASA held that each shuttle f1ight would cost less than $10 million and that the cost of placing a pound of payload in orbit could be reduced to less than $100. Thus, it was argued that the Space Shuttle would certifiably be a cost effective vehicle for the space program.[44]

	NASA's March 1972 estimate	Mathematica's cases: Solid booster	Mathematica's cases: Liquid booster
	(billions--1971 dollars)		
Expected launch vehicle costs	$16.1	$14.6	$14.2
Expected payload costs	26.8	26.8	26.8
Expected total space program costs	$42.9	$41.4	$41.0

Figure 18: *- Comparison of NASA & Mathematica Estimates in June 1972*[45]

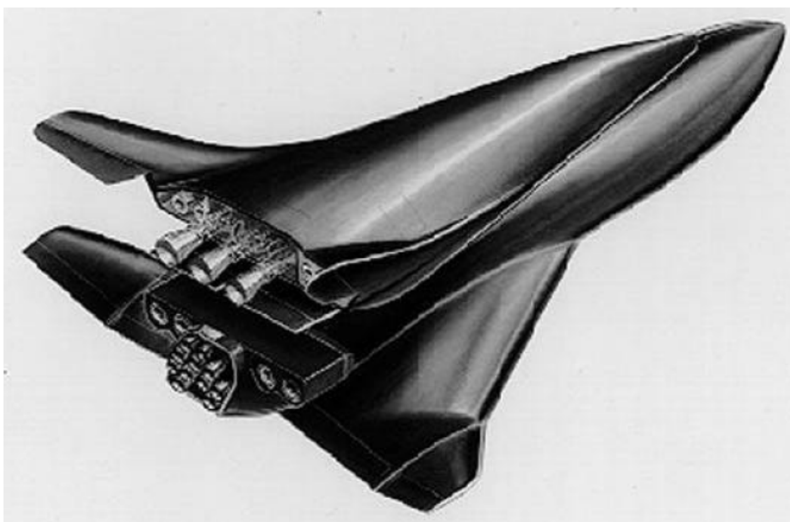


Figure 19: *– 1970's concept for a two stage Space Shuttle*

[40] William Normyle, 'Large Station May Emerge As Unwritten US Goal,' Aviation Week and Space Technology (March 10, 1969), pp 103-109.
[41] 12-29-1971 NASA Letter from James Fletcher to OMB
[42] 5-9-1972 NASA Letter from James Fletcher to OMB
[43] 9-30-1970 NASA Letter from James Fletcher to OMB
[44] Congressional Report Cost Benefit Analysis Used in Support of the Space Shuttle Program 1972
[45] Congressional Report Cost Benefit Analysis Used in Support of the Space Shuttle Program 1972

Don Rice (Assistant Director, OMB) presented a developmental cost of $4 billion and that was believed to have come from North American Rockwell. It was subsequently discovered that Rockwell had given far more information to NASA than to Rice, and Rice's $4 billion left out company profit along with the cost of NASA program support. Indeed, it was the equivalent of numbers that NASA itself had shown.

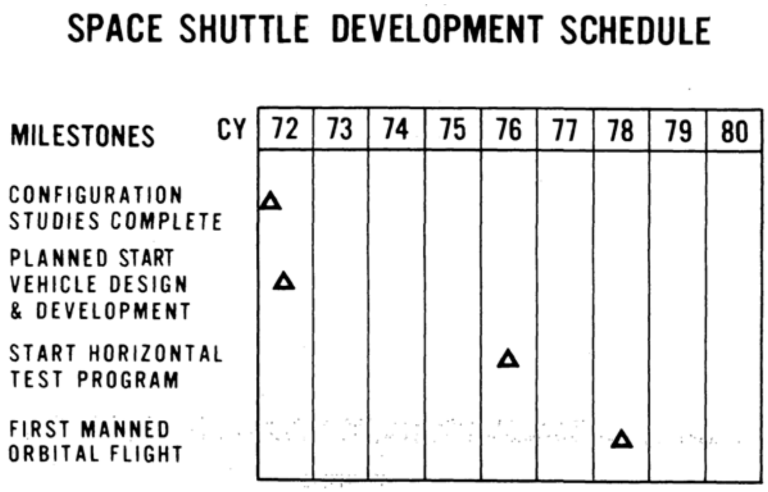


Figure 20: *- 1972 1st flight slipped 2 years*

December 1971 planning showed that the first shuttle launch was scheduled to occur in June 1976 (or 4.5 years from that time) with a planned launch rate of 50 to 150 flights per year. By the early 1980's the planned flight rate was reduced to 24 flights per year. The actual 1st launch date occurred April 12, 1981 or 9.4 years from the December 1971 vantage point. This translated into a 100% + slip in schedule. The maximum shuttle flight rate ever achieved has been eight launches per year, which is ⅓ of the then conservative estimate of 24 flights per year. In addition, the program experienced substantial cost growth in achieving the "reduced" target of 8 flights per year. Had the initial flight rate had been insisted on; a gargantuan amount of additional money would have been needed.

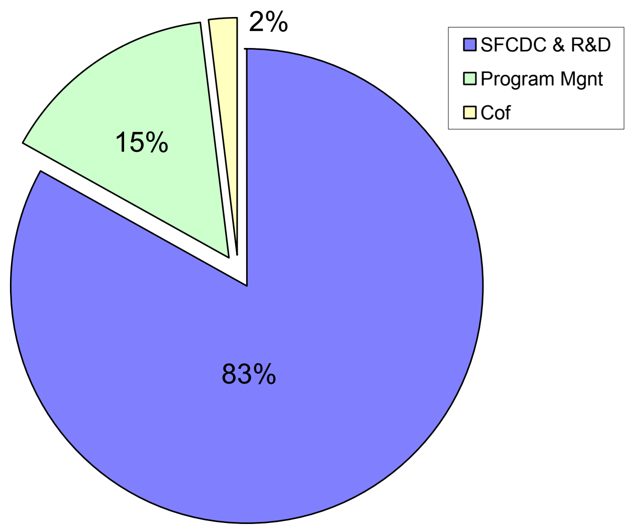


Figure 21: *– Approximate Space Shuttle Budget Distribution - Important: some costs, like civil service salaries are not included due either to difficulty of accurately ascertaining Shuttle-relevant activity, or their insignificance. Adding these categories increases estimates, but probably less than 10%. Also excluded is 3 billion in DOD support, much of which was for the Vandenberg CA. launch site development, and 0.5-1 billion in reimbursable costs from the DOD[46] SFCDC = Space Flight, Control and Data Communications.*

[46] Space policy alternatives / edited by Radford Byerly, Jr. 1992

"In discussing Space Shuttle development approval, 1970 House Representative Joseph Karth (Democrat - Minnesota) was suspicious of NASA's claims for program costs. For projections of robotic missions, Karth referred to such projections as "asinine" and followed up with the words "NASA must consider members of Congress stupid idiots."

SpaceRef.com

	Current Expendable	New Expendable	TAOS Space Shuttle and Tug
EXPECTED LAUNCH VEHICLE COSTS			
Non-Recurring Costs (FY1972-87)	1,620	2,000	7,450
Recurring Costs (FY1977-1990)	10,600	8,760	4,800
Total Launch Costs	12,000	11,000	12,000
EXPECTED PAYLOAD COSTS (SATELLITES)			
RDT&E (FY1975-1990)	11,000	10,600	9,880
Recurring Costs (FY1976-1990)	18,800	18,400	12,700
Total Payload Costs	30,000	29,000	23,000
EXPECTED TOTAL SPACE PROGRAM COSTS	42,000	40,000	35,000

Figure 22 *- 10-28-1971 Shuttle report to the administrator $ in Millions of undiscounted 1970 dollars, assumes 514 flights.*

Result of Studies					
Payload Bay (FT.)	10 x 30	12 x 40	14 x 45	14 x 50	15 x 60
Payload Weight (Lbs)	30,000	30,000	45,000	65,000	65,000
Development Cost (Billions)	4.7	4.9	5.0	5.2	5.5
Operating Cost ($ Millions/Flt.)	6.6	7.0	7.5	7.6	7.7
Payload Costs ($/Pound)	220	223	167	115	118

Figure 23: *– 12-29-71 Letter from James Fletcher to OMB*

The original concept was to use conventional rocket engines for the Shuttle's boosters. However, between January and March, while the development cost of a pressure-fed booster stayed virtually constant, the Space Shuttle Main Engine (SSME), and orbiter costs escalated sharply. A 1972 internal OMB memo from economist Sullivan summarized NASA's own estimate of the changes, in millions of dollars:[47]

	1/3/1972 Est. (Pressure-fed)	Pressure-fed	Current Est. Pump-fed	Solids
Orbiter	**3,058**	**3,660**	**3,660**	**3,750**
Main Engine	**450**	**580**	**580**	**580**
Booster	**1,390**	**1,400**	**1,080**	**350**
Program Support	**602**	**570**	**560**	**470**
Total	**5,500**	**6,210**	**5,880**	**5,150**
Cost/flight	**7.7**	**9.3**	**8.6**	**10.4**

Figure 24: *– Shuttle Booster type cost comparison in Millions*

[47] SP-4221 The Space Shuttle Decision - NASA

Since the White House insisted that NASA stay within a $5.5 billion development cost, NASA was driven to the Solid Rocket Booster (SRB) option. The low estimates gave a strong case of choosing the solid motor even though no one had previously tried to recover and reuse a solid booster. It was decided that the Shuttle would use two 156-inch boosters, the largest allowable size that could be transported on American railroads. Only nine such solids had ever been test fired - five by Thiokol and four by Lockheed. It was clear that Marshall SFC would have plenty to do in bringing the SRB to a level of reliability that would allow delivery of astronauts to space.

By October 1974, the Space Shuttle Main Engine's (SSME) 10 hour life had been reduced to 7.5 hours. Most other systems were still designed for a 10 operation life. The SRB design was delayed due to a bid protest by Lockheed.[48]

A 1977 NASA letter[49] to congress confirmed the current Space Shuttle design, development, test and evaluation (DDT&E) estimate "is still $5.22 billion in 1971 dollars", or "$6.816 billion in the FY 1978 budget" "after adjustment for inflation already incurred and inflation expected during the coming budget year." The first manned orbital flight was projected to slip to mid 1979. Yet further in the same letter, seemingly in conflict with the earlier statement, it reads: "The cost of refurbishing Orbiters 101 and 102 and procuring Orbiters 103, 104, and 105 was originally estimated at approximately $1 billion in 1971 dollars. However, "the decision in the FY1977 budget to defer Shuttle production for one year" resulted in an increase to approximately $1.347 billion in 1971 dollars or $1.988 billion in 1978 dollars. Plus $432 million more was added for Orbiter and KSC facility ground support equipment for a two orbiter in flow processing capability as well as initial spares and crew equipment for the operations period.

The actual cost through 1981's first flight ended up between $13.6[50] and $17[51] billion (or 147% to 258% more than estimated). Total Space Shuttle Program cost through 1990 was approximately $65 billion, compared to the projected estimate of $51 billion. Though this seems like a relatively modest overrun (about 27%) it must be remembered that the $51 billion was to have paid for 580 flights while only 37 flights were actually flown through 1990. The flight frequency schedule was a mere 6.4% of the originally projected service performance. If all 580 flights had been made as initially projected, the cost would have come in at 1 trillion, nineteen billion dollars - more than 35 times the estimate. Thus when comparing apples to apples, the optimism bias reflected in the Shuttle Program was up there with the worst estimates in NASA's history.

Type of Cost	Cost
Design, Development, Testing and Engineering	13,138
Production	3,948
Construction of Facilities	703
Total	17,789

Figure 25: *– Shuttle System Non-Operational Expenditures FY 1972-1982 in Millions of 1982 Dollars.*[52]

[48] Flight International, NASA's Budget gets a Boost, 10-3-1974
[49] 4-12-1977 NASA Letter from James Fletcher to Subcommittee on Space Science and Applications Committee on Science and Technology
[50] Current $ - Pielke 1994, Gehman 2003, 2004 Economic Report of the President
[51] Aviation Week, Space Shuttle Value Open to Interpretation 7-26-1993, Period from 1971-1982
[52] CBO Pricing Options for Space Shuttle 1985

As shocking as the cost growth in the shuttle program was, it was not entirely unanticipated. The President's Science Advisory Committee created a special panel to examine the issue, and appointed Alexander Flax as chairman. An October 19, 1971 interim report[53] stated:

> *"Considering all of the technological and operational unknowns involved in the shuttle development and the fact that no vehicles of similar function have ever been designed before or have ever operated over the range of flight regimes required for the shuttle, prudent extrapolation of prior experience would indicate that estimated development costs may be 30 to 50 percent on the low side. Thus, the estimates of $6.5 billion in RDT&E for the Mk I & Mk II shuttle program may range between $8.5 to $10 billion, reflecting increased program costs of $2.5 to $3.5 billion. Similar uncertainties must be considered to apply to other non-recurring costs such as production and facilities (amounting to about $4 billion). Thus a possible cost uncertainty of about $5 billion for total program costs might be envisioned giving a high estimate of total non-recurring cost of about $15 billion."*
>
> *"The operating cost estimates of $5.5 million per flight for the shuttle, within narrow limits, must be considered to be a very rough estimate at this time, particularly for the early years of shuttle operation. The actual value will depend upon the time between overhaul of equipment not yet designed, refurbishability of thermal protection system materials not yet out of the laboratory, and on the feasibility of operating the shuttle in an "airline" mode radically different from all past experience in space operations."*

The President's Science Advisory Committee was on the right track. Their main oversight was simply not going nearly far enough in suggesting additional dollar requirements. It is generally acknowledged that the Shuttle Program has not met its original objectives either in frequency of flight or efficiency of operation. This is not to say that the Shuttle is not a grand technical achievement -- it is in fact an engineering marvel! However, the specifics of the performance shortfall against the advertised projections and estimates are as follows[54].

- The number of flights have been 1/15th the 1972 prediction.
- 5 Operational Shuttles were budgeted in 1971 but only 4 were built. The "Enterprise" which was intended to be the 5th orbiter, was used for flight tests but was constructed without engines or a functional heat shield. It was not retrofitted for orbital flight due to major design changes.
- The average cost per flight was over 19 times what was promised.
- If the Shuttle were to fly 8 flights per year (which is the maximum ever launched in one year), at $4 billion in average annual appropriations, it would take approximately 68 additional years and approximately $270 billion to reach the original goal of 580 flights.
- Original Space Shuttle requirement called for 65,000 lbs to a 180 km, 28 degree orbit.
- Average capability of the three orbiters is ~49,000 lbs to the same orbit (a decrease of ~25%).

[53] SP-4221 The Space Shuttle Decision - NASA
[54] Space policy alternatives / edited by Radford Byerly, Jr. 1992

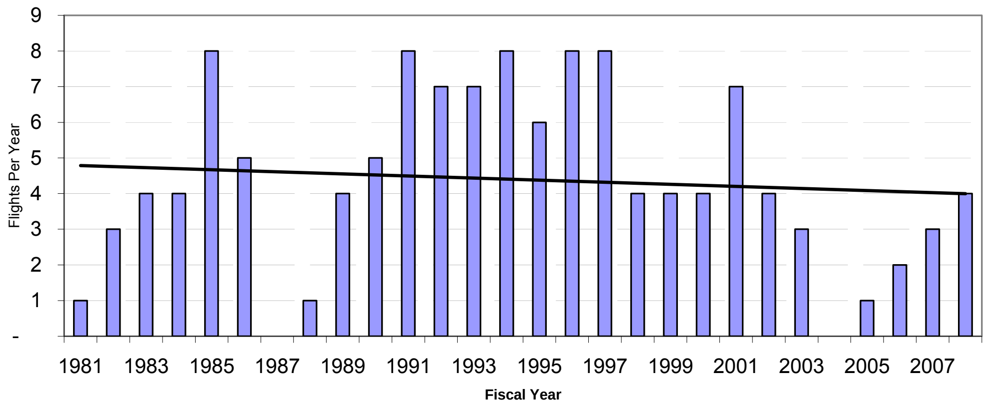


Figure 26: *- Historical Shuttle Launch Rate per year - average rate is 4.4 flights per year.*

Up to February 2005, the entire Shuttle Program cost was approximately $145 billion with $112 billion of that amount occurring since it became operational in 1981. Furthermore, the average cost per flight has been about $1.3 billion over the life of the program with about $750 million per flight over its five most recent years of operation.[55]

In summary, the Space Shuttle is a testament to the ingenuity and flexibility of NASA engineering - leaving a legacy of accomplishment that even the most cynical can admire, but the business case and financial metrics history connected with those technical achievements has fallen far beneath the super-optimistic estimates put forth when selling the concept to congress and the public.

The International Space Station

The Space Station story is an internationally encumbered and complex one - exceeding in sophistication the already difficult "normal" cost estimating/schedule setting arena. In his January 25, 1984 State of the Union address, President Reagan directed NASA to build a space station within a decade and to invite other countries to join the endeavor. In 1991, the US House of Representatives held the first of 22 separate votes on whether to proceed with the program. It came within 1 vote of cancellation in 1993. Construction began in 1998.

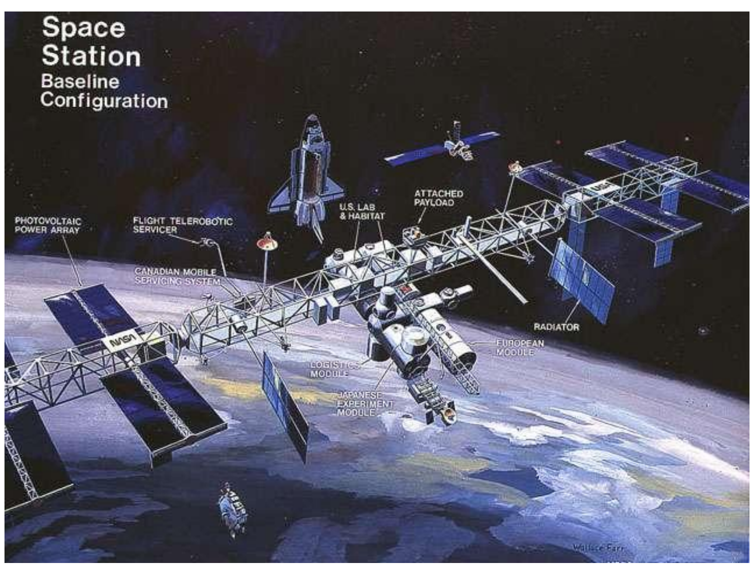


Figure 27: *- The International Space Station Baseline Configuration*

[55] MSNBC, Space Shuttle Cost Get a Reality Check 2-11-2005

> **"For years, the agencies (NASA's) cost overruns and schedule delays supplied ammunition for annual congressional attempts to kill the International Space Station."**
>
> *Florida Today*

Comparing costs associated with the space station is extremely difficult since over the years the scope has changed significantly. The initial $8 billion estimate, expressed in FY1984 dollars (as if all funds were paid out that year). The current design estimate has ballooned to $45 Billion (FY1985-2005, in current dollars), which reflect current and prior year spending unadjusted for inflation, plus future year spending that includes a factor for expected inflation. Cost growth and schedule delays over the past 21 years have subjected space station to repeated downsizings and consequent reductions in capabilities from 1984 design. Space station was originally presented to Congress as a facility with eight functions. Within five years, it had been reduced to one function — a laboratory for world class research. Full assembly was originally intended for completion by 1994. Completion now scheduled for 2010.

Cost Estimates For U.S. Portion of the International Space Station: 1984-2005[56]

Year	Estimate*
1984	$8 billion (FY1984 dollars, R&D only, no shuttle launches).
April 1987	$16 billion, following restructuring in which program was split into two "phases" $12.2 billion for Phase I; $3.8 billion for Phase II (FY1984 dollars, R&D only, no shuttle launches).
April 1989	$30 billion for Phase I (real year dollars (RYD),* through assembly complete, including shuttle launches during assembly and other costs–such as the Flight Telerobotic Servicer and ground facilities). Phase II was "indefinitely postponed," so it is not included in this or subsequent cost estimates.
Early 1990	$37 billion (RYD, through assembly complete, including shuttle launches during assembly and other costs).
December 1990	$38.3 billion (RYD, through assembly complete, including shuttle launches during assembly and other costs).
March 1991	$30 billion (RYD, through permanent human capability, including shuttle launches during assembly and other costs).
Nov. 1993	$17.4 billion. This adjusted cost followed termination of Space Station Freedom (which was to be solely a US constructed space facility) and introduction of the International Space Station (which was a planned partnership with Russia and other nations). (RYD, development costs through assembly complete, no shuttle launches, includes costs for science experiments).
July 1996[57]	GAO $17.4 billion to develop and operate the ISS; from October 1993 through completion of assembly in space, currently scheduled June 2002. With $6.3 billion for prime contractor's costs, $5.5 billion for development of ground-based and on-orbit capabilities, $2.6 billion for development of on-orbit research facilities & other research, $3 billion for financial reserves; NASA did not budget the full amount of contract estimates because it believed that it can negotiate authorized contract changes; *As of April 1996, the prime contractor was $89 million over budget and $88 million behind schedule; there are several instances where the prime contractor's total cost estimates neglect to recognize over-budget conditions;*
March 1998	$21.3 billion (RYD, development costs through assembly complete, no shuttle launches, includes costs for science experiments).

56 CRS NASA'S Space Station program Evolution and Current Status 4/4/2001
57 GAO/T-NSIAD-96-210

April 1998	$24.7 billion (not a NASA estimate), but was an independent "Cost Assessment and Validation Team" estimate headed by Jay Chabrow which concluded what the cost would be through assembly complete.
June 1998	$22.7 billion (RYD, development costs through assembly complete, no shuttle launches, includes costs for science experiments). NASA did not accept the Chabrow figure, but agreed program would cost $1.4 billion more.
June 1998[58]	GAO $95.6 billion total space station costs • Regarding shuttle support, our 1995 estimate was based on 35 flights during development and 50 during operations. However, NASA's 1998 estimate was based on 43 flights during development, including 2 additional flights to the Russian space station Mir, 1 flight to test the crew return vehicle, and flights required by adoption of Revision C to assembly sequence. NASA continues to estimate that 50 flights will be needed during operations.
June 1998[59]	GAO $21.9 billion development cost – higher costs $21.9 versus $17.4 billion—attributable to schedule delays, additional prime contractor effort not covered by funding reserves, additional crew return vehicle costs, & costs incurred as a result of delays in Russian-made Service Module. Increased in-house personnel costs during development—$2.2 billion versus $0.9 billion— attributable to longer development program, higher estimated personnel levels, and more inclusive estimating methodology.
February 1999	$23.4-26 billion (RYD, development costs through assembly complete, no shuttle launches, includes costs for science experiments).
February 2000	$24.1-$26.4 billion (RYD, development costs through assembly complete, no shuttle launches, includes costs for science experiments).
March 2001 (Under Discussion)	$22-23 billion, assuming termination of construction after completion of "U.S. Core" and attachment of European and Japanese lab modules (RYD, development costs through completion of the "U.S. Core"; no shuttle launches; includes costs for science experiments, reduced 40% from previous estimates).
January 2001[60]	$30 Billion NASA explained that program managers had underestimated the complexity of building and operating the station.- Scope was cut in Feb 2001 to stay under $25 Billion cap imposed by congress.
October 2003[61]	GAO $32 billion appropriated by congress since fiscal year 1985 for program. To date, NASA has not fully estimated the potential increased costs and future budget impact incurred due to the grounding of the space shuttle fleet. However, it has identified a number of factors that will likely result in increased costs—including the need to extend contracts to complete development and assembly of the station. NASA estimates impact to station program from Columbia accident to be $22 million in fy 2003 and up to $72 million in fy 2004. NASA maintains that an assessment of total impact cannot be accomplished prior to the fy 2006 budget submission in February 2005.
September 2004	$32.878 Billion[62]
April 2005[63]	$45 billion - $35 billion appropriated by Congress for program (FY1985-2005 concurrent $) and NASA estimates it will cost another $10 billion through the end of construction in FY2010. (Estimates do not include shuttle launch costs.) Cost growth and schedule delays over the past 21 years have subjected space station to repeated downsizings & consequent reductions in its capabilities.

Table 1: *- NASA's Cost Estimates For U.S. Portion of the International Space Station: 1984-2005*

58 GAO T-NSIAD-98-212 SPACE STATION U.S. Life-Cycle Funding Requirements

59 GAO T-NSIAD-98-212 SPACE STATION U.S. Life-Cycle Funding Requirements

60 CRS The International Space Station and the Space Shuttle 11-2008

61 GAO 04-201T Shuttle Fleet's Safe Return to Flight Is Key to Space Station Progress 10/29/03

62 CBO A Budgetary Analysis of NASA's New Vision for Space Exploration September 2004

63 CRS NASA'S Space Station program Evolution of Its Rationale and Expected uses 4/30/05

The above table is particularly revealing as to the volatility of both the aggregate costs and the sluggish timetable for the International Space Station. Of all the programs cited in this paper, The IST provides a maze of fluctuating cost and schedule estimates as the years have unfolded. After evaluating the above table, the words of Robert Young from 1964 take on greater meaning.

> **"The time has GONE when we can re-plan and re-estimate every year."**
>
> *Robert Young - NASA - 1964*

The fiscal illness of failing to identify the entire cost scenario early in the business process has been with NASA a long time. The jury is no longer out on this fact. The agency's cost estimating community could not reasonably require more proof than now exists. The question now is: how does NASA go about altering its "below-the-target" precedent and fixing the cost/schedule realism problem with that same professional skill which has always characterized our efforts in finding technical solutions to difficult engineering challenges? An answer to that question is introduced at the end of this paper.

Quotes Worth Remembering from the Apollo Era

Having completed a cursory review to this point of NASA's most prominent and visible programs, a series of quotes follow from people of influence during the Apollo Program era[64]. Though these statements were made nearly half a century ago, they are still timely and appropriate in our current business climate. Our object in citing these long ago statements is to drive home the point that among the most persistent realities in the science and engineering construction world, none is so well validated as the precedent of <u>*underestimating cost and over-optimizing schedules*</u>.

> **"One of the things that is essential is a realistic set of assumptions on which your estimate is based. If conditions change, you modify the assumptions, and you modify the cost."**
>
> *Charles Beck - President, Philco - 1964*

> **"One of the characteristics *(that is)* different about the Apollo program - and the preceding programs is the fact that initially people *(Congress)* were willing to fund almost any level of money, and they literally did. There wasn't a ceiling established when the program was first formulated. The problem is when the first round of contracts was negotiated, and the first round of run-out costs developed, the estimates were $7 billion. The first statement to Congress was that the cost would be between $30 and $40 billion."**
>
> *Dr. George Mueller - NASA - 1964*

> **"There has been, in all R&D programs, a tendency to underestimate the cost. In DOD programs, where there's been a lot of very careful attention given to costs in the past two or three years, history shows the actual cost to be on average 3.2 times the initial estimated costs."**
>
> *Maj. Gen. Samuel C. Phillips - 1964*

[64] Apollo Executives Meeting Proceedings, June 18,19 1964

"I can think of a lot of programs in the Boeing Company where, if the estimate had been realistic, you wouldn't have had the program. And that is the truth."

W. M. Allen - President, Boeing - 1964

"As the advocates of new programs, government agencies have often encouraged contractors to estimate costs optimistically, recognizing that headquarters might be shocked out of supporting a program where true costs were revealed at the outset. They have sought to disclose cost increases gradually, after programs have gained momentum and cancellation has become difficult."

Dr. Frederic Scherer - Harvard - 1964

"We have practically a whole generation of engineers who have never had to live within estimates they have made. They have lived in an atmosphere where lots of things were there to hang your hat on for overruns, and there's a lot of tongue-in-cheek estimating. You will find engineers, once they get there, (and I have had some sad experiences on that) will start thinking a little better."

R.R. Hough – Vice President, AT&T - 1964

"You have basically built into the entire system a series of events which very much leads to under-estimating what the program is going to cost."

J. S. Parker - Vice President, GE - 1964

"We had a program which we estimated at $115 million - it ended up costing $427 million. The program was overrun by a factor of three. The initial estimates were never furnished to the people who had to get the money."

J. S. Parker - Vice President, GE - 1964

Mars Science Laboratory

The Mars Science Laboratory (MSL), which has ballooned to a $2.3 billion price tag, is a good example of NASA's estimating approach. In 2003, the cost for the MSL was put at $650 million on the National Academy of Sciences wish list.[65] Doug McCuistion (who heads NASA's Mars exploration program) said the $650 million estimate was not an official NASA projection, it was put together by a panel of planetary scientists in 2003[66], and the proper estimate (to start) should have been $1.4 billion officially approved at PDR.

However, what McCuistion doesn't say is that the $650 million estimate WAS used to initially approve the project. By December, the number was up to $1.9 billion. Then technical problems delayed launch plans from 2009 to October 2011 adding another $400 million in costs, including cost of Mars operations from 2012 to 2014. The extra money came from cuts to other science projects.

[65] NASA's Cost Overruns Soar, Too, Baltimore Sun, 3-9-09
[66] Mars Science Laboratory: the budgetary reasons behind its delay, The Space Review 3-2-09

> **"The costs of badly run NASA projects are paid for with cutbacks or delays in NASA projects that didn't go over budget. Hence the guilty are rewarded and the innocent are punished."**
>
> *Allen Stern – Former Chief of NASA Science Mission Directorate*

MSL has been touted as the most capable scientific mission every sent to another planet. Most instruments are unique, cutting-edge items never used before on a space mission. It is also large, at twice the size and five to six times the weight of a Mars Exploration Rover (MER). It requires new entry, descent, and landing (EDL) technology. MER pushed the limits of parachute landing, and MSL would be the first to try a revolutionary lifting body and "sky crane" that would maneuver the envisioned 900-kilogram rover downward to within feet of the surface, and drop it ever so lightly to the ground. MSL was built from the ground up to have a fully redundant Command and Data Handling System (CDHS) unlike the MER rovers which had non-redundant "single string" systems.

Industry Data

Other industry cost/schedule comparisons which while dissimilar to NASA's development projects are useful for trend analysis.

The conclusions of a study titled "Megaprojects and Risk"[67] which examined data from 258 large transportation projects in twenty nations around the world over the last 70 years, appears to correlate strongly with NASA's history of project cost growth. Its findings were that:

- Cost underestimation and overrun have not decreased over the past seventy years. No learning seems to take place;
    - ➢ There have been a few studies that suggest cost growth for NASA and DOD has decreased in later years. However, both the number and size of projects available for analysis diminished during this period. This may be a factor.
- It is found with overwhelming statistical significance that cost underestimation and overrun cannot be explained by error and seems to be best explained by strategic misrepresentation, namely lying, with a view to getting projects started.
- Cost overruns of 50 per cent to 100 per cent in real terms are common in megaprojects; and overruns above 100 per cent are not uncommon.
- Actual project performance/viability typically does not correspond with forecast viability, the latter often being brazenly over-optimistic.

Cost estimates at each successive stage of progress typically move toward a smaller number of options, greater detail of designs, greater accuracy of quantities, and better information about unit price. Thus, cost estimates become more accurate over time, while the cost estimate at the time of making the decision to build is far from final and often misses the mark by a large error of magnitude. Existing research indicates that project promoters routinely ignore, hide, or otherwise leave out important project costs and risks in order to make total costs appear low or within a pre-bid cost/schedule ceiling level.

Costs are underestimated in almost 9 out of 10 projects. For a randomly selected project, the likelihood of actual costs being larger than estimated is 86%. The likelihood of actual costs being lower than, or equal to, estimated costs is 14%.

- Actual costs are on average 28% higher than estimated costs (sd=39).

[67] Megaprojects and Risk: An anatomy of Ambition, by Bent Flyvbjerg, Nils Bruzelius, and Werner Rothengatter (Cambridge University Press, 2003).

- We reject with overwhelming significance the thesis that the error of overestimating costs is as common as the error of underestimating costs (p<0.001; two-sided test, using the binomial distribution). Estimated costs are statistically biased, and the bias is caused by systematic underestimation.

Project Type	Number of Cases	Average Cost Escalation (%)	Standard Deviation	Level of Significance (P)
Rail	58	44.7	38.4	<0.001
Fixed-Link	33	33.8	62.4	<0.004
Road	167	20.4	29.9	<0.001
All Projects	258	27.6	38.7	<0.001

Figure 28 *- Inaccuracy of transportation project cost estimates by type of project*[68]

When Eurotunnel (the private company that owns the tunnel [referred to as Chunnel] under the English Channel) went public in 1987 to raise funds for the project, investors were told that building the tunnel would be relatively straightforward. Regarding risks of cost escalation, the prospectus read:

> **Whilst the undertaking of a tunneling project of this nature necessarily involves certain construction risks, the techniques to be used are well proven. . . . The Directors, having consulted the Mâitre d'Oeuvre, (project manager) believe that 10% (contingency). . . would be a reasonable allowance for the possible impact of unforeseen circumstances on construction costs.**
>
> *(The Economist "Under Water," October 1989, p. 37-38)*

The Chunnel project, which opened May 6, 1994, subsequently ended up being 80 percent over on construction costs and 140 percent over on financing costs. Consequently, the project did not make any profits until 2007 and didn't pay its first dividend (four European cents per share) until 2009[69].

Similarly, a 1988 RAND[70] study found that for 52 very large civilian projects with an average cost of about $2 billion (the smallest was 500 million in 1984 dollars), the average cost growth was 88 percent (measured from the beginning of the detailed engineering phase).

Facility Type	Mean	Std. Dev	Minimum	Maximum	N
Refineries	1.63	0.52	0.99	2.54	12
Process Plants	1.67	0.68	0.98	3.22	16
Minerals Extraction	1.99	0.86	1.27	3.71	7
Civil/Transport	2.14	1.26	0.97	4.53	6
Nuclear Plants	2.57	0.67	1.63	3.41	6
All Projects	1.88	0.80	0.97	4.53	47

Figure 29: *- Cost growth in the RAND Megaprojects database*

[68] Underestimating Costs in Public Works Projects Error or Lie? APA Journal, Summer 2002 Vol. 68, No. 3
[69] Eurotunnel Will Pay its First Dividend, WSJ 3-5-09
[70] RAND Understanding the Outcomes of Megaprojects - 1988

Facility Type	Mean	Std. Dev	Minimum	Maximum	N
Refineries	1.08	0.16	0.91	1.50	12
Process Plants	1.16	0.18	0.82	1.45	16
Minerals Extraction	1.25	0.29	0.93	1.63	7
Civil/Transport	1.12	0.28	0.97	1.80	6
Nuclear Plants	1.39	0.20	1.19	1.60	6
All Projects	1.17	0.23	0.82	1.80	47

Figure 30: *- Schedule slippage in the RAND Megaprojects database*

RAND attributed this cost growth and schedule slippage to:

- Project complexity
- Poor project definition
- Changes in project scope
- Regulatory issues
- Degree of technical innovation
- Type of ownership (e.g., public, private, or joint)
- Extent of existing infrastructure
- Faulty execution

Several spectacular examples of cost overrun and schedule slippage are[71];

- Suez Canal (1,900 percent)
- Sydney, Australia Opera House (1,400 percent)
  - The original 1957 estimate was $7 million with a completion date of 1963[72].
  - The final cost came in at $102 million with a completion date of 1973.

Figure 31: *- The Sydney Australia Opera House*

- Concorde - the supersonic airplane (1,100 percent)
- Boston's Big Dig experienced a 275 percent overrun and a total cost of $11 billion.

[71] http://www.answers.com/topic/cost-overrun-3
[72] http://www.answers.com/topic/sydney-opera-house

The Transportation Security Administration (TSA)

In February 2002, the Transportation Security Administration (TSA) awarded a $104 million contract to NCS Pearson, Inc. to test and hire airport passenger and baggage screeners. In less than one year, the contract ballooned to $741 million.[73] Despite this expenditure, the rate at which screeners fail to detect weapons has remained unchanged for over four years.[74]

In August 2002, TSA entered into a $1 billion contract with Unisys Corp. to upgrade airport computer networks.[75] It appears that Administration officials misled Congress about the true costs of the contract. According to the IG, contract officials at TSA estimated that the contract costs would reach $3 to $5 billion but decided to set an artificial ceiling of $1 billion in the public forum. The former chief information officer at TSA said that he was instructed by senior administration officials to cite the $1 billion cost figure to congressional officials, which was "a number out of the air" that "would be more palatable."[76]

Project Scope

Research by the Construction Industry Institute (CII) shows project scope is the major determinant of the cost of a project.[77] CII research also shows that the lack of scope definition is the root cause of cost overruns, late completion dates, excessive rework, unnecessary disputes among project participants, and other problems associated with construction projects.[78]

Cost Overrun in Major Construction Projects Completed Between 1956 and 1977
Adjusted for Unanticipated Inflation and Changes in Project Scope

Project	Initial Estimate Amount (millions)	Initial Estimate Date	Actual Result Amount (millions)	Actual Result Date Completed	Unadjusted of Ratio of Final to Initial Cost	Ratio After Adjusted For Unanticipated Inflation	Ratio After Adjusted For Change in Scope of Project	Compound Annual Rate of Cost Overruns, after Adjustments in Percent a
Bay Area Rapid Transit Authority	996.0	1962	1640.0	May-76	1.647	1.297	1.037	0.31
New Orleans Superdome	46.0	1967	178.0	Jul-75	3.870	3.219	3.219	15.73
Toledo Edison's Davis-Besse Nuclear Power Plant, Ohio	305.7	1971	466.0	May-75	1.524	1.401	1.401	11.89
Trans-Alaska Oil Pipeline	900.0 b	1970	7700.0 c	Jul-77	8.556 c	6.926	4.250	22.96
Cooper Nuclear Station, Nebraska Public Power Dist	184.0	1966	395.3	1974	2.148	1.748	1.748	7.23
Rancho Seco Nuclear Unit No. 1, Sacramento	142.5	1967	347.0	1974	2.435	2.026	1.239	3.11
Dulles Airport, Washington, D.C.	66.0 c	1959	108.3 c	1,962	1.641 c	1.641 d	1.486	14.10
Second Chesapeake Bay Bridge	96.6 c	1968	120.1 c	Jun-73	1.243 c	1.104	1.104	2.00
Frying Pan Arkansas Project								
Ruedi Dam	12.8 c	1962	22.9	1972	1.789 c	1.636	1.145	1.36
Sugar Loaf	6.1	1962	10.2	1973	1.672 c	1.500	1.500	3.75
Boustead Tunnel	9.2 c	1962	21.2 c	1973	2.304 c	2.078	1.233	1.92
Rayburn Office Building, Washington DC	64.0 c	1956	98.0 c	Jun-66	1.531 c	1.531 d	1.342	2.99
Weighted Average					3.93	3.21	2.21	10.07

SOURCE: Walter J. Mead, With George W. Rogers, and Rugus Z. Smith, Transporting Natural Gas from the Anartic, American Enterpirse Institute for Public Polich Research, Washington, D.C., 1997, pp 88-89.

a The compound annual rate expression is only used as a convienient method of comparing initial cost estimates with the sum of all actual costs at the termination of the project. This device permits a comparision of overruns on several projects construction periods.

b In May 1974, the Alyeska Pipeline Service Co. re-estimated capital cost at $4 million; then in October 1974, costs were again estimated at $6 billion for the completed pipeline. By June 1975, the estimate was raised to $6.375 billion. In 1969, the $900 million fcost estimate for Alyeska assumed a capacity of 500 mb/d. The scope was changed to permit a capicity of 1.2 million b/d. The cost of this change in scope was $700 million, raising the initial capital cost estimate to $1.6 billion

c Does not include interest

d Observed inflation less than anticipated.

Figure 32: *- RAND Review of Cost Estimating for New Technology*

73 Letter from Peter A. Iovino, Assistant Administrator for Legislative Affairs, Department of Homeland Security, to Rep. Henry A. Waxman (Sept. 2, 2005)
74 Contracting Rush for Security Led to Waste, Abuse, Washington Post (May 22, 2005).
75 Department of Homeland Security Inspector General, Transportation Security Administration's Information Technology Managed Services Contract (Feb. 2006) (OIG-06-23).
76 Contractor Accused of Overbilling U.S., Washington Post (Oct. 23, 2005).
77 Construction Industry Institute, Project Change Management, Special Publication 43-1 (Austin, Tex.: November 1994).
78 Construction Industry Institute, *Improving Early Estimates*, Implementation Resource 131-2 (Austin, Tex.: September 1998).

Pharmaceutical Development Projects

A further illustration of our findings regarding the ever-common occurrence of expanding development costs and time, consider the results of an early study in the drug industry.[79] Detailed data was obtained for two major drug firms regarding errors in the cost and schedule estimates that were made at the beginning of drug-development projects. Over 80 percent of the projects in one firm exceeded actual costs and schedules. The average ratio of actual to estimated cost was 1.78 to 1.0. The average ratio of actual to estimated time was 1.61 to 1.0. Cost and time estimates proved less reliable for new chemical entities than for compounded products and alternate dosage forms. In the development of proprietary drugs, the average ratio of actual to estimated cost was 2.11 to 1.0, and the average ratio of actual to estimated schedule was 2.95 to 1.0. Again, the overruns became even greater for the more ambitious projects.

The Congressional Visitors Center Project

Though Congress throws tantrums when government agencies overrun projects, they haven't performed any better themselves. The numbers vary depending on the source, but the Congressional Visitors Center (CVS) is commonly acknowledged as a boondoggle[80].

The 580,000 sq. ft. subterranean facility was initially conceived in the mid 1970's[81] and in the early 1990s was projected to cost $71 million.[82] Construction began in June 2000 with a budget of $265 million and a completion date of 2004.[83] Construction was finally completed five years behind schedule in December 2008 for a whopping $621 million or a 775% cost growth above the initial budget estimate and with a 234% cost growth against the construction budget.

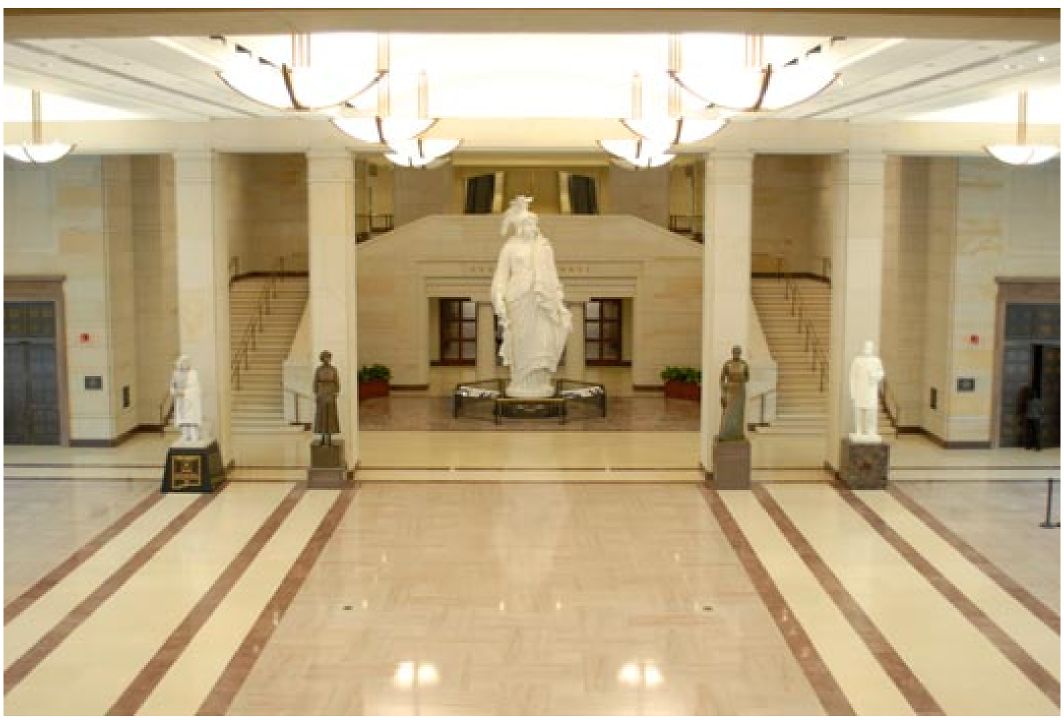


Figure 33: *– Inside the Congressional Visitors Center*

[79] NIST Estimating Social and Private Returns from Innovations Based on the Advanced Technology Program: Problems and Opportunities
[80] Gateway to American History or Fort Capitol? Examining the Policy Evolution and Project Management of the U.S. Capitol Visitor Center Jocelyn Jones Evans Angela Achen
[81] CRS Report for Congress The Capitol Visitors' Center: An Overview Stephen W. Stathis
[82] http://biz.yahoo.com/bw/081202/20081202005386.html?.v=1
[83] http://www.time.com/time/nation/article/0,8599,1625694,00.html

European and Australian Perspectives

A number of European and Australian studies have demonstrated that initial estimate optimism is so pervasive, that the English government recommends project appraisers should make explicit "uplift" adjustments to the estimates of project costs, benefits, and duration based on empirical data to inform project decisions[84].

The English recommend the following adjustments for cost and schedule, always starting with the upper bound, and subjectively adjusting, based on project perceived risk, project phase, in place mitigation. The selected optimism bias adjustment factor is then multiplied by the projects total cost and schedule respectively. Clear and tangible evidence of risk mitigation must be observed prior to reducing bias optimism adjustment.

Project Type	Optimism Bias (%)[2]			
	Works Duration		Capital Expenditure	
	Upper	Lower	Upper	Lower
Standard Buildings	4	1	24	2
Non-standard Buildings	39	2	51	4
Standard Civil Engineering	20	1	44	3
Non-standard Civil Engineering	25	3	66	6
Equipment/Development	54	10	200	10
Outsourcing	N/A	N/A	41*	0*

Figure 34: *– English Optimism Bias Adjustment*[85] *- Project appraisers (analysts) should note that the upper bound percentages relate to the average historic optimism bias found at the outline business case stage for traditionally procured projects. Higher optimism bias adjustments may therefore be required at an earlier stage in the appraisal process*

A Closer Look at the JCL Problem

The current confidence level assessment approach used by NASA has several critical deficiencies. There are key factors excluded from our estimates approach that ought to be reflected, e.g. risks that are highly likely to occur over the life of the program.

Project costs often exceed the stated maximum probable cost (this is a result of multiple things that have been excluded). For example the Ground Operations (GO) International Space Station, Initial Operations Capability (ISS IOC or LEO IOC) budget increased substantially between 2007 & 2008 as a result of new content. In theory, we should be at ~85-90% confidence level. However, since the potential of new content was excluded from our analysis we are not. Congress will not care that the scope changed due to "new requirements" which in fact are not really new but were simply not included in the original project baseline "back when." The root requirement remains the same as it was when we started - e.g. to develop and use available capability to put a man on the moon and beyond.

[84] The Green Book – Treasury Guidance 2003

[85] The Green Book Supplementary Guidance – Optimism Bias 2003

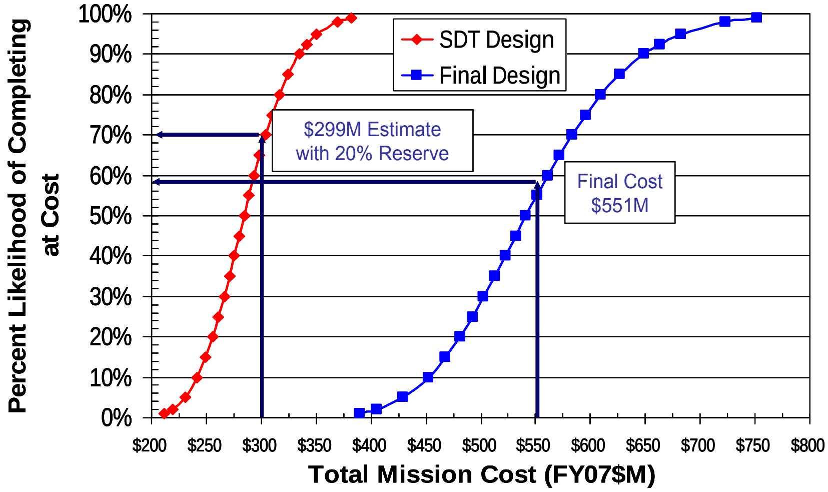


Figure 35: *– David Bearden Chart*[86]

Another question that crops up when formulating a cost risk policy is that of determining which risks to consider as part of a complete analysis. In terms of policy, a desired characteristic of any risk analysis is that it be comprehensive, reflecting all relevant, identifiable uncertainties. If an analysis is not truly comprehensive, factors that can drive the overall cost uncertainty will likely be omitted. Any resulting analysis will then have under-specified the true cost. Although it is impossible to have a detailed comprehensive list of risks for all programs, it is possible to identify broad areas of risk and uncertainty. Risks that are common to programs should always be considered. True risk distributions may really be *bimodal*, *trimodal* or even *multimodal* depending on the sequence of events, and decisions made by the project manager and the whims of congress. In other words, decisions that are made along the path of programs execution, can introduce alternative risk distribution curves in how program really unfolds.

> **"By their very nature, we have limited experience regarding rare events, and a purely statistical determination is not feasible"**
>
> *RoSrinivasa Varadhan - Mathematician*

The cost and schedule growth chart below from PA&E is for semi *routine* projects currently in development.

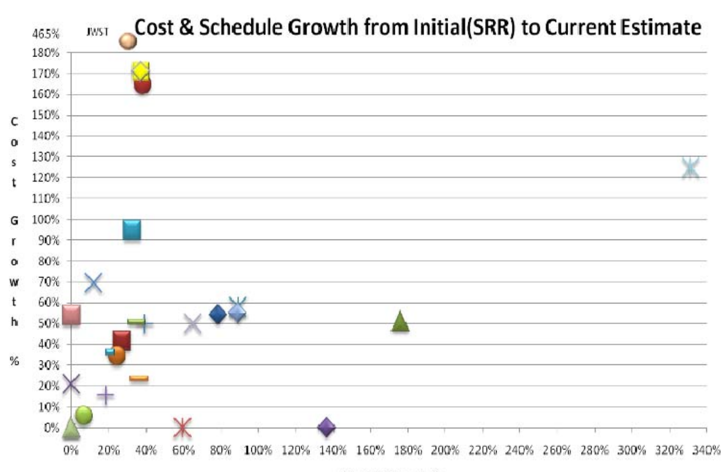


Figure 36: *- Cost and Schedule Growth for 25 Robotics Missions in development 12/2007 PA&E*

[86] Perspectives on NASA Mission Cost and Schedule Performance Trends – GSFC Symposium, Aerospace David Bearden 2008

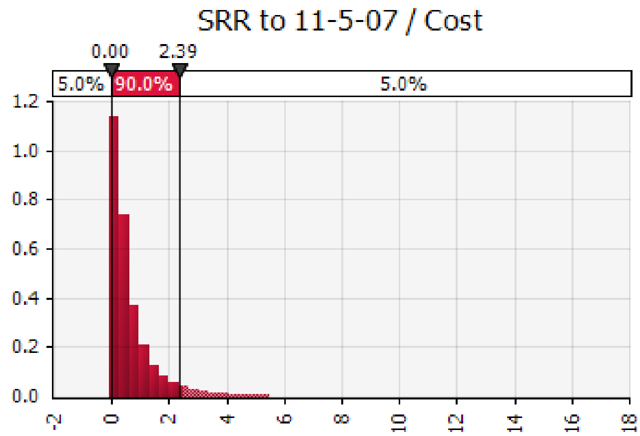


Figure 37: *- Cost Growth for 25 Robotics Missions in development 12/2007 PA&E*

Here are the best fit distributions showing cost and schedule growth of the semi routine robotic missions shown above. Most of these missions are still in development. Realistic JCL estimate ranges must meet or exceed those reflected in these semi-routine missions. If not we are probably not being realistic.

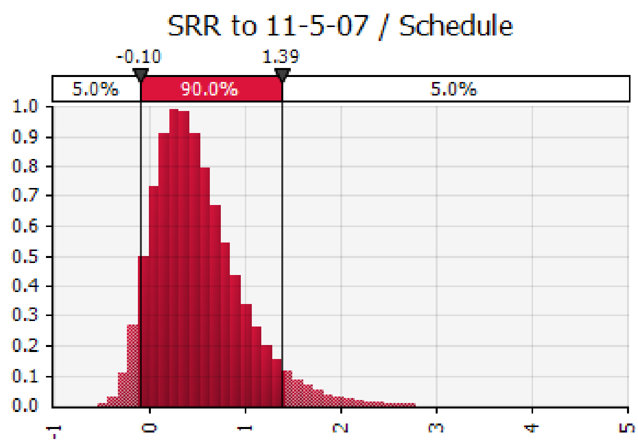


Figure 38: *- Schedule Growth for 25 Robotics Missions in development 12/2007 PA&E*

The PERT Approach

A Well Known 1960s/1970s Attempt

PERT, an acronym for *Program Evaluation and Review Technique* was the original probabilistic scheduling method and was later expanded to include cost. Rumored to have emanated from West Germany sometime in the 1950s, PERT was selected in late 1957 as a method to plan and accelerate the Navy's complex $11 billon (1967 $) Polaris missile program. A RAND report[87] suggests that PERT was only used on a small portion of the Polaris program. PERT relied on the use of subject matter experts to determine the optimistic, probable, and pessimistic time estimates. The possibility of natural disasters or any other unusual events were NOT considered in the analysis. In the early 1960s PERT results & techniques were tied to cost, and adopted by the

[87] RAND Quantitative Risk Analysis for Project Management, 2004

project management community. Its primary goal was to deflect congressional interference by providing a cover of disciplined, quantitative management oversight carried out by modern methodologies. A 1960's Air Force study concluded that PERT costs averaged between 0.1%-0.5% of total project costs.

PERT's reputation rose to grandiose proportions. PERT was praised by Project Management Institute (PMI) and during the late 1960s and early '70s. PERT was applied to just about everything around the world by many organizations including NASA Soon thereafter it fell out of favor, so that by mid to late 1970s (despite the hype) users concluded that PERT did not work very well on most projects. PERT has been subsequently referred to as a "gimmick" by a Polaris program expert. [88] Meant to dazzle and inspire congressional confidence. In fact, a Polaris follow-on project (the Trident program) using PERT, earned the unsavory reputation of having been the single worst managed project in US military history[89].

It has been theorized that part of the problem with PERT was the shortage of computer processing power. However, when the PC and its processing capacities were exploding in the late '70s and early '80s, PERT disappearance was unabated. If PERT were truly value added, it would have experienced a resurgence, which did not happen. This suggests other reasons for its demise. From our analysis, PERT's shortcomings included the predominant problems of 1) optimism bias and 2) the fatal assumption that there is no correlation between project activities and the exclusion of negative impacts due to unlikely events.[90] [91]

The Real Reason Behind the Polaris Success

The authors' supposition as to the real reason for the success of the Polaris program was the creation of an entirely new elite unit to manage the program, called the Special Projects Office (SPO). To motivate the project team they wore special uniforms, worked 5 ½ days a week, had all of their mail shipped "High Priority," and *were told to "think big or get out"* and unusually, enjoyed first-class travel arrangements and hassle free expense accounts. The SPO had a special slush fund to pursue outside suggestions and pacify scientific and/or academic doubters. Because schedules were critical, the SPO demanded and received personal pledges from contractors, and contractor's employees that their portion of the work would be completed on time.

The programs headquarters occupied very modest offices in Washington DC with the goal of being seen as frugal by Congress. In hopes of garnering long-term and wide political support, the SBO often forfeited short term gains to avoid making enemies of the program. In this vein, the program often avoided taking the lead role in every project. They focused instead on integrating all of the components. The SBO always developed two or three options for every critical component, which allowed them to choose the best solution between the competing options. Further, they always employed a fall back strategy in case all three options failed.

The SBO was very receptive to innovative ideas and actively sought out honest progress reporting of goals both up and down the entire organization. What commenced in 1955 with 90 people ultimately grew to 1,800 team members. Tremendous pressure was applied with the goal of total honesty in progress reporting. Lying was a cardinal crime that carried severe consequences. Tight centralized control was avoided to minimize deception and personnel talent was not wasted in bureaucratic paperwork.

[88] The Polaris System Development, Harvey Sapolsky, 1972
[89] The Polaris System Development, Harvey Sapolsky, 1972
[90] Project Management Demystified: Today's tools and techniques, by Geoff Reiss 1995
[91] A Management Guide To Pert/CPM, Jerome West & F. Levy 1969

Ramifications for failure were swift and sure. SBO branch heads were dismissed within 24 hours for failure, and contractor personnel were prohibited from returning to their previous positions if they failed. The program required long hours, and strained the staff. Promotions and awards were liberally granted for meeting or beating project deadlines.

Five Possible Methodologies

Figure 38 shows a notional comparison of four methods to determine estimate confidence levels. These approaches could be used to account for the unknown events in any development discipline.

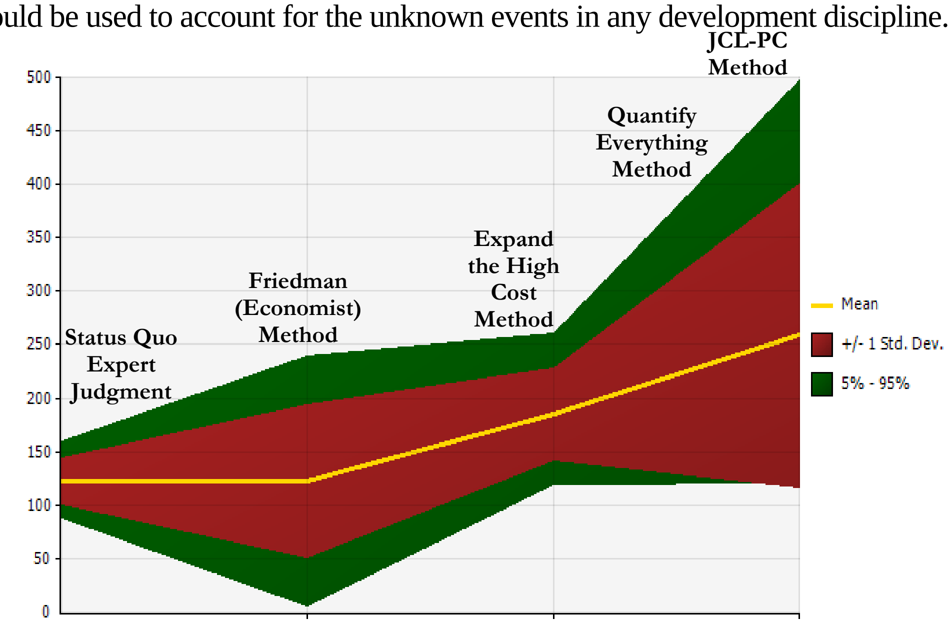


Figure 39: *- Notional Comparison of Approaches*

Status Quo (Expert Judgment Method)

Risk Identification & Tracking Method

Approach one on the above chart is the Risk Identification & Tracking Method. Often relying on expert judgment, it attempts to quantify all potential risks and enter them into a software risk tracking package such as CxIRMA.

Pros of the Risk Identification Software Tracking Method:

- *It is quasi defensible.*
- *It will increase required reserves.*

Cons of the Risk Identification Software Tracking Method:

- *This approach places a tremendous burden on already strained resources since each risk specified must be "touched" regularly.*
- *It is open to arguments, speculation, and manipulation.*

Estimates Occurring Early in the Process

Early estimates of important parameters are inaccurate in two respects. First, such estimates are strongly biased toward over optimism. Secondly, compounding the "yes we can" unrealistic problem, there are secondary cognitive errors on the part of the estimators that demonstrate departure from sound, evaluative thinking.

Often it is not what we know that will get us. It isn't even what we know that we don't know that bodes trouble. It is what we don't know that we don't know that hoses things up. This is a cognitive blindspot created by the fundamental nature of knowledge that has not yet been encountered.

We focus on what we know. We look at facts based on our previous experience. We create mental models based on those things we know. The curse is that the smarter we become and the more we know, the more likely we will become self confident, and then arrogant about what we know. When we become excessively confident about our knowledge, the blind spot increases in size. When we become arrogant we stop listening and the bigger our blind spot becomes. In reality, there is not much difference between over confidence and arrogance.

History is littered with examples of brilliant, yet arrogant, people who through they knew what was and was not, possible. One of the most accomplished scientists of the 19th Century was Lord Kelvin, President of the Royal Society, the United Kingdom's national academy of science. Lord Kelvin defined the absolute temperature scale (named after him), created the first physics laboratory at a British university, conducted research leading to the second law of thermodynamics, championed the undersea cable, introduced Bell's telephone to Britain, published more than 600 scientific papers, and filed 70 patents. In 1895, Lord Kelvin declared: "Heavier than air flying machines are impossible." He was subsequently proven wrong one year later in 1896 when Samuel Langley flew an unmanned steam powered aircraft nearly a mile.[92]

Admittedly, some probable "events" are difficult to quantify; but difficult or not, the <u>need</u> to quantify them still remains. A best effort attempt must be performed with the object of arriving at a quantified number as close to its future actuality as possible.

During the early project stages (especially for technologically advanced projects) cost estimators may have limited relevant data available. In this case, cost estimators often turn to subject-matter experts to help subjectively estimate costs and variability of key drivers. This process requires an expert to specify key parts of the distribution for one or more inputs. Experts may be asked to supply numbers according to their view of what the maximum, minimum, and most likely values will be with respect to the activity/process/event in question. However, regardless of how expert a human being is, judgment in a given area is still subject to one's own biases; these "expert subjective determinations" can impose inaccuracies on the probability distributions derived from the expert's inputs.[93] Generally experts place too narrow of a range on a possible problem. Further, biases can be intensified by the way the polling is done, to include 1) how the questions are phrased, 2) the order in which the questions are presented, and 3) the amount and type of pre-judgment feedback given to the expert about the implications of the judgments being requested.

A significant[94] body of psychological research done at Harvard suggests that people have a poor appreciation for numerical differences in magnitude of risks. Further, people's willingness to pay for risk reduction is usually much less than the proportional risk reduction benefit to be gained. The fact is that people are notoriously poor at understanding probabilities.

Anchoring Bias

There have been many studies on the effect(s) of anchoring bias. One[95] such study had subjects spin a wheel of fortune. Prior to spinning the wheel, the subjects first looked at the number on the wheel which

92 The Vision for Space Exploration and the Retirement of the Baby Boomers, The Space Review
93 RAND Impossible certainty : cost risk analysis for Air Force systems, Mark V. Arena 2006
94 Willingness to Pay for Health Protection: Inadequate Sensitivity to Probability?, James Hammitt, John Graham, 1999
95 The Black Swan: The Impact of the Highly Improbable Nassim Nicholas Taleb 2007

was randomly chosen. They were then asked to estimate the number of African countries in the United Nations. Those who were shown a low number on the wheel estimated a low number, and inversely those with a high number on the wheel estimated a high number. Caution in divulging specifics is advised when questioning experts to avoid inadvertently skewing their answers.

Experts Have a High Opinion of Their Own Opinions

Experts often have an unjustified bias in favor of their own opinions. They are much tougher when critiquing the validity of information that undercuts one of their currently held theories than they are in supporting information that apparently endorses one of their own tenets. Thus employing this double standard, they tend to dismiss new information that doesn't fit with what they already believe. The danger which this self-styled arrogance creates can be illustrated by a 1982 experiment by Harvard researchers Albert and Raiffa.

> **"Our brains have evolved (enough) to get us out of the rain, find where the berries are and keep us from getting killed. Our brains did not evolve (sufficiently) to help us grasp really large numbers or to look at things in a hundred thousand dimensions."**
>
> *Ronald L. Graham - Mathematician*

Researchers took a room full of Harvard Business School students and asked each to independently estimate a high/low range of numbers that answered a series of questions in such a way that they believed they had a 98 percent chance of being correct, and a less than 2 percent chance of being wrong. In other words, whatever they were guessing about had a 2 percent chance of falling outside their arbitrarily selected range. For example, *"I am 98 percent confident that the population of Vermont is between 2 million and 20 million."* The students were free to set their range as wide as they wanted. The experiment was not designed to test their subject matter knowledge, but rather to test their confidence levels of their own knowledge (e.g. to what extent they feel certain that they know something). The students failed miserably with an error rate on the series of questions close to 45%.

This experiment has subsequently been replicated dozens of times, across various populations, professions, and cultures. The results regarding self-supporting gravitational thinking are always the same. The expected error rate of 2 percent is actually on average between 15-30 percent! The conclusion is that we over-estimate what we really know and under-estimate the possibility of our being wrong. Our tendency to think well of our own notions can have dramatic results in the negative.

Philip Tetlock's 1999 study[96] of twenty seven thousand predictions by nearly 300 experts who believed their predictions were narrowly bounded is highly instructive. The results of the study did not vindicate their "expertness" as was anticipated. The error rates were many times what these experts had predicted. Intriguingly, Tetlock found that there was no differential advantage for those experts holding graduate degrees versus those with only undergraduate degrees. His primary intent was not to demonstrate the competence level of experts, but rather to investigate why the experts themselves did not recognize that they were not as proficient in their judgments as they had supposed themselves to be.

The point here is NOT that we should become chronically suspect of "expert" opinion nor discount its validity when acquiring subject matter expert inputs for project estimation purposes. Rather, the conclusion is that *in addition to* our reliance on experts, other estimating factors must be present in our equation in order to build an accurate joint cost/schedule calculator.

[96] Expert Political Judgment How Good is it? How Can we Know? Philip Tetlock 2005

Friedman (Economist) Method

Milton Friedman, a Nobel winning economist penned an essay in 1966 titled "The Methodology of Positive Economics". This essay presents a theory often cited by modern economists that loosely states – *realism of assumptions is irrelevant as long as the theory predicts well, since the only goal of economic theories is to predict*. This theory has been tested by Spyros Makridakis who set up competitions between forecasters who practiced econometrics. He compiled experts' forecasts of real life events and then he evaluated the accuracy of those forecasts. He reached the conclusion that "statistically sophisticated or complex methods don't provide more accurate forecasts than simpler ones (methods)."

> **"Everything should be made as simple as possible, but not simpler."**
>
> *Albert Einstein*

The Friedman (Economist) Method represents a second approach to acknowledging that an inductive event will (or at least could) happen.

Pros of the Friedman (Economist) Method:

- *It is fast.*
- *It is better than no method at all.*
- *It can be implemented to affect confidence levels only above the 65% level, so reserve levels are not affected.*

Cons of the Friedman (Economist) Method:

- *It is Indefensible – other than the Friedman theory.*
- *It is open to arguments, speculation, and manipulation.*

This Friedman (Economist) method could be utilized using a combination normal and discrete distribution. The discrete probabilities are set for a 30% likelihood that an unplanned event will occur. This will render confidence level distribution with fat tails. In the world of probability, this means that cost estimate "potentials" will be higher and schedule estimate "potentials" will be longer. The net effect is that the probability of a cost/schedule estimate overrunning the 95% mark will decrease. The following chart shows two "S" curves. The blue line is a "normal" distribution. The red line is a discrete (Friedman type) distribution. Note the minimum, maximum, mean, and standard deviation data for both models shown at the right of the chart. It will be noted that the Friedman distribution reflects substantially higher cost numbers.

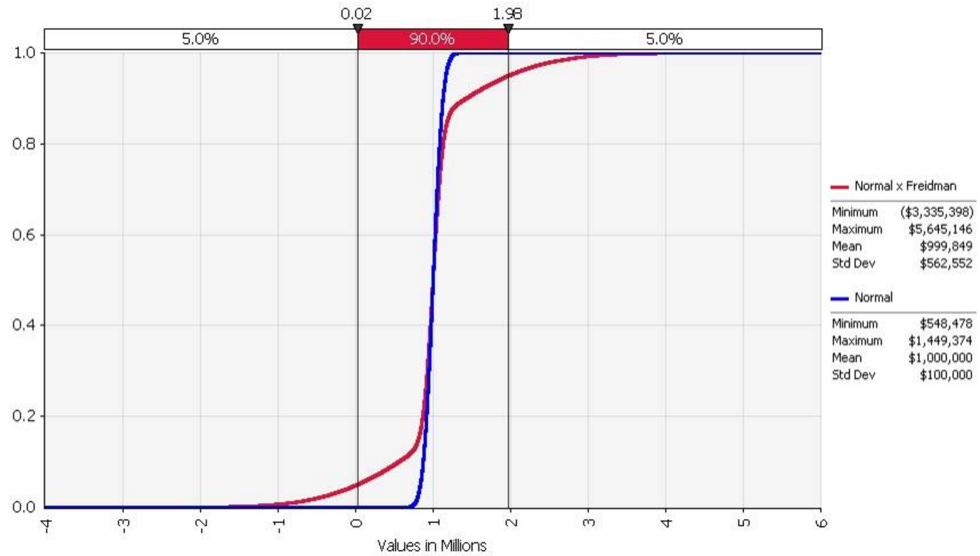


Figure 40: *- Friedman Style Approach*

Expand the High Cost Method

Approach three is the Expand the High Cost Method. It ignores the elephant in the room and notionally increases the worst case event for all modeled risks. It is subjectively arbitrary and claims nothing more.

Pros of the Notional Method:

- *It is fast.*
- *It is better than no method at all.*
- *It will increase required reserves.*

Cons of the Notional Method:

- *It is indefensible.*
- *It is open to arguments, speculation, and manipulation.*

Quantify Everything Method

Approach four is the Quantify Everything Method. It attempts to list and quantifies every conceivable risk, no matter how unlikely, (internal and external) and place a best available risk distribution on each.

> **"Anything you need to quantify can be measured in some way that is superior to not measuring it at all."**
>
> *Gilb's Law*

NASA's safety and mission assurance office (SM&A) spends a large quantity of resources to actively track and manage risks with likelihood of occurrences of one in several thousand. Not only are these risks tracked, millions of dollars are spent on engineering solutions to mitigate these risks.

A recent example is an emergency egress system (EES). EESs have been installed at every U.S. launch pad built for manned space flight - but have never been used. NASA is currently designing a new roller coaster EES at launch complex 39 B with estimated life cycle costs of $40 to $80 million dollars for design, build and operation. This system has a calculated probably of use of 1 time in 2,000 launches, and a probability that it will be successful in carrying an injured person away from the pad of 1 in 4,000. Despite these low probabilities, a strong case was made to add another $15 to $30 million of life cycle costs to double the length of the EES to allow immediate access to medical care. This additional feature of the EES was not approved due to lack of funding. This example stands in stark contrast to cost and schedule risk management mitigation events that for some reason must show a much higher probability of occurring before they are accepted and reflected as a risk worthy of tracking.

Pros of the Quantify Everything Method:

- *It is quasi defensible.*
- *It is a much better approach than what is currently used.*
- *It will increase required reserves.*

Cons of the Quantify Everything Method:

- *This approach is very labor and time intensive.*
- *It is open to arguments, speculation, and manipulation.*

JCL-PC Method

Approach five is the JCL-PC method. Introducing this method is the primary objective of this paper. JCL-PC is the recommended solution set in answer to the sophisticated challenges confronting the cost estimating community within NASA. In essence, the JCL-PC method achieves a quantify Everything Method, but does so in a mathematical way, bypassing the time/labor intensive effort connected with method four. It anticipates 99% of the conceivable risks (internal and external), no matter how unlikely they are to occur and provides the decision maker with a best available risk distribution scenario.

A full explanation of the JCL-PC method will be presented on page 85 in the "Path Forward" Section of this paper.

Pros of the JCL-PC Method:

- *It is historically defensible.*
- *It is a much better approach than any method currently used.*
- *It is not labor and time intensive.*
- *It will increase required reserves.*
- *It anticipates 99% of conceivable risks and gives the decision maker a best available scenario.*

Cons of the JCL-PC Method:

- *A 1% likelihood of unknown event possibilities still remains*

A 1981 RAND Study

A 1981 RAND Study titled *Understating Cost Growth and Performance Shortfalls in Pioneer Process Plants,* reviewed 106 estimates for 40 large projects and examined the reasons for cost growth.

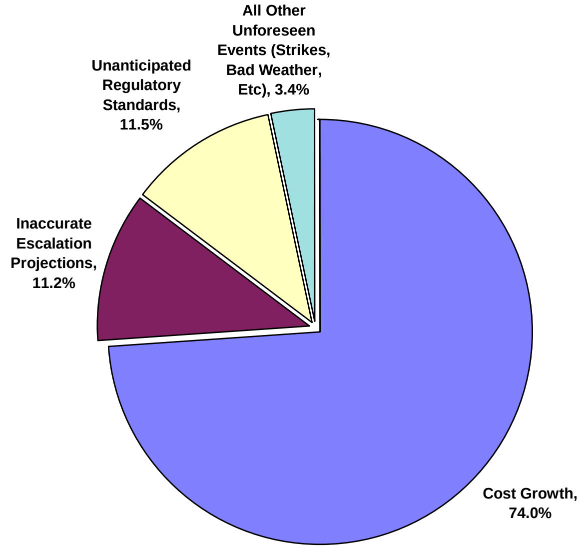


Figure 41: *- Reasons for Understating Cost Growth and Performance Shortfalls*

"These initial estimates were on average very poor predictors of actual costs. Moreover, the range of mis-estimation was so large that it would have been difficult to apply a simple factoring ratio to correct for the underestimation."

RAND excludes "scope growth" on the following basis;

"One of the most commonly cited causes of cost growth is a gap between planned and actual scope of the plant. A clear definition of the plant's scope provides the first critical information necessary for accurate cost estimation, and changes in scope can be a leading cause of misestimating. Because 'scope changes' can be variously defined, however, people often seize on the term and use it retrospectively as an amorphous catch-all to explain away cost growth. We use the term here to encompass only what the plant will produce and at what rate. We define scope changes, in other words, to include only discretionary changes in the plant's design capacity or product slate.

During the course of a project, plant scope may be changed for a variety of reasons, such as changes in expected market conditions; if it is changed by altering the plant's design capacity or product slate, cost estimates must be adjusted accordingly. Defined in this manner, scope changes are largely exogenous, or external, to the accuracy of an estimate.

On the other hand, cost growth frequently occurs as more precise design information is obtained during a project, particularly for pioneer processes. Strictly speaking, we do NOT define these as scope changes. They are rarely discretionary, but result from previously unrecognized design requirements. As engineering design progresses, more detailed process requirements become plain and often require additional investment in equipment specifications or process configurations not anticipated earlier."

Example Risks

What follows over the next number of pages is a short list of possible risks, some admittedly unlikely, with easily available historical data that does allow bounding of the event. However, we believe most fall well within the 1 in 2,000 probability of occurrence.

Labor Strikes

Influence from labor unions has waned in recent decades but they may again regain strength before program completion. Historically, strike durations at KSC have ranged between 1 and 154 days. Strikes may involve one or more unions and work slowdowns surrounding the strike often have negative impact both before and after the actual strike event. Sometimes non striking unions show solidarity by refusing to cross a picket line which, of course, magnifies the event. Available data was reviewed to compile the following list of past strikes. Many more strikes were averted through last minute agreements.

Apollo Period Strikes

"Work stoppages resulted in a total loss of 87,374 man-days at Cape Canaveral during a 4 1/2-year period in the late 1950s and early 1960s. Wildcat strikes, slowdowns, and a deliberate policy of low productivity further delayed progress." (Source: Moonport)

- November 14, 1960 - KSC
- October 31, 1964 – Hold Down Post Supplier Plant
- February 1964 – Railroad Workers
- April 1964 – VAB Steel Supplier
- June 3, 1964 – KSC
- June 8, 1964 – KSC
- September 16, 1965 – Boeing Nationwide

Shuttle Period Strikes

- 1971 – KSC
- October 4, 1977 – KSC
- November 10, 1977 – KSC
- 1978 – KSC
- February 27, 1980 – KSC
- November 1980 – KSC
- February 1981 – KSC
- July 6, 1984 – KSC
- March 1, 1985 – KSC
- July 6, 1984 – KSC
- November 2005 – KSC
- June 2007 – KSC

Weather

NASA schedules and cost estimates are based on normal weather patterns and assume no hurricanes or tornados directly impacting a NASA center, or for that matter anywhere in their region.

In the event of a direct hit to a center, Congress will likely allocate emergency repair funding - but this may prove insufficient to mitigate impacts to new or ongoing projects. Demand surge, is a term that describes the cost and schedule impacts imparted by a natural disaster. Due to the sheer volume of work to be done repairing the aftermath of the storm, labor and material shortages often abound. Result, a weather impact anywhere in the region of a center may affect projects in work or the entire programs cost and schedules through secondary impact.

Probability of a KSC Hurricane Strike

Hurricane season occurs from June 1 to November 30, peaking sharply in early September.

A great deal of research has been done on the probability of a hurricane landfall in the KSC vicinity. This data can be examined at: http://www.e-transit.org/hurricane/welcome.html. Summary analysis provides the following probabilities of a hurricane strike in Brevard County:

- **Tropical storm force (40-75 mph winds)**
  a. 1.8% direct hit in 2008
  b. 51.5% of direct hit 50 year period
  c. 14.9% vicinity hit in 2008
- **Hurricane force hit (≥75 mph winds)**
  a. 0.4% of direct hit in 2008
  b. 16.3% of direct hit 50 year period
  c. 3.9% of vicinity hit in 2008
- **Intense hurricane force hit (≥115 mph winds)**
  a. 0.1% of direct hit in 2008
  b. 2.9% of direct hit 50 year period
  c. 0.7% of vicinity hit in 2008

Hurricane Impacts Without Making Landfall

In the event of a hurricane or tropical force wind event anywhere near a NASA center with the likelihood of landfall within 72 hours, requires termination of all work along with the implementation of detailed protection plan activities. Man-hour losses would be significant.

Hurricane Impacts Making Landfall Anywhere in the Southeastern US

Demand surge occurs whenever building materials and construction contractors are in short supply following one or more major catastrophes. The 2004 hurricane season saw a high demand surge when Florida and other Southeastern states experienced four hurricanes within 37 days. These storms resulted in over 2 million claims, nearly three times the volume resulting from Hurricane Andrew in 1992. This led to a surge in demand for materials and labor. Restrictions placed on out-of-state contractors further limited the supply of labor in Florida and exacerbated the recovery effort.

In “super catastrophes” like Hurricane Katrina, losses become nonlinear, i.e., the scale of the event itself causes losses to increase still further. Demand surge encompasses all those elements of the costs that are resource-constrained. Demand surge, itself a function of the overall economic loss, introduces a nonlinear feedback in the estimation of economic loss. Nonlinear behaviors of economic shocks are described by Leontief input-output economic models.

Building Damage

The cost of damage incurred by a hurricane is an inverse square to the multiplier of wind speed and exponentially related to the number of hours with winds measured more than 50 knots. This is a consequence of a cyclic loading of materials which results in building fatigue.[97]

[97] Dr. Bob Bailey of ASB Consulting

We have developed a damage model that estimated facility repair cost at both Stennis & Michoud Space Center with ~8% accuracy using only basic data hours after Katrina's landfall. All of the inputs events could be modeled and used to determine ultimate risk exposure.

Schedule Slips

The unexpected has a one sided effect when considering projects. It pushes in a single direction outward, resulting in higher costs and a longer time to completion.

The default for cost and schedule variances is not necessarily additive. Schedule variances, however, can become cost variances as additional work (overtime) is often required to regain schedule, or if the delay creates a schedule slip.

On an established project, the only thing more costly than stretching the schedule is accelerating it. Compressing the timeline is itself the most costly action known to man. [98]

A review of Kennedy Space Center 197 historical Construction of Facilities (CoF) and 1,250 Ground Support Equipment (GSE or STE) projects indicate a wide range of data dispersion. This subject appears to be complex enough to warrant additional study. However, a quick analysis reveals that the average and median completion dates are always beyond originally scheduled durations, sometimes well beyond. These values were calculated with the formula;

Project Close out Date - NTP = Actual Days

Actual Days ÷ Original Contract Duration – 1 = % Change from Original

The boxplot below shows data distribution of schedule slips for various project types & durations.

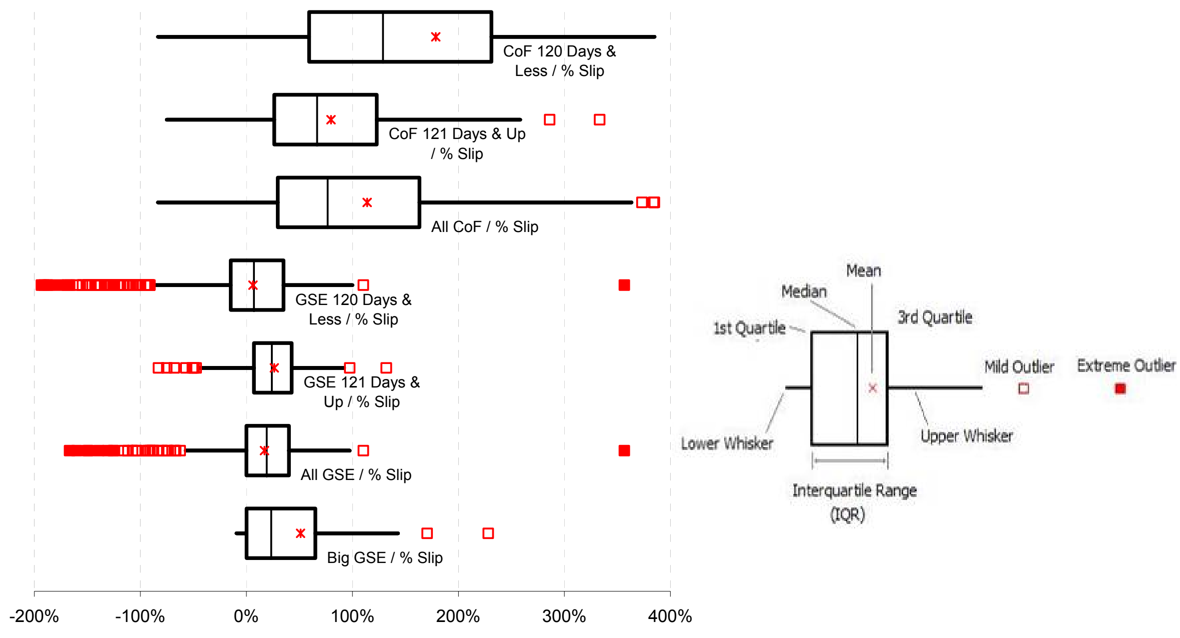


Figure 42: *- Boxplot comparing schedule slips of various types of GSE & Facility projects*

"It always takes longer than you expect, even if you take Hofstadter's Law into account."

Hofstadter's Law

[98] Augustine's Laws, 6th Edition Norman R. Augustine

Schedule slips affect cost. With cost plus contractors, the correlation between cost and schedule is fairly high at ~70%. On fixed price contracts, schedule slips affect cost to a much lower extent, nevertheless, oversight cost for FTE and WYE personnel must still be accounted for. In addition, if the project procurement date is delayed, additional escalation for the "slip period" must also be accounted for.

Validation, verification & activation activities often uncover supplemental operational requirements that need to be resolved or capability brought on line that was previously unknown. This is the time and these are the people that have to make what was delivered "really" work - the tail end of the dog. Validation - verification activity is a prime category for schedule slip - and for that matter cost growth.

Sundry Work Interferences with Cost and Schedule Impact

There are a number of affiliated impacts which can affect project schedule and costs. Some of the more prominent potential interferences are discussed below.

Bid Protests

It is not uncommon for work schedules to be delayed due to bid protests following contract award either for alleged mistakes in the bid or for claims of non-compliance in following competitive protocols. Bid protests can delay project start for 85+ days if the express resolution option is exercised and/or 120+ days if the normal process is used, and assuming no lawsuits result.

Funding Timeliness

Confidence planning assumes that funding will be received when it is required; unfortunately, this is often not the case. Continuing resolutions, budget cuts, delays of up to six months for receipt of funding at the centers, complying with CoF regulations requiring 3-8 month timeframes for re-programming/re-directing of monies if funding is available from other government sources - all have the potential for delivering serious consequences to cost and schedule.

It has been observed that Congress will often appropriate the same amount of funding for the upcoming year that was approved for the prior year, plus or minus three-fourths of whatever change the administration is then requesting, minus 4-percent tax[99] It can be readily seen that this legislative practice can wreak fiscal havoc on dependable costing strategies with direct impact on related schedules.

Accidents

Accidents, which sometimes are fatal, are regretfully a side effect of large construction projects. One such example is Launch Complex 37 which experienced two fatalities that stopped work during the investigation period and negatively impacted morale. In all, 29 OSHA recordable accidents occurred during~1,800,000 work hours on the LC 37 project.

Worker Sabotage

Often on large projects, a few bad seeds exist in the personnel pool. These individuals can substantially affect progress by sabotaging projects, slowing down the work, or reporting a bomb threat. This radical behavior usually manifests itself when the job is nearing completion and workers are facing layoff.

- *On a past launch complex construction project there were two bomb threats as project completion drew nye, each with a direct cost of ~$125,000 (excluding cost of overhead and equipment) for each event in FY08 $.*

[99] Augustine's Laws, 6th Edition Norman R. Augustine

- *Sabotage costs, though difficult to quantify, can be substantial with history confirming that they do exist.*

Operations Impacts

During the Apollo and Shuttle buildup periods, Kennedy Space Center was (for the most part) NOT operational. Since both of those development projects had priority status, scheduling milestones were more easily achieved. This same development emphasis will not be the case during Constellation readying activity. The shuttle program will continue to require full center support until 2010 and possibly longer and Shuttle operations historically have priority when scheduling conflicts occur. This affects outage windows and will, to some extent, prevent efficient work progress on Constellation. Preparation work on Launch Complex 39B has already been delayed as a result of the Hubble Space Telescope's final maintenance/upgrade mission.

The USA VAB door refurbishment project was substantially delayed because of operations impacts with project costs increasing from 9 million dollars to over 56 million dollars.

Launch days can also affect delivery of equipment and/or materials for other programs making access to certain sensitive areas difficult and sometimes impossible. In the event of a "scrub" for the mission, 4 to 20 days per year of lost productivity for hundreds or thousands of people can result. Since launch days are often a moving target, a further unproductive element of uncertainty exists for those trying to plan deliveries and events. The reality is that schedules often slip so fixing firm dates becomes problematic and further scheduling delays frequently occur.

Late Delivery of GFE or Facilities

Specialized components are often ordered as Government Furnished Equipment (GFE). This is done for two primary reasons. The first is to save money with economies of scale ordering and the second is to shorten project schedules due to the government placing orders that can precede the letting of a given contract. Long lead times can thereby be mitigated. However, once we opt for GFE involvement, if we fail to provide parts or equipment to the contractor in a timely fashion in accordance with contract requirements, the contractor has a just claim against cost and schedule increases.

Additional slow-downs can also occur when the government has contracted with multiple firms on the same end product. In such cases, the first contractor must complete their part of the work before the second contractor can start. If the first contractor is delayed for any reason, the second contractor must wait until the preliminary work has been completed, and is eligible for a claim.

Helium Shortage

Helium is a vital commodity in the space program with unique properties and many uses including purging hydrogen systems, spin starting the RS68 engines, and cooling cryogenic tanks. Helium can not be replaced by other gasses in most instances. Because of its unique properties Helium is very expensive to store, handle and transport. Virtually all helium is processed and shipped to its final user as soon as it is extracted from the ground. To compound the problem, scientific research has multiplied the uses of helium over the past 50 years. It is needed to make computer microchips, flat-panel displays, and fiber optics. Helium is required to operate magnetic resonance imaging (MRI, scans) and used in many welding processes and in super-conductor research. The technology explosion is sucking up helium supplies at dizzying rates. U.S. helium demand is up more than 80% in the past two decades and is growing at more than 20% annually in developing regions such as Asia.

Helium is found in varying concentrations in the world's natural-gas deposits and is separated in a special refining process. The easiest-to-get helium supplies have been tapped and are declining.

Supplies in the world's largest helium reserve near Amarillo, Texas, are expected to run out in six years. Stored in a depleted natural-gas cavern known as the Bush Dome near Amarillo; it supplies 35% of the helium consumed in the world. The U.S. government started the reserve in 1925, but by the mid-90s decided to sell it to pay off debt it incurred from stockpiling helium over the years. Under law, the entire contents of the Bush Dome should be sold by 2015.[100] Once the Bush Dome reserve is gone, there will be no stored helium to supply the market in case of disruptions at production facilities, making for spotty deliveries and even higher prices. The Constellation program will require two to three times KSC's current helium storage and pumping capacity. The expected helium shortage and resultant price hikes will likely ding the budgets by requiring a larger helium storage system, bigger commodity budgets, and possibly an expensive helium recovery system.

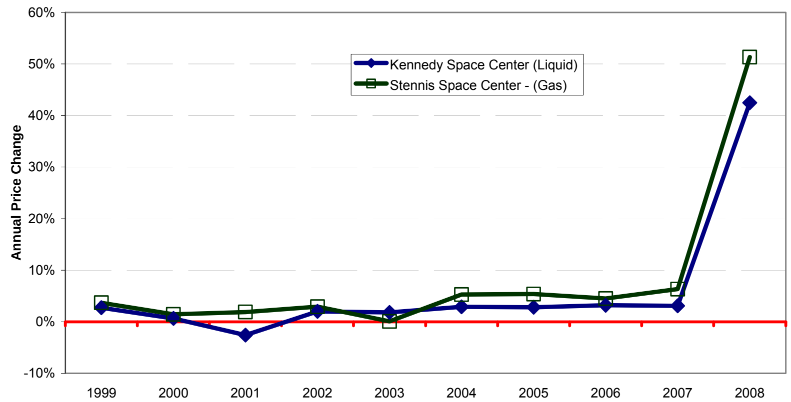


Figure 43: *- Helium annual cost change*

Space Junk

We often think of the "vacuum of space" as a vast nothingness. In reality, space is more like a typical teenager's bedroom - full of clutter from the past. It's been estimated there are millions of pieces of man made debris circling the earth. Tracking networks only monitor about 18,000 of the largest objects measuring four inches or larger. This debris, which remains in orbit for many years, carries the force of a hurtling 400 pound safe.

> **"There is a whole class of particles that can't be tracked, can't be shielded against, and are very dangerous."**
>
> *David Wright – Director Global Security Program*

In February 2009, an accidental collision occurred between an Iridium 33 Communications Satellite and a Russian Cosmos 2251. This is the ninth significant crack up in two years. Each prior event left behind thousands of fragments in an environment where any debris larger than a pea can be devastating. Even a paint flake can crack the shuttle's windshield.[101]

> **"A crash (with another satellite) wasn't on the top 10 list of problems . . . not even the top 150 list."**
>
> *Liz Decastro – Iridium Spokesperson*

In February 2008, a U.S. Navy ship launched a missile that took out a dying, hazardous spy satellite. The test boosted the credibility of missile defense advocates. In 2007, China destroyed one of its own

[100] Rising Demand Makes for Helium Shortage, WSJ, 12/5/07
[101] Harmless Debris on Earth is Devastating in Orbit, WSJ, 2-27-09

defunct satellites with a ballistic missile. Russia recently announced they are working to develop anti-satellite weapons to match efforts by other nations,[102] The Russian effort which will culminate in a weapons test, leaving even more debris.

> **"Many spacecraft including the space shuttle are in some places venerable to particles five millimeters in size or below."**
>
> *Nicholas Johnson – NASA Orbital Debris Office*

In the 1980's it was estimated that the chance of a satellite collision with space junk or with other satellites was one in bazillions (1 followed by 30 or 35 zeros). Since that time, the collisions that have occurred along with additional launches have lopped off about 20 of those zeros[103]. This trend will continue and will ultimately grow to become a major risk in the years ahead.

Counterfeit Parts

According to a recent US study, trade in counterfeit items has increased from $5.5 Billion in 1982 to $600 billion in 2008. Counterfeit equipment recently discovered includes aerospace components embossed with logos from prominent aerospace manufacturers. In 2008, NASA found a counterfeit part on the Kepler spacecraft that resulted in a nine-month delay in launching the unmanned probe. Kepler (which was finally launched in March of 2009) is designed to probe for earth-like planets in our region of the Milky Way Galaxy.[104] Failure caused by a counterfeit part could ultimately result in loss of mission or loss of crew.

> **"Some of the cost overruns besetting the space agency stem from counterfeit parts inadvertently installed on space craft."**
>
> *Christopher Scolese – Acting NASA Administrator*

Unfunded Mandates

New unfunded mandates are fairly common in government projects. These mandates are usually sold as being low or no cost. The reality is they often grow cost and push schedules to the right. Some examples are:

- ***Conversion from US to metric***
  - a. *Appears to increase facility costs by ~5%*
  - b. *Higher likelihood of errors being missed during design reviews. A prime example of a catastrophic metric oversight was the Hubble Telescope when it was initially activated in orbit and began sending back blurred images due a mistake in fabricating the mirror curvature which resulted from failure to convert measurements from US to metric.*
- ***Leadership in Energy and Environmental Design (LEED) Requirements***
  - a. *Cost impact can vary substantially depending on project size & type*
  - b. *The plan is to continually increase certification standards*
- ***Environment (Other)***

[102] Russia Building Anti-Satellite Weapons, Associated Press, 3-5-09
[103] The Odds, When Birds, Subs, and Satellites Collide, WSJ, 3/4/09
[104] NASA Official Says Counterfeit Parts a Growing Problem, Houston Chronicle, 3-5-09

a. *Historical preservation*
b. *Endangered species acts*
c. *Wetlands mitigation*
d. *Storm-water retention*
e. *Green fuels for rockets & spacecraft*
    i. *Hypergols, perchlorate, greenhouse gasses & carbon taxes*
f. *Impacts due to global climate change issues*
    i. *Chemicals outlawed*
    ii. *Commodities impacts - hydrogen, oxygen, methane, etc.*

Escalation / Inflation

Inflationary movement during the first quarter of 2009 isn't as yet apparent, but recent stimulus packages and the multiple bailouts agenda totaling $3-$8+ trillion dollars by the time it's all done will mean a serious influx of money in the system. Monetary escalation at this aggregate level and rapid pace has never been seen before and promises to create a classic inflation scenario.

Numerous issues are at play; exchange rates, energy costs, business cycles, government regulations, hedge fund influences, etc. The net effect is proving difficult for even the financial experts to predict.

	Maximum amount	Current amount
Federal Reserve -	**$5.255 trillion - 62%**	
Commercial Paper Funding Facility LLC (CPFF)	1,800,000,000,000	270,879,000,000
Term Auction Facility (TAF)	900,000,000,000	415,302,000,000
Other Assets	601,963,000,000	601,963,000,000
Money Market Investor Funding Facility (MMIFF)	540,000,000,000	0
Unnamed MBS Program announced 11/25/08	500,000,000,000	0
Term Securities Lending Facility (TSLF)	250,000,000,000	190,200,000,000
Term Asset Backed Securities Loan Facility (TALF)	200,000,000,000	0
Other Credit Extensions (AIG)	122,800,000,000	122,800,000,000
Unnamed GSE Program announced 11/25/08	100,000,000,000	
Primary Credit Discount	92,600,000,000	92,600,000,000
ABCP Money Market Fund Liquidity Facility (AMLF)	61,900,000,000	61,900,000,000
Primary Dealer and Others (PDCF)	46,611,000,000	46,611,000,000
Net Portfolio Maiden Lane LLC (Bear Sterns)	28,800,000,000	26,900,000,000
Securities Lending Overnight	10,300,000,000	10,300,000,000
Secondary Credit	118,000,000	118,000,000
Federal Deposit Insurance Corporation -	**$1.788 trillion - 21%**	
FDIC Liquidity Guarantees	1,400,000,000,000	0
Loan Guarantee to Citigroup*	249,300,000,000	249,300,000,000
Loan Guarantee to Lending arm of General Electric	139,000,000,000	139,000,000,000
Treasury Department -	**$1.15 trillion - 13.5%**	
Troubled Asset Relief Program (TARP)	700,000,000,000	350,000,000,000
Fannie Mae / Freddie Mac Bailout	200,000,000,000	0
Stimulus Package	168,000,000,000	168,000,000,000
Treasury Exchange Stabilization Fund (ESF)	50,000,000,000	50,000,000,000
Tax breaks for banks	29,000,000,000	29,000,000,000
Federal Housing Administration -	**$300 billion - 3.5%**	
Hope For Homeowners	300,000,000,000	300,000,000,000
Total - 100%	**8,490,392,000,000**	**3,124,873,000,000**

Figure 44: *– Bailout Range as of Dec 2 2008.*

As of 3/31/09 The U.S. government and the Federal Reserve have spent, lent or committed $12.8 trillion, an amount that approaches the value of everything produced in the country last year, to stem the longest recession since the 1930s.[105]

The economy is cyclical, with well defined periods of expansion and contraction, which consequently result in periods of high and low inflation. This cyclical pattern has been documented as far back as the late 1700's. [106]

A number of studies dating back to 1752 have found that a nominal quantity of money and the inflation level are closely related. Milton Friedman stated in 1963 "Inflation is always and everywhere a monetary phenomenon." There is little disagreement that the long term correlation between monetary supply and inflation is very strong. However, correlation is lower over the short term.[107]

> ***"The current efforts to help revive the economy are likely to produce inflation that could be worse than what the country suffered in the late 1970s."***
>
> *Warren Buffett (2009)*

[105] Financial Rescue Nears GDP as Pledges Top $12.8 Trillion (Update1), Bloomberg.com, 3/31/09
[106] Measuring Business Cycles, Burns and Mitchell, 1946
[107] Federal Reserve Bank Are Money Growth and Inflation Still Related? Second Quarter 1999

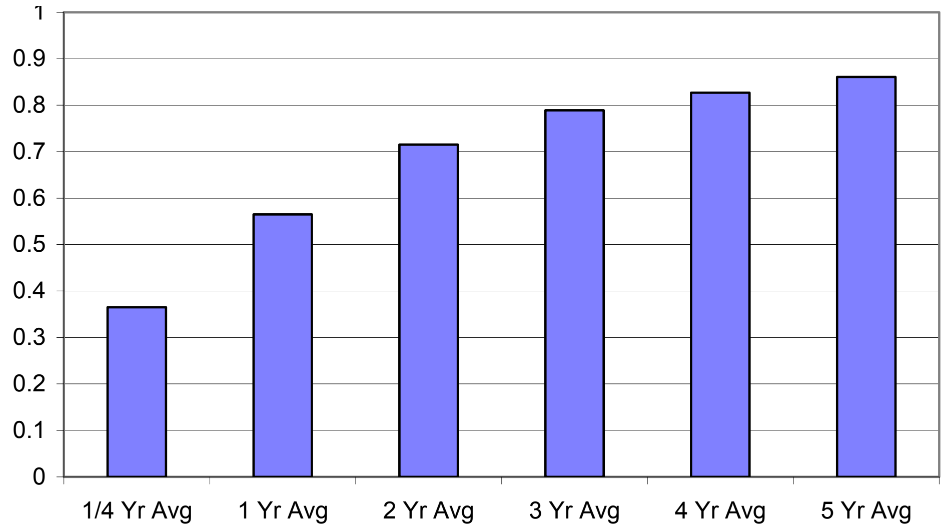


Figure 45: *- Correlation between the Money Supply and Annual Inflation Rates from 1953-1997* [108]

Escalation rates used in NASA estimates are set at 5% for CoF and 3% for R&D projects. These rates are not currently modeled, and could vary substantially. The 2009 version of the NASA New Start index projects future annual inflation rates from 2.6%-2.9%, despite the fact that an analysis of the actual data contained in the index from 1959-2009 (50 years) tell us that these projections only provide a probability from 10%-15% that they will not be overrun in a given year. In other words, there is an 85-90% probability we are not using nearly enough escalation in our calculations. To obtain a 50% confidence level a projected annual inflation rate of 4.6% per year is needed even without the severe fiscal manipulation activities currently in work by the Federal Reserve and the Treasury Department. Factor in the recent government intervention wild card and things could heat up to a much higher inflation rate with 6-7% per year not being an unrealistic projection.

> **"Without a change of policy (in government's pay-as-you-go health and retirement system), a higher rate of inflation can be anticipated in the United States."**
>
> *Alan Greenspan (2007)*

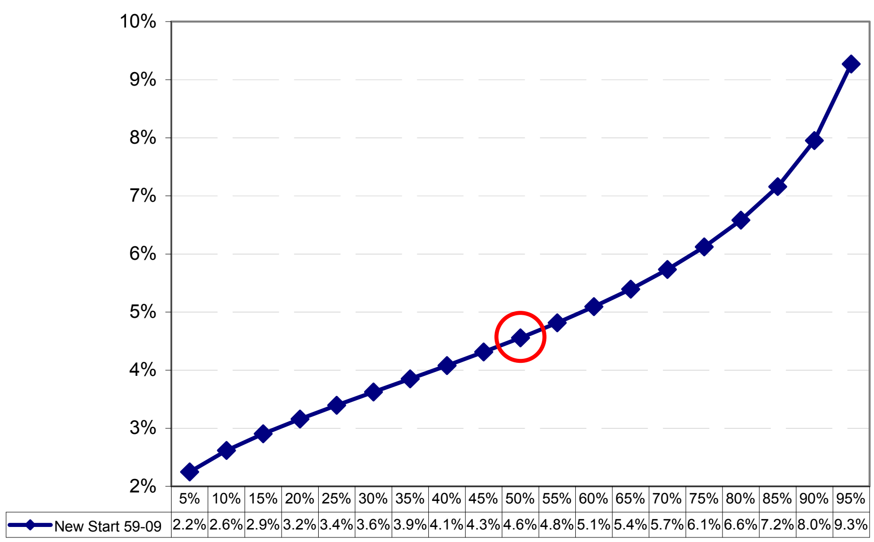
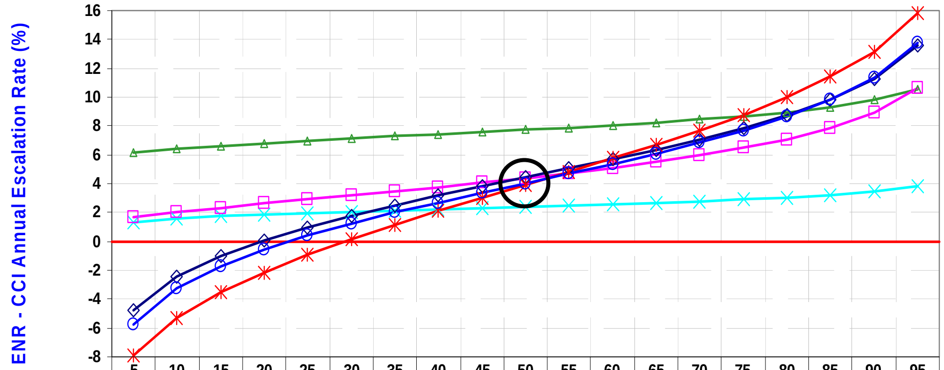


Figure 46: *– NASA New Start Index 1959-2009 probability of an overrun for a given percentage*

[108] Derived from data from Federal Reserve Bank Money Growth and Inflation in the United States April 2001



	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
1968-1983	6.1	6.4	6.6	6.8	7.0	7.1	7.3	7.4	7.6	7.7	7.9	8.1	8.3	8.5	8.7	9.0	9.3	9.8	10.6
1984-2003	1.3	1.6	1.7	1.9	2.0	2.1	2.2	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0	3.2	3.4	3.8
1940-2006	1.6	2.0	2.3	2.6	2.9	3.2	3.5	3.8	4.1	4.4	4.7	5.1	5.5	5.9	6.5	7.1	7.9	8.9	10.7
1915-2006	-4.8	-2.4	-1.0	0.1	1.0	1.8	2.5	3.2	3.8	4.4	5.0	5.7	6.3	7.1	7.8	8.7	9.8	11.3	13.6
1904-2006 Normal	-7.9	-5.3	-3.6	-2.1	-0.9	0.1	1.1	2.1	3.0	3.9	4.8	5.8	6.7	7.7	8.8	10.0	11.4	13.2	15.8
1904-2006 Logistic	-5.7	-3.2	-1.7	-0.6	0.4	1.2	2.0	2.7	3.4	4.0	4.7	5.4	6.1	6.9	7.7	8.6	9.8	11.3	13.8

Probability of NOT Exceeding (%)

Figure 47: *- Construction Cost Escalation Probabilities*

Figure 48 contains the @ Risk Best Fit Distributions for the ENR Construction Cost Index and Building Cost Index. These equations were used to produce the graphical lines in the table above.

Year	CCI	BCI
1915-2006	=RiskLogistic(0.04421, 0.031153)	=RiskLogistic(0.0371, 0.030702)
1940-2006	=RiskGamma(2.0559, 0.020279, RiskShift(0.0086651))	=RiskInvgauss(0.055277, 0.153698, RiskShift(-0.010448))
1968-1983	=RiskExtvalue(0.073327, 0.010914)	=RiskLogistic(0.075144, 0.016628)
1984-2003	=RiskLoglogistic(-0.028251, 0.052313, 12.387)	=RiskLognorm(0.034878, 0.013847, RiskShift(-0.012949))
1904-2006 Normal	=RiskNormal(0.039235, 0.07215)	No Data
1904-2006 Logistic	=RiskLogistic(0.040401, 0.033168)	No Data

Figure 48: *– @ Risk Best Fit Distributions*

Scope Changes

NASA's confidence level analysis methodology assumes that current baseline scope is the correct scope up through the end of construction and into the sustainment period. This potentially invalid assumption could be a very costly oversight. Scope changes during the design process often result in critical path schedule delays and retarded procurement activities. In addition, change orders nearly always equate to cost growth.

Potential Items for Scope Expansion

Most projects take an optimistic view of the all of the elements required for project success, and omit items that are not 100% certain to be required, but are highly likely to be needed. For example, the Constellation program is not currently carrying any costs for the Orbiter Processing Facility. The assumption has been that it will not be used. Chances are favorable that this thinking may be reversed. This is but one of a number of other items that could become requirements in the future. Following is a partial list of *potential requirements*.

- **OPF:** *The Orbiter Processing Facility may be needed for upper stage checkout and storage of Ares I, or Ares V.*
- **ENGINE SHOP:** At KSC f*or engine issues*

- **CRAWLERWAY:** *May not be able to support the weight of the Constellation Aries V Launch Vehicle (CALV)*
- **TRANSPORTER:** *May not be able to support the weight of the CALV*
- **CALV:** *The current plan is to convert the Shuttle Mobile Launcher Platform (MLP) to CALV usage. Weight constraints may require new platform.*
- **NEW CLEAN ROOM:** For CALV v*ertical load of hypergols & faring installation*
- **JJ RAILROAD BRIDGE:** *If the JJ RR Bridge were to fail prior to scheduled replacement, the entire program will stop.*

Requirement Changes

We have already added many "new requirements" to our baseline. However, the following items had been anticipated and were included with initial estimates - but were withdrawn when we were informed those estimates were "too high." Some examples follow:

- **VAB:** *Fabricate and install new platforms in lieu of refurbishing existing platforms.*
- **VAB:** *Perform life safety and fire suppression modifications.*
- **MLP & PAD:** *Plumb for cold helium.*
- **LCC:** *Add more data review rooms in the Launch Control Center.*

Change Orders Cost More

Change orders cost more than competitive bid work. Due to schedule constraints, Constellation Project changes (some of which are substantial) are being planned as change orders. Historical data derived from evaluating 2,752 change orders determined that (on average) the negotiated cost of change orders was 29.7% higher than government estimates with a 5.2% margin of error. Inversely, competitively bid projects (over 1 million dollars in value) are (on average) 2.2% lower than government estimates rendering the net change order penalty (29.7% + 2.2%) = 31.9%.

- On average, a change order submitted by a contractor is 76.1% higher than the government estimate.
- On average, the negotiated price above the government estimate was 29.73%.
- On average, a competitively bid (over a million dollars) project is 2.2% below the government estimate.

Of course, averages only tell part of the story. The box plot below shows the probable change order penalty for changes over a million dollars. *(The chart includes the 2.2% delta.)*

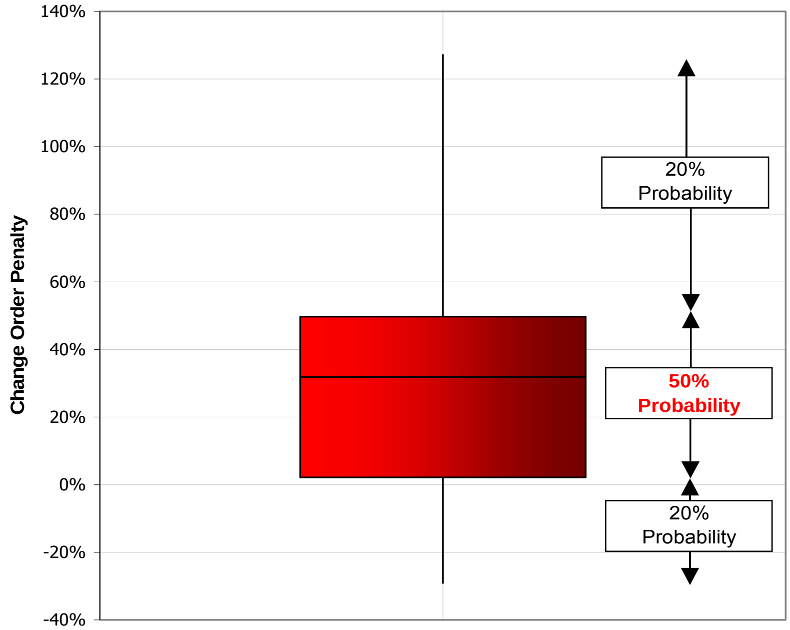


Figure 49: *- Summary of Total KSC Historical Change Order Penalty*

Design Errors

Design errors are a common occurrence and must be considered the rule rather than the exception. We can continue to expect impacts to be substantial.

Recent Example:

The United Space Alliance (USA) design team has been working on a VAB door refurbishment project that required an access platform. The weight was calculated using STAAD software to be 145 tons. The platform was then built and hooked to the VAB 175 ton crane. However, the crane would not lift the platform. Weighing equipment was then brought in and the measured weight turned out to be 205 tons. This was a 41.1% delta. The project stopped while cause was determined. The net result was a 2 month delay and a $500K to $1M cost increase. The ultimate potential impacts could have been even higher.

Security Reverberations

Recent security regulation changes require any one holding a KSC access badge for a period of over 90 days for any reason to undergo a full background investigation. Many construction workers and delivery drivers have marginal records. Complicating the problem is the fact that many are foreign born and/or are illegal immigrants. The following statistics are revealing:

- ~25% of all construction workers are illegal
  Source WSJ 12-19-2006
- 55% of all concrete workers are foreign born Hispanics
  Source WSJ 9-18-2006
- 22% of all painters are illegal
  Source WSJ or ENR 2006
- A 10% increase in worker supply = a 3% decline in local wages. A 50% increase in worker supply = a 15% decline in local wages.
  Source Harvard Immigration Economist George Boras 2006

Despite the prevailing policy that illegal immigrants are not to be allowed on the Center, a recent KSC construction project was raided twice by INS. Time and effort to excluding nonqualified workers could extend schedules and increase costs.

Catastrophic Events

Terrorist Attack Reverberations

A major terrorist attack anywhere in the US has the potential to severely affect cost and schedule performance on all work performed at KSC.

The September 11, 2001 terrorist attack resulted in a substantial cost and schedule impact to the LC 37 development project. The entire project was shut down for several days due to security concerns. Then it was open to essential personnel only. We were required to develop and submit a plan to resume work that had to be approved by the base commander. Following that submission and approval process, it took several more days to put the plan into action.

At that time, all workers met outside the base and were bused onto the Center and taken to their worksite in the morning - then bused off in the evening. The workers were paid for their travel time. Many additional security guards were hired to escort delivery vehicles in and out. The total direct cost in 2001-2002 $ was ~3 million, excluding the widespread negative productivity impacts. Because workers were paid for 8 hours but actually worked fewer than that (~7 hours) a ~13% quantifiable loss in productivity was experienced. Some actual losses were higher due to unique and subtle nuances to the general plan.

After this, the Anthrax biohazard events occurred later in 2001. This had less of an effect on KSC projects, but it did have repercussions to other NASA sites where there were several Anthrax scares.

Ricin was the next biohazard challenge with terrorist events starting during 2003. This contaminant was sent to the White House, a South Carolina postal facility, and a US Senate mail room in 2004. Resulting filter down effects were felt here at the Center in terms of time delays which always attend elevated threat levels.

Major Accidents

> **"Human space flight is inherently dangerous."**
>
> *Mike Griffin, NASA Administrator*

The Space Shuttle has experienced two major incidents to date. The Apollo Program had one. Every major incident results in massive cost and schedule impacts. Even with the "no risk is acceptable" protocol endorsed by NASA in today's world, there is at least some chance of a major incident that will result in loss of vehicle, loss of mission, or loss of life.

CHALLENGER Incident

The STS 51 **Space Shuttle Challenger** disaster occurred on January 28, 1986 when Challenger broke apart 73 seconds into its flight. All seven crew members lost their lives. The Shuttle disintegrated over the Atlantic Ocean, off the coast of Florida, at 11:39 a.m. EST. Disintegration began 73 seconds into its flight when an O-ring seal in its right solid rocket booster (SRB) failed at liftoff. The O-ring failure caused a breach in the SRB joint it was meant to seal, allowing a flare of pressurized hot gas from within the solid rocket motor to impinge upon the adjacent SRB attachment hardware and external fuel tank. Roughly 73 seconds into launch, the SRB joint breach flare led to the severing of the right-hand SRB's aft attachment. This caused the structural failure of the external tank, dumping the liquid hydrogen fuel load all at once and causing a massive explosion as this fuel was immediately ignited by various flame sources surrounding the hardware. Maverick aerodynamic forces promptly broke up the orbiter following the loss of attitude control.

The Challenger disaster resulted in a 32-month hiatus in the Shuttle Program. The Rogers Commission (appointed by President Ronald Reagan to investigate) found that NASA's organizational culture and decision-making processes had been a key contributing factor to the accident. NASA managers had known that contractor Morton Thiokol's design of the SRBs contained a potentially catastrophic flaw in the O-rings since 1977, but they failed to address it properly. They also disregarded warnings from engineers about the dangers of launching on such a cold day and had failed to adequately report these technical concerns to their superiors. [109].

The budgetary effects of the accident[110] can be segregated into two categories:

- CATEGORY 1: "Reconstitution" costs, including the expense of investigation, any shuttle system modifications suggested by investigation, and replacement of equipment lost in the accident.
- CATEGORY 2: Those costs and savings that result from the lower flight rate forced on NASA by the loss of the Challenger.

Following are NASA's preliminary estimates: Replacing the capability lost in the explosion (exclusive of the orbiter) through modifying the system will require $240.5 million in 1986, $245.5 million in 1987, and related spending of a combined $205 million for future years. Of this amount, $350 million will be spent to modify the shuttle-$200 million in 1986 and $150 million in 1987.

According to the Congressional Budget Office (CBO's) preliminary analysis, the NASA cost estimates above may be low. Net savings in NASA operations may offset these new costs by $98 million in 1986 and $130 million in 1987. Of this amount, $45 million in 1986 and $124 million in 1987 would be saved by not operating the shuttle. Additional net savings--$53 million in 1986 and $6 million in 1987--are estimated for research and development and for space tracking and data communications activities.

	Fiscal Years 1986/1987	Balance to Completion	Total
Anomaly (Problem) Resolution and Corrective Action	605	193	798
Actions in Response to the Rogers Commission	170	410	580
Total	775	603	1,378

***Figure 50** - Challenger Accident Incurred Costs (In millions of dollars of budget authority)*[111]

A 1992 White House advisory committee concluded that recovering from the Challenger disaster cost the country $12 billion, which included the cost of building the replacement Orbiter named Endeavour[112].

[109] Vice President's Space Policy Advisory Board, *A Post Cold War Assessment of U.S. Space Policy*, December 1992
[110] CBO Budget Effects of the Challenger Accident Staff Working Paper March 1986
[111] CBO The 1988 Budget and the Future of the NASA Program Staff Working Paper March 1987
[112] Vice President's Space Policy Advisory Board, *A Post Cold War Assessment of U.S. Space Policy*, December 1992

The CBO Analysis excluded consideration of longer-term budgetary issues, such as the procurement of a replacement orbiter. The cost of replacing the orbiter and the existing orbiter spare parts that would be consumed by a new orbiter is estimated by NASA to be $2.4 billion over four years. $2.6 billion[113] was appropriated for a new orbiter in 86-87.

Out-year operational costs of shuttle are likely to increase each year as the accident promotes more conservative and costly operational procedures. An expendable launch vehicle program to fill the deficiency left by the loss of an orbiter could be at least as expensive--for example, the Air Force recently purchased 10 rockets for $2 billion, roughly the cost of one shuttle. The new orbiter, *Endeavour*, was produced for $1.8 billion[114] [115]dollars, 14% under its initial 2.1 billion estimate, and made its first flight in May 1992.

COLUMBIA Incident

The Space Shuttle Columbia: At approximately 9:00 a.m. EST on February 1, 2003, STS 107 broke apart during it's re-entry into the atmosphere while traveling at more than 12,500 miles per hour at an altitude of 207,000 feet. Immediately following the accident, NASA activated a contingency plan to preserve all information related to this flight by establishing a Mishap Investigation Team to coordinate the identification, retrieval, and storage of debris and any human remains. NASA also established the Columbia Accident Investigation Board (CAIB). NASA developed budget estimates for implementing the CAIB recommendations required to return the space shuttle to flight - but not for all of the CAIB recommendations. The NASA Budget Office provided documentary support for portions of the return to flight estimate but the OMB found it to be insufficient. The agency's projected cost for returning the shuttle to flight was slightly over $2.2 billion. This estimate remained uncertain until the completion of the first shuttle missions to the International Space Station in fiscal year 2005.[116] All Space shuttle Missions were halted until July 26, 2005 in order for the accident investigation to proceed and for the resulting recommendations to be implemented.

Activity	Fiscal Year				Total
	2003	2004	2005	2006-2009	
Orbiter reinforced carbon-carbon inspections	$ 2	$ 38	$ 7		
On-orbit thermal protection system inspection and extravehicular activity tile repair	20	68	130		
Orbiter workforce	-	5	37		
Orbiter thermal protection system hardening	-	28	34		
Orbiter certification/verification	-	47	26		
Orbiter other	-	15	16		
External tank items (camera, bipod ramp,	11	114	94		
Solid rocket booster items (bold catcher, camera, etc.)	1	8	26		
Ground camera ascent imagery upgrade	8	40	58		
Kennedy Space Center ground operations workforce	-	32	36		
Other (systems integration, hardware processing and operations systems verification, and space shuttle main engine	-	67	177		
Stafford-Covey team	-	3	1		
Total	$ 42	$ 465	$ 643	$ 1,067	$2,217

Figure 51: *- November 2004 Return To Flight Cost Estimate – Real year dollars in millions* [117]

[113] CBO The 1988 Budget and the Future of the NASA Program Staff Working Paper March 1987
[114] GAO NASA Program Costs 1992
[115] Another source lists Endeavour cost as $1.897 billion, $950 million for payload bay platform, and $947 million for orbiter
[116] GAO Space Shuttle Costs for Hubble Servicing Mission and Implementation of Safety Recommendations November 2004
[117] GAO Space Shuttle Costs for Hubble Servicing Mission and Implementation of Safety Recommendations November 2004

Review Status	Fiscal Year 2003	2004	2005	2006	2007	2008	2009	Total	Percent of total
Control board review complete; directive issued	$ 31	$ 319	$ 117	$ 53	$ 47	$ 49	$ 39	$ 616	29
Been to control board; directive not yet issued	11	146	217	117	125	134	109	750	39
In review process	-		309	162	84	79	70	634	32
Total Return to Flight activities	$ 42	$ 465	$ 643	$ 331	$ 257	$ 261	$ 218	$ 2,217	100

Figure 52: *- November 2004 Return To Flight Cost Estimate – Real year dollars in millions* [118]

NASA's current aggregate total for Columbia's Return-To-Flight now stands at over $2.2 billion[119]

APOLLO Incident

On January 27, 1967, the three-man crew of the first Apollo mission died when a fire erupted in their Apollo command module during a pre-launch test. The three astronauts were Virgil "Gus" Grissom, Edward White, and Roger Chaffee. A NASA investigation determined that electrical arcing in the modules wiring caused the fire in the oxygen rich environment. Modifications were made to the Apollo design and test procedures before Apollo flights resumed 21 months later. Cost and schedule impacts in total are not known.

USSR (Multiple Incidents)

At least four Soviet cosmonauts have perished during spaceflights.

Cosmonaut Vladimir Komarov died during the first Soyuz flight on April 24, 1969. The spacecraft's parachute tangled during descent and Soyuz 1 struck the ground with great force, killing Colonel Komarov. Soviet human spaceflights were suspended for 18 months while the Soviets investigated and remedied the problem.

Three cosmonauts died aboard Soyuz 11 on June 29, 1971 when an improperly sealed valve allowed the spacecraft's atmosphere to vent into space. The cosmonauts - Georgiy Dobrovolskiy, Vladislav Volkov, and Viktor Patsayev - were not wearing spacesuits and were asphyxiated. There were no Soviet human spaceflights for 27 months while modifications were made to the spacecraft.

There have been serious problems during re-entry of Soyuz capsules. In April 2008, the Soyuz capsule missed its landing area for the third time since 2003 due to equipment malfunctions. Investigators suspect that the ballistic re-entry was caused by an electrical short in the cable that connects the crew capsule's control panel with the Soyuz descent hardware.

Information on the replacement cost and loss of operations costs for these combined USSR incidents is not available.

Large Scale Catastrophic Events

The above items are all somewhat "likely" to occur. Events such as the foregoing relate directly to mission fulfillment activities and mission execution comes with little to no margin for error in pursuit of success. Failures, oversights, and emergencies in technical affairs won't generally terminate program continuance. It is safe to predict that the work will go forward notwithstanding costly incidents and unwanted consequences from time to time.

[118] GAO Space Shuttle Costs for Hubble Servicing Mission and Implementation of Safety Recommendations November 2004
[119] NASA's Implementation Plan for Space Shuttle Return to Flight and Beyond, June 2006

There are, however other "non-space" events that are far less likely to occur but which would certainly have more far reaching results. These types of events would be of such a magnitude that program(s) could be shelved completely and/or be so severely affected that recovery will never take place. These kinds of major catastrophe events must not be excluded from analysis. They include such things as:

- World War Three
- A pandemic (worldwide disease event)
- A nuclear detonation on American soil
- The collapse of the US economy or a major restructuring of government's infrastructure
- A catastrophic event on the Shuttle Program, the Constellation Crew Launch Vehicle (CLV) or Cargo Launch Vehicle (CALV) during pre-launch processing, launch, mission, or landing
- An administrative decision preventing or delaying continuance for any reason(s)

Examples from History

The Ripple Effect - A Case Study

Often, changes to a prevailing design or existing contract have an unintended ripple effect. Launch Complex 37 was designed using the best available information - but it was not good enough! Due to new requirements, the Mobile Service Tower (MST) needed additions to various systems. The aggregate effect of these additions/changes was that the steel support structure became overloaded. The structure was summarily reinforced (at great expense) to support the extra loads. The total weight increase to the structure was 24.7%. It was then determined that the concrete bridge over the flame trench (installed 2 years previously) was not strong enough to support the now 9.6 million pound MST. The flame trench bridge repairs became a huge effort that diverted valuable project resources and cost (~$6 million dollars in 2001 $) and pushed the schedule out ~10 months (excluding the additional evaluation and decision time preceding the time to work the repairs). Effectively demonstrated here in the case of LC 37 was the cost-schedule ripple effect with its long tail of consequences.

***Figure 53:**- Ripple effect repair work being accomplished at Launch Complex 37*

In summary, all of the required changes to the MST were estimated and approved. Premium prices were paid for each change and the schedule deviations were absorbed. Then the MST overweight impacts occurred and the cost and schedule consequences were again absorbed. Then, numerous contractors who were involved in the changes summarily submitted additional claims, which were negotiated down and subsequently paid. These claims included extended overheads, stacking of trades, etc. So the *summom bonum* cost for a projected one million dollar change to the MST ultimately cost six times that amount when all related costs and impacts were calculated.

POINT: If the "final" total cost for the CR described in the preceding example would have been known and budgeted for by those of us in *Cost Estimating* then submitted prior to CR approval, we would have been accused of padding the numbers. If our figures would somehow have been accepted, the cost benefit analysis may have prevented the CRs from being approved in the first place. The point being made here is that changes often cost MUCH more than initially envisioned by those responsible for completing the work. Often, at the beginning of a modification effort, a grossly inadequate cost ceiling is levied by some well meaning manager up the line. But well meaning or not, such a declaration doesn't make the final cost less real. It is what it is. CONCLUSION - NASA can do better at calculating and accepting more robust and realistic estimates and have the courage to hold to those estimates in the public forum. Not only CAN we do this - it is our fiscal responsibility to do so!

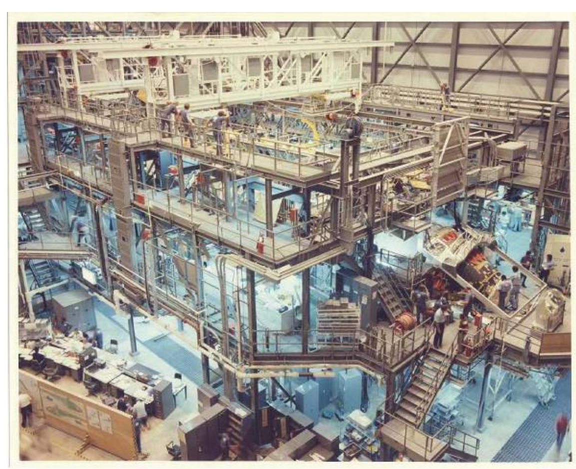
The Orbiter Processing Facility

The Space Shuttle's Orbiter Processing Facility is another prime example of looking at the world through the rose colored glasses of early estimating. Original Shuttle concepts envisioned that maintenance between launch events would be like those associated with the servicing of a jet bomber - requiring a minimum number of qualified technicians in a wide open hanger, scooting their ladders up to the big bird, performing the needed servicing on a weekly turn-around schedule, and then towing it out the hanger door and on to the launch pad ready for the next mission.

Due to the extreme complexity of the shuttle and the fundamental differences between space flight and atmosphere-bound flight, there ended up to be almost no similarities between the servicing needs originally conceived and the actual maintenance tasks that surround a Shuttle's return to orbit. Any similarities between that early concept and what really evolved have long since disappeared. The current Orbiter Processing Facility is a honeycomb of steel platforms that surround the Shuttle and house sophisticated testing and refurbishing equipment in ready proximity to the world's most complicated space cargo vehicle. The pictures below tell the story more effectively than words. The equation for this story would look something like this:

What was estimated [in 1974] ≠ what was needed and built [today]

Shuttle Operations Concept in 1974
This is what was estimated.



The Orbiter Processing Facility Today
This is what was needed & built.

Figure 54: – The support scaffolding and service area that was actually required to maintain the Space Shuttle provides an excellent example of the inaccuracies inherent in "early" estimating.

The point here is that it will probably never be possible in a high tech development engineering environment for a team of experts to "foresee" the end result at the beginning of the development journey nor predict the myriad of in-work alterations that will be needed to bring a program through to completion. The following famous quote will have particular meaning to the NASA community:

"I think as I write . . . as I think as I write . . . as I think as I write."

Pearl Buck

NASA people too must always *think as they work* in a series of repeating cycles while they move toward successful fulfillment of early but often inadequately defined concepts. The end result may be but a distant cousin to the original notion - just as the end cost and schedule may bear little resemblance to the earlier optimism. The challenging duty of the cost estimator is to correctly project the delta before it is known - a difficult task to be sure - but one that can be accomplished more reliably through the use of better tools.

More NASA Troubles

Despite many NASA successes, such as the Pathfinder and Exploration Rovers on Mars, the loss of life, unsuccessful missions, and unforeseen cost overruns have recently increased congressional concerns over the benefits of such exploration. NASA has had difficulty bringing a number of projects to completion, including several efforts to build a second generation of reusable human spaceflight vehicle to replace the space shuttle. NASA has attempted several expensive endeavors such as the National Aero-Space Plane, the X-33 and X-34, and the Space Launch Initiative, among others. None have completed their objective of fielding a new reusable space vehicle. The GAO estimated[120] in 2006 that these unsuccessful development efforts have cost approximately $4.8 billion since the 1980s.

NASA has tried unsuccessfully to develop a number of vehicles to replace the shuttle over the past three decades. In the 1980s NASA initiated the National Aero-Space Plane (NASP) to build and test a manned experimental flight vehicle for demonstrating single-stage-to orbit space launch and sustained hypersonic cruise capability. NASA canceled the program as it was experiencing cost overruns, schedule delays, and technology problems. GAO reported that from 1986 to 1993 NASA spent $398 million for the NASP program.

In the 1990s, NASA began the X-33 program to develop single-stage-to orbit technology and the X-34 to demonstrate reusable two-stage-to - orbit technologies. According to a 2006 Congressional Research Service report, NASA terminated the X-33 and X-34 in March 2001—after spending over $1.4 billion—because the cost to complete them was too high relative to the benefits. In 1999, GAO reported that technical problems and unrealistic cost estimates on the X-33 project alone led to cost overruns of $75 million and over a year's delay.

In 2004, after the announcement of the *Vision for Space Exploration*, NASA canceled the Space Launch Initiative (SLI) program, which was to provide both launch capabilities and an emergency crew return from the ISS. NASA's Inspector General reported that NASA did not verify and validate basic requirements for its second generation space transportation, while GAO reported that key management controls could not be implemented until such requirements were defined. GAO estimates that from 2001 to 2005 NASA provided the SLI program with about $3 billion in funding.

[120] GAO-06-817R Exploration Cost and Schedule, 2006

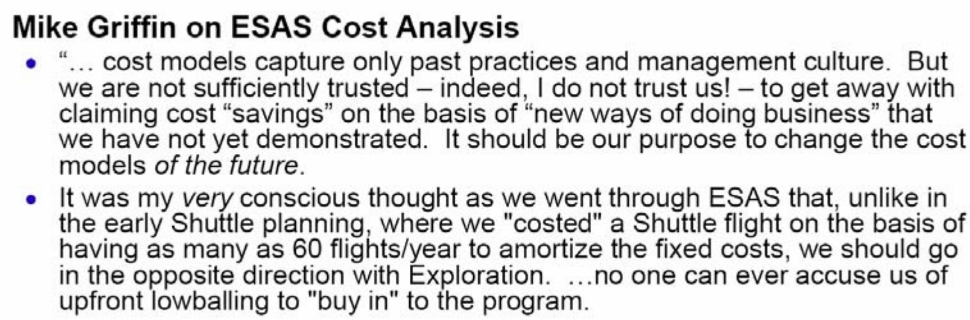


Figure 55: *– Mike Griffin on ESAS Cost Analysis*

Constellation Program – Ares I and Ares V

This brings us to the work at hand. Any meaningful discussion of the Constellation Program's joint probable cost and schedule must candidly acknowledge our track record through the historical perspective as discussed on the previous pages. Conclusions, determinations, and insights on how to go forward with improved approaches that will produce more reliable cost and schedule projections is the object and purpose of this paper.

The content we have selected is meant to illustrate and substantiate a long pattern of underestimating both cost and schedule, not only by NASA, but by DOD and other industries. Early confidence level analysis that does not even consider the possibility of triple digit cost and schedule growth is willfully ignoring historical precedent and the full cannon of possible risk factors that show up as game-changing players on the field of cost estimating.

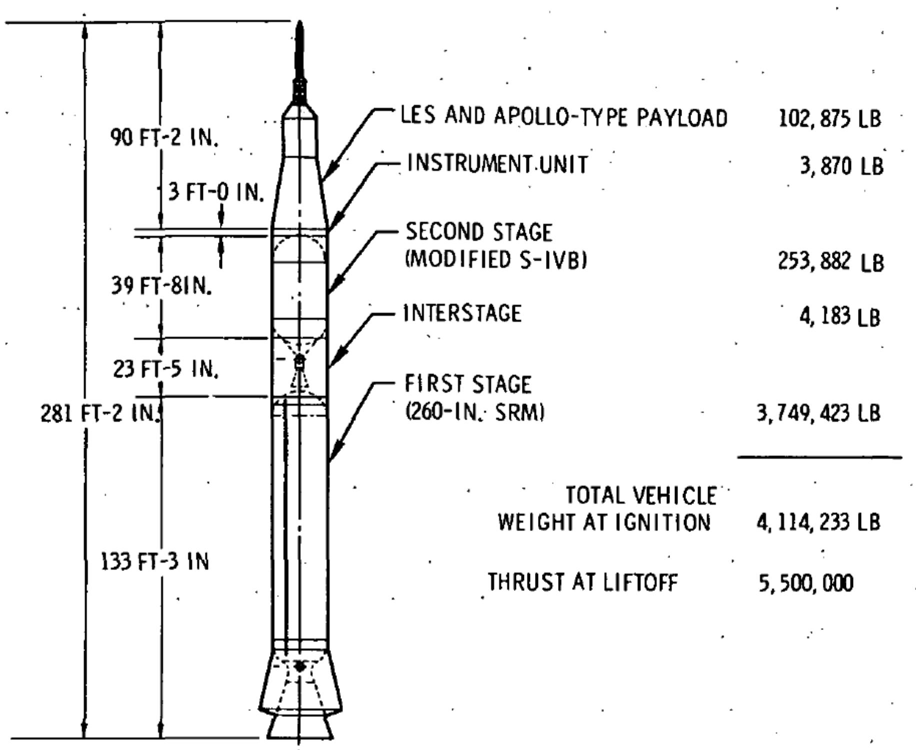


Figure 56: *– The 1967 Concept of Ares I Vehicle with 260" SRB*[121] *(Shuttle & Ares use 156" SRB's)*

[121] Launch Facilities and Operations for Large Solid Motors Study, Final Report Vol II DAC-58O79 12-28-67

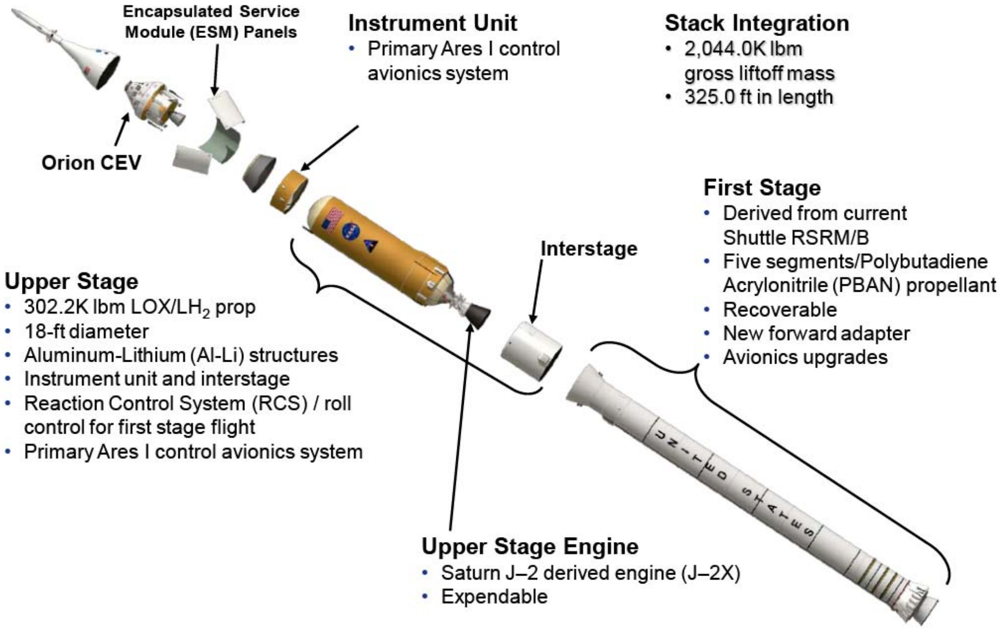


***Figure 57:** – Ares 1 Rocket DAC 2 TR6 Overall Length 320.81'*

In the authors opinion, many of the components of the Ares 1 launch vehicle in their assembled and stacked configuration are either new or require major redesign and development. The "new development" label is fully apropos when discussing most of the hardware associated with Constellation.

Constellation ought to be benefiting from the best and most accurate cost and schedule projections ever submitted on a NASA program road map. It is our opinion that unwelcome fiscal news provided early in the process to the Congressional Budget Office is preferable to discovering the very same information from an after-the-fact historical perspective. It will save us time, money, and effort in the long run if given realistic numbers from the start. Eventually acknowledging the same programmatic conclusions when Constellation is in the history books isn't value added. Cost estimating should always be more about credibility and reliability up front - than about patronizing expectations along the way.

In September 2004, the Congressional Budget Office analysis of NASA's New Vision for Space Exploration[122] stated.

"Costs over the 2005-2009 budget period for the lunar return mission would total $6.4 billion, NASA projects, all of which would be used to develop the CEV. Through 2020, total funding for human exploration would be about $66 billion, (2005 $) in NASA's estimation, which includes $2.2 billion between 2018 and 2020 for follow-on missions after the first human lunar return landing. (The exact content of those missions is undetermined.) With the potential exception of those additional funds, NASA's budget projection through 2020 does not include explicit development and procurement of other systems that would be necessary for establishing a lunar outpost or for carrying out future human missions to Mars."

"Initial development of the CEV, including test flights, is expected to last from 2005 through 2014. The first CEV test--of a partially capable prototype--is planned for 2008; the first

[122] A Budgetary Analysis of NASA's New Vision for Space Exploration, CBO, Sept 2004

unmanned test of a fully capable unit is scheduled for 2011, and the first human flight, for 2014. NASA's plans for both the test flights and the lunar mission are based on using an EELV to boost the CEV into low-Earth orbit.

NASA's projected funding covers the procurement of four operational vehicles for about $730 million each. Including research and development, testing, and operations, costs for the CEV through 2020 would total roughly $24.7 billion."

This pre-phase A data is provided as a base reference, since the program has evolved from the initial concept.

NASA's Projected Budget for the First Human Return to the Moon, 2005 Through 2020

(Billions of 2005 dollars)	**2005-2009**	**2010-2020**	**Total**
Crew Exploration Vehicle	6.4	18.3	24.7
Lunar Lander	0	13.4	13.4
Heavy-Lift Launch Vehicle	0	17.9	17.9
Operations	0	7.9	7.9
Total	**6.4**	**57.5**	**63.8**

Figure 58: *– NASA Budget for First Human Return to the Moon 2005 Through 2020*[123]

CBO's 2004 analysis also presumed costs for the new exploration mission grew might grow by 45%, based on analysis of 72 prior NASA programs. If this occurs on Constellation (and there are no indicators to suggest that it won't) the CBO's analysis indicates that NASA's total funding needs through 2020 will require adding $32 billion[124] to NASA's proposed 63.8 billion budget - making the completion mark a $95.8 billion. However, historical data makes a strong case that more complex programs of longer durations (which Constellation is) experience the greatest rate of growth. The full range of growth in budgeted costs for the 72 programs the CBO used was -25 percent to 274 percent.

In reference to the Bush VSE Program: ". . . one of the biggest unfunded mandates that we have had in all of government history."

Former Senator John Glenn

An additional potential for cost overrun is the unresolved, uncovered asset base (both facilities and personnel) during the interim period between Space Shuttle standown - but prior to re-engagement of those assets under the Constellation Program. An example would be a "flight controller" who will certainly be needed again but not for a few years. Retaining qualified people and needed facilities during the "dead space" could become a very costly proposition.

In the 72-program set in the CBO analysis, average cost growth fell from 140 percent in the 1970s to about 20 percent in 2000. Happily, NASA's estimates appear to be improving, but the improvement is measured against smaller programs. The average cost of NASA's programs has declined from about $3.5 billion in the 1980s to about $500 million in the 1990s and apparent accuracy improvement may prove illusionary.

The Agency's past three decades showing ever lowering levels of cost growth may not be applicable to Constellation's new exploration initiative. Constellation projections should use former development efforts of similar size and magnitude if accurate forecasting results are hoped for.

123 CBO A Budgetary Analysis of NASA's New Vision for Space Exploration, 9-2004

124 $63.8 x 145% = $28.7 The CBO's figures apparently include some expected cost growth in other NASA's programs

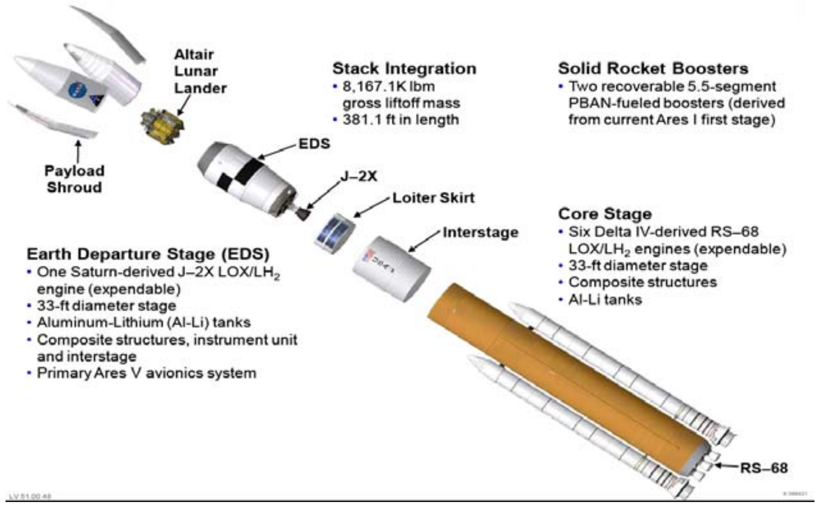


Figure 59: *– Ares V LV 51.00.48*

A 2006 GAO report[125], is cause for chagrin at NASA HQ. They emphasize the absence of cutting edge proficiency in the cost estimating world within the agency when contrasted with the world renowned scientific and technological respect enjoyed by NASA scientists and engineers. To wit:

"Although NASA is continuing to refine its exploration architecture cost estimates, the agency cannot at this time provide a firm estimate of what it will take to implement the architecture. The absence of firm cost estimates is mainly due to the fact that the program is in the early stages of its life cycle.

According to NASA cost-estimating guidance, early life cycle phase estimates are generally based upon parametric models, which use data from projects with similar attributes to predict cost because there are usually many unknowns and actual cost or performance data are not available. NASA preliminarily identified the resources needed to implement the architecture as outlined in the architecture study primarily through the use of such models. NASA conducted a cost risk analysis of its preliminary estimates through fiscal year 2011. On the basis of this analysis and through the addition of programmatic reserves (20 percent on all development and 10 percent on all production costs), NASA is 65 percent confident that the actual cost of the program will either meet or be less than its estimate of $31.2 billion through fiscal year 2011.

For the cost estimates beyond 2011, when most of the cost risk for implementing the architecture will be realized, NASA has not applied a confidence level distinction.

Since NASA released its preliminary estimates, the agency has continued to make architecture changes. For example, following the issuance of the architecture study, NASA conducted several analysis cycles during which various aspects of the architecture have evolved, such as the diameter of the CEV, the engine used to support the upper stage of the CLV, and the size of the Reusable Solid Rocket Booster on the CLV. While these changes and others are appropriate for this phase of the program, when concepts are still being developed, they leave the agency in the position of being unable to firmly identify program requirements and needed resources, which can also be expected at this phase of the program.

According to NASA officials, once they receive more detailed contractor inputs, the agency will be able to produce higher-fidelity estimates of program cost. NASA plans to commit to a firm cost estimate at the preliminary design review (PDR) in 2008, when the program's requirements, design, and schedule will all be baselined. NASA will be challenged to implement the architecture recommended within its projected budget."

[125] GAO-06-817R Exploration Cost and Schedule

Given this budgeting challenge, let's look at the Apollo Program. The 2005 NASA Exploration Systems Architecture Study (ESAS) - the official phase A study - states that the historical cost in current 2005 dollars for the Apollo Program through the first lunar landing (FY61–FY69) was approximately $165B. The $165B figure includes all civil service salaries and overheads along with all Government "service pool" costs. The ESAS architecture for Constellation has an estimated total cost of $124B through the first lunar landing (FY06–FY18) and takes into account anticipated productivity gains and the use of Shuttle derived hardware and evolved available technologies.

With all else being equal, the NASA/Air Force Cost Model (NAFCOM) would predict that most Apollo flight hardware developed 50 years later would cost 33 percent less to develop and 22 percent less to produce than in 1967. Some subsystems (such as avionics) have an opposing trend toward increasing the cost over time due to increased functional requirements. This ESAS assumption is based on annual productivity gains of ~ 2.1%.

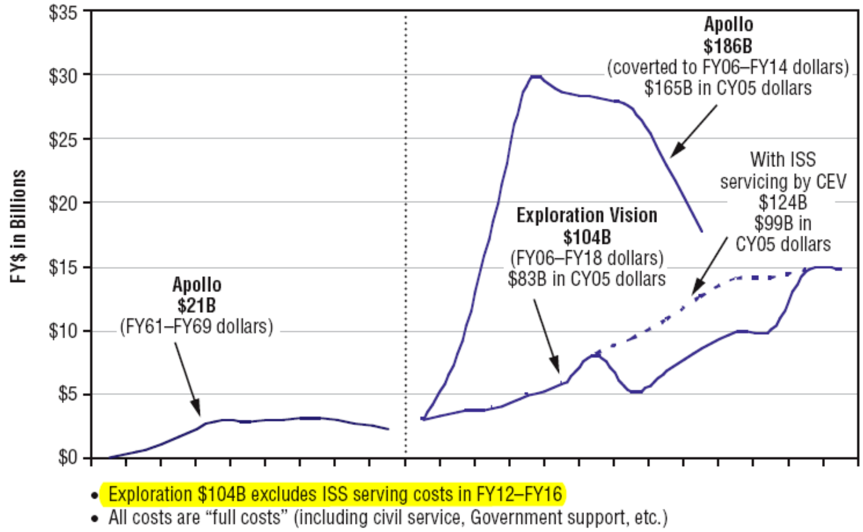


Figure 60: *– Constellation's Exploration Systems Architecture Study in comparison to Apollo costs*

These credit adjustments in the foregoing analysis may not prove valid because:

- *Constellation is developing two new rockets - not one.*
- *Use of Shuttle developed hardware is substantially less than anticipated in the ESAS study.*
- *Apollo placed two crew members on the moon for 3 days; whereas the Ares architecture places four crew members on the moon for 7 days (4.6 times more working days on the lunar surface per sortie mission).*
- *Ares architecture also calls for access to the entire lunar surface; whereas Apollo was confined to the equatorial regions.*
- *Ares architecture will be designed for anytime return from any lunar location, thus requiring more sophistication and enhanced delivered capability over Apollo.*
- *The Ares capsule has three times the volume of the Apollo Command Module.*
- *Astronauts are no longer expendable with a 0 incident standard in place. Initial Apollo & Shuttle flights were launched with many items (rumored to be in the hundreds or even thousands) that were not cleared for flight. These required a management waiver to "go for launch."*
- *NASA escalation rates used in NAFCOM may be too low given the historical data.*

- *Legacy costs may not be fully accounted for. An example would be the unfunded mandate to switch all systems to S.I. units. This has the potential for massive cost increases since thousands of systems, drawings, specifications, and operations manuals must be changed, proof read, and tested if applicable to achieve the upgrade/conversion.*

- *Overall technical sophistication has resulted in systems growing in complexity and redundancy since Apollo.*

- *Parts made from composite materials and lightweight alloys are generally more costly to design and manufacture in comparison to unalloyed metal parts.*

Conclusions

We have presented evidence that cost and schedule growth is pervasive and biased toward underestimation - and has been that way since at least the late 1800's. If we keep doing things the same way, we will keep getting the same results. Until we address and factor in all the causes of cost growth and schedule extension, (internal and external) the real outcomes we will inevitably continue to get, will dwarf not only our original estimates but also our follow-on estimates as well.

The authors have chosen to be guided by the following axiom: *'If unwelcome (even pessimistic) opinions are suppressed, while optimistic projections are welcomed and rewarded, an organization's ability to think critically and realistically will be undermined.'* The material chosen for this paper gives a reasonably accurate picture of the many variables involved in predicting the outcome of complex development projects. The truth is that *estimating* as a discipline, has produced a track record replete with inaccuracy - a fact that none of us are satisfied with. We also believe there are many who feel as we do - that *better estimating* is achievable, notwithstanding the resistance that may arise from those who feel we must live and die by optimistic budgets - ignoring mind the facts of history in the archives of the past.

The cost-schedule paradox is a formidable opponent. Clashing forces create a volatile fulcrum (cost affects schedule - schedule affects cost). If funding for a given year is exceeded, that portion of the work that was supposed to be accomplished - can't be done. Inversely, if the schedule slips (for any reason) escalation and fixed costs will continue to accrue, producing a steady rise in the price tag as it marches onward in time. Like interest, development costs never sleep - because time never stops.

After a review of over 500 contracts, the Office of the Under Secretary of Defense for Acquisition has observed that once a contract is 15 percent complete, if it is over budget, it is highly unlikely to realign itself with original cost/schedule projections, and the final percent overrun will be greater than the percent overrun to date. Despite this fundamentally important and subsequently proven[126] [127]observation, contractor and governmental personnel often claim that THEIR programs will be different. To our dismay, those of us who know better have not yet found the persuasion or the influence to recalibrate the thinking of those who wield power in the fiscal circles of influence; nor have we been able to infuse the courage within them to tell it like it is and then hold their ground. The quest for this essential modis operandi is still out there somewhere.

To provide trustworthy joint cost-schedule confidence level assessments, the estimator must 1) research and obtain the most reliable input from subject matter experts in the system or systems in question, 2) incorporate valid mathematical risk analysis, 3) infuse perceptive and candid scheduling projections, and 4) make probability estimates that border on the prophetic. These combined forms of expertise are

[126] RAND Predictability of Costs, Time and Success of Development 1959

[126] Christensen, Davis S. and Kirk Payne. 1992. Cost Performance Index Stability – Fact or Fiction? *Journal of Parametrics* 10, (April), pp.27-40

[127] Heise, Capt Scott R. 1991. A Review of Cost Performance Index Stability. MS Thesis, AFIT/GMS/LSY/91S-12. School of Systems and Logistics, Air Force Institute of Technology, Wright-Patterson AFB, Ohio

rarely found synergistically assembled. That is, those who understand a system best in the aggregate are not consistently the best at expressing their expertise.

This paper has stated that a deeply embedded leadership "culture" contributes to cost growth and schedule extension in the form of *natural optimism* by senior management. This occurs not only during the genesis stages of program development but often throughout all program activity stages. Most senior managers are "can do" type people who do not respect adequately the peripheral possibilities for productivity hiccups or admit to their organization achieving less than optimum performance. To fail is a genuine four letter word to them and rather than aggressively consider ALL the potential skeletons in the development closet, they opt to only "deal with those things" when and if the unwelcome events arise. They regard themselves as optimists who must convey that message to their "people" if they are to successfully give their organization the chance to succeed. Few leaders walk the walk of a realist.

The paradigm of the joint confidence estimator is this: *optimism* does have its place, which place is for those who lead to approach the project with confidence that it CAN be achieved with *caution*. But it does NOT mean that program objectives are a given, nor can they be realized without due consideration for ALL the potential pitfalls that can come to pass during project fulfillment. To ignore these "potentials" isn't optimism - it's naiveté. Whenever optimism blinds managers to those things that may be, they become *reactive* from that moment forward. They lose their *proactive* privileges. Unfortunately, most charismatic standard bearers have never learned this important leadership truth.

"Ninety percent of the time things will turn out worse than you expect. The other 10 percent of the time you had no right to expect"[128] as much as you got.

Augustine's Laws, 6th Edition - Norman R. Augustine


"We did report problems, but it was certainly in my best interests to be very optimistic about what we could do."
ED NOWINSKI
Boeing's point man on the satellite program and ex-C.I.A. employee

Boeing was "unprepared to exercise judgment in certain areas because it wasn't within their own experience."
DONALD M. KERR
former satellite agency director

"I shouldn't have allowed it to go forward."
KEITH R. HALL
agency director who chose Boeing to build the satellites

"The train wreck was predetermined on Day 1."
A. THOMAS YOUNG
ex-aerospace executive who led a panel examining the project

"We have lost double-digit billions on satellite programs that weren't effectively managed by the government."
CHRISTOPHER S. BOND
Republican senator from Missouri

Figure 61: *– Quotes from NYT Article on NRO Satellite program Future Imagery Architecture* [129]

When there is a lot of money on the table, no wants to say they can't do it. The contractor's ethic is: *win the program at any cost and sort it out later. Correct the government's sins and my sins with overruns.*

Exceptional parallels can be drawn between personal portfolio management in the news of late and project risk management which we have been discussing. A Wall Street Journal article[130] really puts the subject into perspective. The article succinctly points out how the best strategies, developed by the best and brightest minds, often find their way into the trash can, victims of the "human condition."

Examples from the article are:

- *Harry Markowitz, recipient of a Nobel Prize for his mathematical treatment of relationship between risk vs return in portfolio management, ignored his own prized work in managing his personal investments, preferring to follow an "emotional" strategy.*
- *John Bogle, investment guru and retired founder of Vanguard funds, holds to the belief that investors should re-balance their portfolios on a regular basis. But Bogle admitted that he hasn't altered the allocation in his personal holdings since March 2000.*

[128] Augustine's Laws, 6th Edition Norman R. Augustine
[129] FAILURE TO LAUNCH In Death of Spy Satellite Program, Lofty Plans and Unrealistic Bids By Philip Taubman NYT 11-2007
[130] WSJ "Investing Experts Urge 'Do as I Say, Not as I Do'" Jason Zweig 1-3-09

- *Don Phillips, managing director at Morningstar, highly recommends placing tax-inefficient assets in retirement accounts but never has followed his own advice and thus pays preventable taxes year after year.*
- *Burton Malkiel, Princeton economist and author of "A Random Walk Down Wall Street," and an intellectual godfather who praises the virtue of index funds, confesses that individual stocks comprise a substantial portion of his personal investment portfolio.*

All of these examples have one thread in common, namely: emotion trumps education. This will come as no surprise to those of us who are regularly engaged in risk management activities. We know full well how significant and serious these so called "soft issues" of risk management can become. It's not a difficult stretch to consider how resultant problems can expand exponentially and stymie participants in the world of joint confidence level analysis.

We in the NASA Cost Estimating community can recommend the most wonderful and efficacious *algorithms, heuristics, and quantitative techniques,* much as do the experts who advise those in portfolio risk management - but - if the advice we provide is not followed, we have accomplished nothing except that of informing and educating the crew of a sinking ship - and the right to say "we told you so" when things start to flounder - which provides no satisfaction for anyone. Our role as joint confidence level analysts is intended to supply intelligence that will save the ship, not stand by and watch it list for a while and then capsize into budget over-runs and missed milestones in spite of the warnings we tendered from the beginning. Our not yet accomplished objective in the cost estimating community is to find a way to not only be heard by top management, but to be believed and valued as actual contributors in the mapping process of NASA's complex development programs. We must not be content to merely take a benign position as placeholder-type personnel in the organizational scheme of things. This paper is an attempt to move us toward this worthy objective - that of making the discipline of cost estimating a genuinely respected agency component that will make a difference on the bottom line of the NASA Budget.

We've attempted to summarize the objectives of this paper by diverting from our traditional role as information advisory personnel to that of taking the liberty of critiquing managerial influence on organizational dynamics. We have only done so with the desire to provide valuable steering influence in the cost estimating genre to those who manage and guide - but not in any way to imply disrespect or cast dispersions toward the individuals burdened with the heavy responsibility of leadership. Mr. Jefferson said it well:

> **"History . . . by apprising (people) of the past . . . will enable them to judge the future."**
>
> *Thomas Jefferson*

Summary

Studies indicate that the accuracy of an estimate has a direct relationship to the stage of development of a project. Another way of saying this is that *estimates improve as development progresses*. It also has become apparent that estimates for developmental projects containing only "modest technical advances", tended to be more accurate than those projects which are more ambitious - where the development threshold is being pushed substantially.

Many factors contribute to cost and schedule growth, but over-optimism in initial designs, changes in scope over time, inherent technical difficulty of maturing technologies, and external influences are common themes. NASA is not the only federal agency facing cost and schedule growth issues. The causes outlined above are not unique to NASA. The NASA/DOD procurement system has been analyzed for decades. Commissions, panels, and academic studies report causation do to these same issues. The fundamental challenges of good cost and schedule estimating and work performance are remarkably similar across federal agencies.

Valid JCL probabilistic estimating of cost and schedules depends on the stability and soundness of the baseline. Inasmuch as each project's estimate is developed with many inputs, it holds that any changes to those underlying inputs (assumptions) will reduce the program's cost and schedule confidence. Substantial differences of opinion exist within the cost-estimating community on how to develop and interpret these probabilistic estimates.

> **"In some cases, the content or complexity of the technical baseline is underappreciated. In other cases, the initial estimate of technical resources such as mass or power is inadequate or reliance on heritage systems is overstated. The initial inadequate technical baseline and/or poorly defined requirements lead to an artificially low initial cost estimate resulting in significant cost growth beyond the project's internal cost reserves. Furthermore, optimism may be introduced into the cost estimating process from empirical cost models that do not incorporate cancelled missions, missions currently in development that are experiencing difficulties, or missions whose actual costs have been omitted or modified based on "unusual" circumstances. Another key driver of a project's final cost is schedule risk, which is often not adequately captured, making the initial schedule incompatible with the budget, resulting in an overall plan that is not executable. In summary, the optimism in the initial design starts the cycle, which is exacerbated by limitations in the cost estimating process."**
>
> *Gary P. Pulliam, Vice President Aerospace Corporation 2009*

The day of reckoning is drawing near. Bipartisan legislation (*called the Weapons Systems Acquisition Reform Act of 2009*) has been introduced to Congress. It gives greater leeway to kill programs with unchecked cost overruns and seeks to establish realistic cost estimates.[131] Currently, Pentagon officials are required to notify Congress when a program goes significantly over budget - but it is relatively easy for the Defense Department to then obtain a waiver based on a claim of necessity. The new bill is designed to ensure that more pentagon contracts are fixed price awards instead of the cost plus contracts currently so prevalent. In the new government contracting environment, arriving at estimates that are very close to eventual reality will become more important than ever before.

> **"Dealing with these cost and schedule issues is hard, and there's no simple fix or the situation would have been resolved long ago."**
>
> *Gabrielle Giffords, chairwoman House Subcommittee on Space in Aeronautics*

A study of historical disasters[132] suggests that the proximate cause of failure is rarely a single event; usually it was one small problem that precipitated a cascade of errors or unlikely events, which were often made worse by poorly trained human operators. In a few cases, superior training and experience saved the day, preventing serious technological failures from turning into headline-busting news.

[131] Bill Targets How U.S. Buys Weapons, WSJ 2-25-09
[132] Inviting Disaster, James Chiles, 2001

> **"Individuals, processes and organizations are perfectly designed to achieve whatever results they are currently getting, so if you're not happy with what you are achieving, its time to reconsider your assumptions and approaches to your process and product design methods."**
>
> *Andy Grove, Chairman of Intel*

With history as our guide, we can expect budget cuts, plus ups, continuing resolutions, strikes, natural disasters, and other problems that are beyond NASA's control. We know the future will be impacted by improbable events, we just don't know what or when. Lack of control in these matters, however, does not have to equate to the absence of contingency planning. Though the unexpected always brings with it unwanted impact, real confidence level assessment also includes balancing factors to offset these unknown risks.

> **"There is significant competitive pressure, both within NASA and among its contractors, to initiate a mission at the lowest possible cost."**
>
> *Gary P. Pulliam, Vice President Aerospace Corporation*

> **"The space acquisition system is strongly biased to produce unrealistically low cost estimates throughout the acquisition process; these estimates lead to unrealistic budgets and un-executable programs."**
>
> *Joint Task Force on Acquisition of National Security Space Programs*

Everyone agrees that space flight is difficult. The United States and many other nations have blown up a lot of missiles and rockets in the past in pursuit of reaching for the stars. No one argues that failure is part of the business. In fact, people in all walks of life have coined a euphemism for something that is difficult to do. They refer to it as *rocket science*. One of the pervasive root causes for cost growth is the realization that we can't aim for the stars unless we at least begin the journey - that we can never get there if we don't start. And getting started is why we deliberately estimate optimistically.

When adequate cost and schedule reserves are available, often as through a self fulfilling prophecy budgets expand and schedules grow. A self fulfilling prophecy is the phenomenon that occurs when a given expectation evokes certain behaviors that make the expectation come to pass. "In other words, once an expectation is set, we tend to act in ways that are consistent with that expectation. Surprisingly often, the result is that the expectation, as if by magic, comes true."[133] If people accept the notion that budgets and schedules have reserves available, they will go forward with the assurance that their pet project should be initiated, or that overruns are acceptable. At some point along the road of execution the reserves are expended, "on nice to haves" and reserves are not available for the "must haves". Strong management resolve is required not to allow this phenomenon.

> **"Invariably, the Department of Defense and the Congress end up continually shifting funds to and from programs – undermining well-performing programs to pay for poorly performing ones. At the program level, weapon system programs are initiated without sufficient knowledge about requirements, technology, and design maturity. Instead, managers rely on assumptions that are consistently too optimistic, exposing programs to significant and unnecessary risks and ultimately cost growth and schedule delays."**
>
> *GAO Report 09-362T*

[133] Social Theory and Social Structure, Robert Merton, 1957

It is critical that estimates be "real and adequate" right from the beginning and that all the players on the fulfillment team realize that the budget is the budget. Dedication to "living within ones means" will apply equally to the world of work just as it does ones private finances.

Conversely, if a project/program has more resources on hand than it needs, management must be firm in reversing the old anecdote that claims *projects will expand to fit the allocated time and budget*. The "use-it-all-up" philosophy should be ferreted out and eliminated from NASA organizational behavior. More money can always be spent and more time can always be used. Real program needs vs. exorbitant wants are often separated by a thin wavering grey line. As a basic practice, management should frequently ask themselves the question: *just how important is it to trim a day off the processing time or acquire this additional capability?*

As a corollary, "management reserves" should never be used to cover the cost of scope growth. ***The meaning of "reserve" is "set-aside money" which is to be held back for the purpose of accommodating the completion of existing program/project scope and static baselines.*** As a core guiding principle, *new scope* should always mean *new money*.

Some uncertainties are within the realm of the project's control. Proposers can be overly optimistic in their efforts to provide the most attractive package in a competition. The cost savings assumed based on the use of "heritage technology" for spacecraft or instruments can be over estimated. New technology development can ultimately be much more challenging than anticipated. Sometimes inadequate time is planned for early engineering efforts and refinement of requirements. These are all areas within project accountability."

Christopher Scolese – Acting NASA Administrator

With regard to risks and planning for the unknown, it is often argued that some cost and schedule risks should NOT be modeled since they have not recently occurred or in some instances every happened. Just because we have not yet died does not mean we are immortal. Rare events (some of which may be catastrophic) must be included in our JCL analysis to safely claim we have provided "good" confidence level guidance.

"Out of the ten NASA projects in the GAO QuickLook Report that exceeded the Congressionally-mandated cost and schedule thresholds, <u>approximately half did so as a result of external factors</u>; some with limited solution options open to NASA."

Christopher Scolese – Acting NASA Administrator

Just as the occurrence of an unlikely event can substantially affect project cost and schedule, problems can arise if something minor (which was not expected to be a problem) becomes one. For example during the development of the SRB, it was discovered that the production of a certain type of rayon fiber (an ablative material) anticipated for use on the SRB, was being phased out due the demise of bias ply tires - something not associated with space related acquisition.[134] Mitigation resulted in a project impact.

[134] Congressional Record 1977 NASA Authorization Volume 1, Part 3

> **In recent years, NASA has commissioned several studies to determine the primary contributing factors to cost and schedule growth. These studies, as well as others in the field, identified several common themes: significant optimism in initial designs, changes in scope associated with the evolution of the design over time, the inherent technical difficulty of developing world class technologies, and the effect of external influences . . .**
>
> *Gary P. Pulliam, Vice President Aerospace Corporation*

One final example is offered. From 1940 through the 1970's only a few US banks failed. Twenty five banks failed in 2008.[135] More will fail in 2009 despite the massive federal financial bailout effort. The Capital Purchase Program (CPP) reports that 400 banks in 47 states have received federal funds under this program[136]. Many more financial institutions are on the verge of insolvency or were absorbed by mergers prior to the fact. Large brokerage houses and insurance companies have failed or have required massive bailouts to sidestep their closure. Why is this so shocking? Because it simply wasn't supposed to happen! The banking industry, brokerage houses, and insurance companies employ thousands (probably tens of thousands) of risk experts - people with masters and PHD degrees who are there to secure the way ahead. These companies have spent untold millions on sophisticated risk models and hedging strategies. But their banks failed nonetheless due to reasons no one seemed to have power to prevent. Why? - *Because they failed to include the possibility of the occurrence of rare events.*

The object of this paper has been to introduce and defend the following point. Claiming a specific JCL for a project without including consideration of 1) over-optimism in initial designs, 2) changes in scope over time, 3) inherent technical difficulties connected to maturing technologies, and 4) external influences where rare events and potential risk possibilities are included in the probabilistic assessment process, 5) possibility of triple digit cost growth - will ultimately fall short of its aim. That aim is to provide credible and accurate fiscal guidance to those who authorize the resources and those who oversee the fulfillment activities. Anything less than this is simply NOT acceptable.

The Path Forward

The acid test of whether NASA will find the institutional resolve and clarity of purpose to raise a banner in support of our recommendations calling for candid realism on the part of all managers at all levels of the joint confidence level playing field - is yet to be determined. NASA's fiscal game plan - to tell it like it is on public and congressional stages - should become as transparent as it has been within the private offices and institutional corridors of the agency. A recent editorial from NASA's Wayne Hale is relevant and timely, an excerpt of Mr. Hale's article is inserted here:

> ". . . I have been out of the Shuttle Program manager job for almost a year now and a trusted coworker just a week ago told me that people in his organization had been prevented from giving me important alternative choices for some program choices that occurred a couple of years ago. This was staggering. It was happening right in front of me and I was totally unaware that people - whom I trusted, who I hoped would trust me - kept their lips sealed because somebody in their middle management made it clear to them that speaking up would not be good.
>
> "Astounding.

[135] http://www.fdic.gov/bank/individual/failed/banklist.html

[136] Top 20 banks receiving US aid are lending: Treasury, www.breitbart.com 2-17-09

"About two weeks ago an activity that Mike Coats started at JSC had an all day report out period. The Inclusion and Innovation Council was to propose ways to improve innovation at NASA. Various teams reported out, including one team of young employees who has the task to talk about the barriers to innovation at NASA -- specifically at JSC.

"The video attached was their result. I found it extraordinarily funny and not at all funny. These young people have obviously found themselves in situations RECENTLY in which managers at various levels applied sociological and psychological pressures to keep them from bringing ideas forward.

"I am convinced that if we asked the managers who were the models for this little morality play whether they stifled dissent or welcomed alternate opinions, they would respond that they were welcoming and encouraging. Probably because they have that self image.

"But actual behavior, not inaccurate self perception, is what we really need. . .

"I feel like the early civil rights pioneers must feel; the overt bad behavior is gone underground. People say the right things in public discussion of how they should act, then behave in the bad old ways in small or private settings.

"Since these behaviors are still being practiced at NASA, here is what I believe managers need to do.

"1. Break out of the sandbox. Even if it is not your area, the agency needs the best ideas (in order) to succeed in our goals. If you have subordinates who have ideas for improving other areas, it is important to get those ideas into the open where they can compete in the marketplace of ideas, or at least get a technical review.

"2. If a subordinate has an idea that has been tried before and didn't work, consider that times may have changed and it might work now or (might work) with improvements that you know of. In the final extremity, your subordinate needs more than the curt dismissal that it's been tried before and didn't work - you need to explain it to them.

"3. Managers at all levels need to provide safe places and times for interaction that skips levels in the chain of command.

"Well, that is enough to start with. Looks like we still have a long way to go and the first step is to know that you still have a problem."

Wayne Hale, NASA Shuttle Manager

As authors of this work, we find ourselves in the immensely important but unenviable crucible of proposing a hard doctrine to those above us. The challenge of correcting a cost and schedules estimating culture that predominantly has held to the hazardous precedent of over-optimizing performance projections is a daunting foe indeed. However, in the hope that intelligent dissent is valued NOW more than ever at NASA, we are prepared to raise the bar on the joint confidence level concept - believing that a *new day* in business practices at NASA will genuinely welcome a *new way*. Changing the landscape has never been easy, but when a "better way" is finally endorsed, it is always worth it!

The (JCL-PC) Method

We introduce here a landscape changing JCL equation that mathematically compensates for the optimism bias inherently present in NASA cost estimating activity. It is called the Joint Confidence Level - Probabilistic Calculator (JCL-PC) and will correct the overly optimistic cost and schedule estimates that have long plagued the NASA cost estimating community. The JCL-PC will safeguard the agency against submitting dangerously optimistic numbers with the resultant loss of credibility for NASA. Using the JCL-PC will avert the consequences of missed cost targets where plus-ups have become a way of life within the agency. We propose that several key individuals at NASA HQ be trained in the use of the tool. These individuals would become the "window" for the submits coming from the various NASA Centers prior to forwarding funding requests to the Congressional Budget Office (CBO). We are confident this process will produce numbers that prove out much closer to reality when viewed from the vantage point of history.

The JCL-PC is a holistic algorithm that effectively compensates (at any stage of a program or project) for the unidentified risk events that have not yet occurred or cannot yet be acknowledged or discovered. As a program/project progresses forward and a risk item moves from a "potential" event to being a "discrete" entry in the baseline, the JCL-PC equation will become less weighted in direct proportion to actual work performed and actual schedule achieved. In this way, the JCL-PC is a fully cooperative player with earned value concepts. In short, the JCL-PC is the self-adjusting constant in the cost estimating law of relativity. It achieves mathematically what human monitoring cannot yet determine and foreshadows illusive fiscal requirements and schedule adjustments so important to good cost estimating. The JCL-PC is the missing link to realistic budgets and PPBE planning.

Bayesian Statistics Growing Out of Elicitation

Elicitation of subjective probability distributions is an area of research arising from several developments in the 1950s and 1960s. The first was a renewed interest in Bayesian statistics. Practitioners of Bayesian statistics argued that probability should reflect a subjective state of knowledge in which a rational person would use Bayes' theorem to modify an initial state of knowledge about some item of interest. In our case, that happens to be the final cost/schedule of our programs. So . . . we start with the *initial probability distribution*, and then modify it with acquired data to form an updated probability distribution (referred to as the *posterior probability distribution*). This argument is contrasted with the prevailing school of Frequentist statistics which holds that the only basis for assigning probability to an event was its random chance of occurring in a large run of experiments. Bayesian statistics, therefore, requires two steps: 1) eliciting the prior distribution and then 2) performing the mathematical calculations required to apply Bayes' theorem in pursuit of a more accurate prognosis.

A Capsulated View of The JCL-PC

The JCL-PC estimating method is based on the hypotheses that in the beginning phases of a project there are many unknown risks - and over time the project will have a high probability of exceeding estimated costs and scheduled duration. Examples of these risks have been discussed in detail in the preceding pages. As the program/project progresses, optimism biases will fade and hard realities will set in. It is then that time and money resources must be applied to effectively deal with those unforeseen events. Work as it was initially planned will inevitably change. Quantifiable risks become clearer and NASA's S-Curves will tend to lay down as the work goes forward. Keep in mind that it's not the project that is becoming inherently riskier. It's a matter of participants fully identifying the real work that was "out there" all along. Even though the scope of the work wasn't fully perceived "back when" - progress has continued to identify the risks and quantify the corrective actions. History is written in real time and that history differs to a greater or lesser degree from what was anticipated. The JCL-PC helps us better plan for and manage that difference.

> **"While useful and necessary for the initial planning phase of a mission, early estimates are, at best, educated guesses made with preliminary conceptual information."**
>
> *Christopher Scolese – Acting NASA Administrator*

The JCL-PC method strikes a needed balance between subjectivity and anticipated risk variability leaving only one remaining probability influence factor to deal with. - namely, assigning the percentage complete of the subject project. This % complete factor includes both subjective and objective elements.

"The devil is in the assumptions. Often in engineering reliability one has sufficient experience to make the model accurate. However in financial or aviation models it is extremely difficult to get the assumptions right. All the money and expertise on Wall Street was incapable of producing models that accurately predicted the risk that banks were running when buying complicated financial instruments."

David McDonald - Mathematician

The proposed project is generally not what is finally built. Likewise, the initial cost estimate is not representative of the final, as-built configuration. Required changes were unavoidable as understanding of the design evolved. In essence, cost estimators are trying to estimate a moving target as projects progress toward their final design form.

A recent study of 40 NASA science missions (which are relativity small projects) found only 12.5% did not experience any cost or schedule growth above the project's internal reserves.[137] Surprisingly, this result is close to the construction industry mega project average where 14% of projects were completed for the original cost estimate.[138]

"Unanticipated risks often manifest themselves late in the development cycle during integration and test, when it is often too late to make adjustments."

Gary P. Pulliam, Vice President Aerospace Corporation

Several NASA research efforts with respect to Figure 62, confirms that the Agency's cost and schedule performance is better when measured from the KDP-C gate than when measured from the earlier milestones.[139] This supports our aforementioned hypothesis and the body of historical data that estimates improve with project progression. Since available data suggests that cost estimates are more susceptible to large overruns than schedule estimates, our example will be built on cost - but the same methodology is applicable for schedule estimating.

[137] Gary P. Pulliam, Vice President Aerospace Corporation, Congressional Testimony Subcommittee on Space and Aeronautics, 3-5-09
[138] Megaprojects and Risk: An anatomy of Ambition, by Bent Flyvbjerg, Nils Bruzelius, and Werner Rothengatter (Cambridge University Press, 2003).
[139] Christopher Scolese, Acting NASA Administrator, Congressional Testimony Subcommittee on Space and Aeronautics, 3-5-09

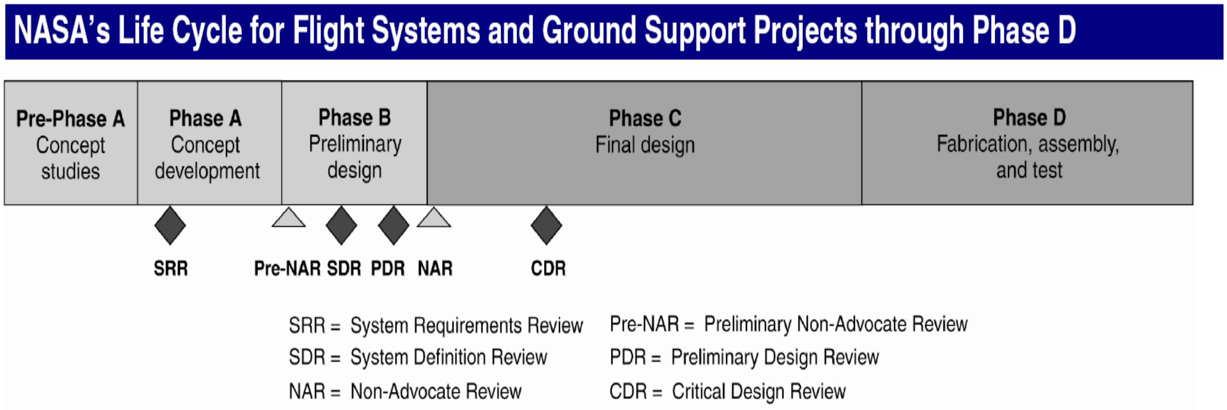


Figure 62: *– NASA defined life cycle phases through Phase D*

Figure 63 below shows the cost growth for 96 historical projects, from the first available estimate to the last available cost estimate. The average growth was 93%, the median growth was 51%.

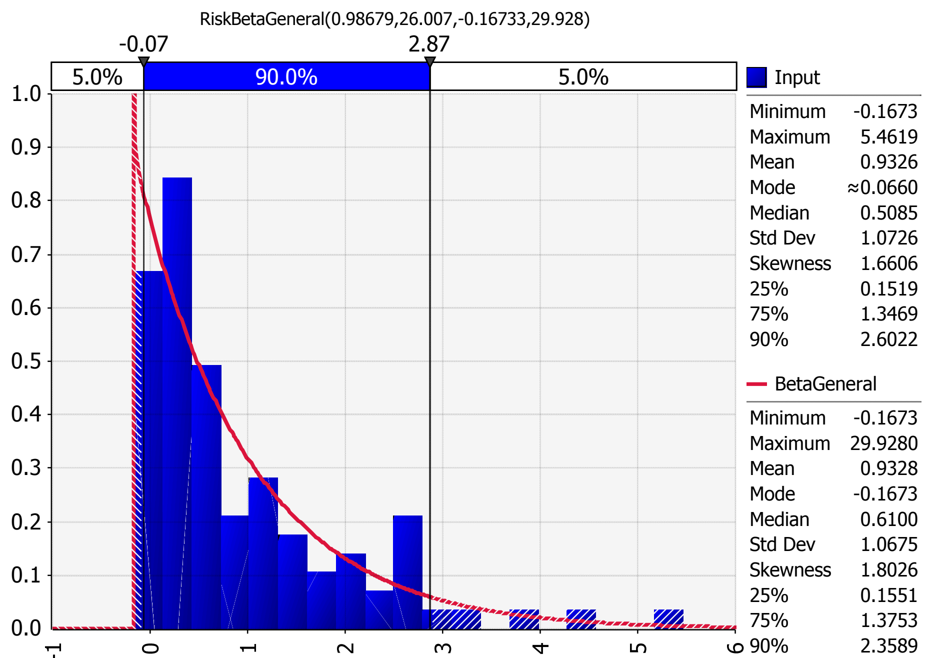


Figure 63: *– Historical percentage cost growth for 96 NASA projects*

Shockingly - these numbers are probably low! Since many of these projects are still in development. Projects are often re-baselined multiple times - as shown in Figure 64 below. Occasionally, projects are canceled due to cost growth. But here's the telling point. Growth is historically calculated against the latest baseline - NOT against the initial baseline. So . . . if cost growth were computed against the initial baseline, numbers would be more aggressive and margins considerably greater.

Although Figure 63 is the basis of our example, the 96 aggregate projects may not be applicable due to Simpson's Paradox. It's a well accepted rule of thumb within that the larger the data set, the more reliable the conclusions. Simpson's paradox, however, is a contradiction to that rule. Caution must be used when amalgamating data from multiple projects types because conclusions can be flawed. This is caused by lurking variables or skewed data from unequal sized groups being combined into a single data set which distorts the output Therefore, when using the JCL-PC method, care must be taken to only compare “like projects” when estimating probable cost and schedule growth.

Then-year dollars in millions

Program	Baseline in millions	FY 2000 by quarter (1 2 3 4)	FY 2001 by quarter (1 2 3 4)	FY 2002 by quarter (1 2 3 4)	FY 2003 by quarter (1 2 3 4)
Renamed Spitzer SIRTF[a]	$472			July $534 ▼	Jan $638 ▼ Apr $669 ▼ Aug $712 ▼
MERs	$657		Oct $697 ▼	Mar $729 ▼	Apr $767 ▼
GP-B	$530	May $615 ▼	Apr $631 ▼	May $667 ▼	Feb $709 ▼

Figure 64: *– Re-baselining of 3 NASA projects illustrates frequency of occurrence*[140]

The best way to explain this is with a simplified example. When examining world track and field records we see that for the 100 Meter Dash, the record is *9.77 seconds*. The world mark for the Marathon is *2 hours, 4 minutes and 55 seconds (7,495 seconds)*. The average for time for both races is *3,752 seconds*. Therefore, the expected time for the next *100 Meter Dash is 3,752 seconds* and the expected time for the next *Marathon is also 3,752 seconds*. Statistically impressive, however, is the expected time for the next *Half Marathon - which is also 3,752 seconds* and wouldn't you know it, that time is close to the record for a Half Marathon (record 3,500 seconds). The point is easy enough to see. Terribly inaccurate projections could be made from the data without conscientiously allowing ONLY "like races" in the evaluation set.

Simpson's paradox should be respected when applying the JCL-PC method and making business decisions in the NASA environment. Results may be deeply misleading if the schedule slip of a small planetary mission was used to project the schedule slip for the development of a new rocket system that will place a manned craft near the polar regions of the moon. Schedule slips are not feasible on most planetary missions since they will miss a launch window that may not come again for many months or years. Inversely, schedule may well be traded for cost reductions on large projects where schedule can be reasonably modified. Firmly holding to a particular launch window in such an instance may not be critical to mission fulfillment.

Notionally, "like missions" in the NASA environment could be segregated as follows: *1) Planetary, 2) Satellite, 3) Manned Space Flight, and 4) Other.* Further data analysis should determine the proper allocations.

Figure 66 demonstrates the JCL-PC estimate multipliers for various probability ranges. Basically, it adjusts for what we know to be true - that early estimates are optimistic and that the project is very likely to overrun. The red line shows that at the beginning of a project if you want to achieve a 40-50% confidence probability, the costs will be ~1.6 times the estimated costs. However, as the project progresses and unknown risks become more fully identified - resulting in optimism bias decreases - then at a 40% project completion point, the 50% estimate is considered to truly have a 50% probability. An ever decreasing amount of unknown risks, however, will still remain until the project is completed.

[140] GAO-04-642 Lack of Disciplined Cost-Estimating Processes Hinders Effective Program Management

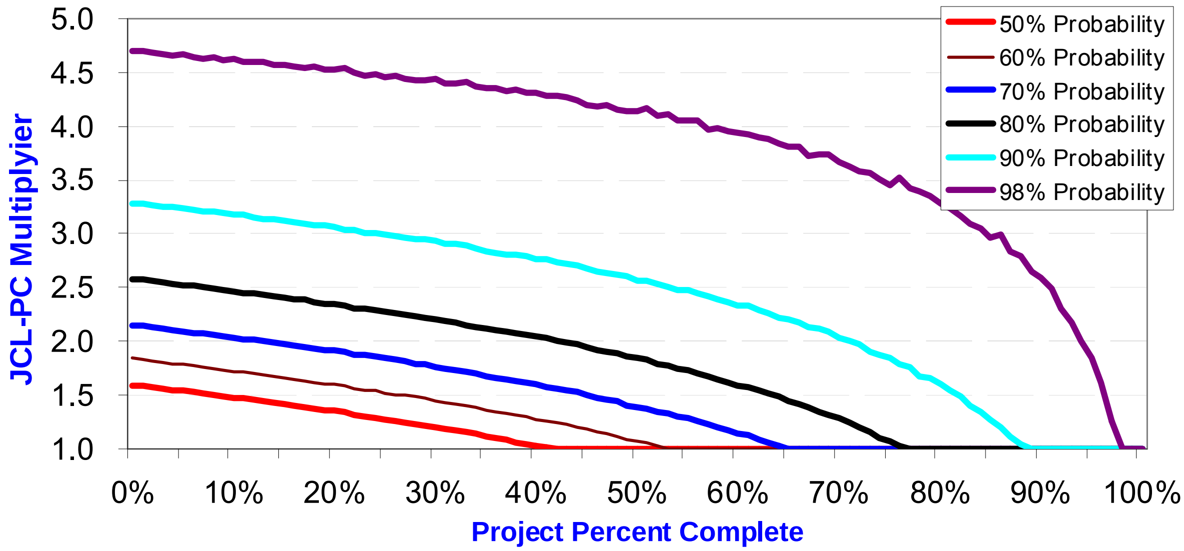


Figure 65: *– JCL-PC multiplier applied at various project phases*

To demonstrate the concept Figure 67 shows an S-Curve comparison for a fictional $1 million dollar project point estimate, with no other risks induced.

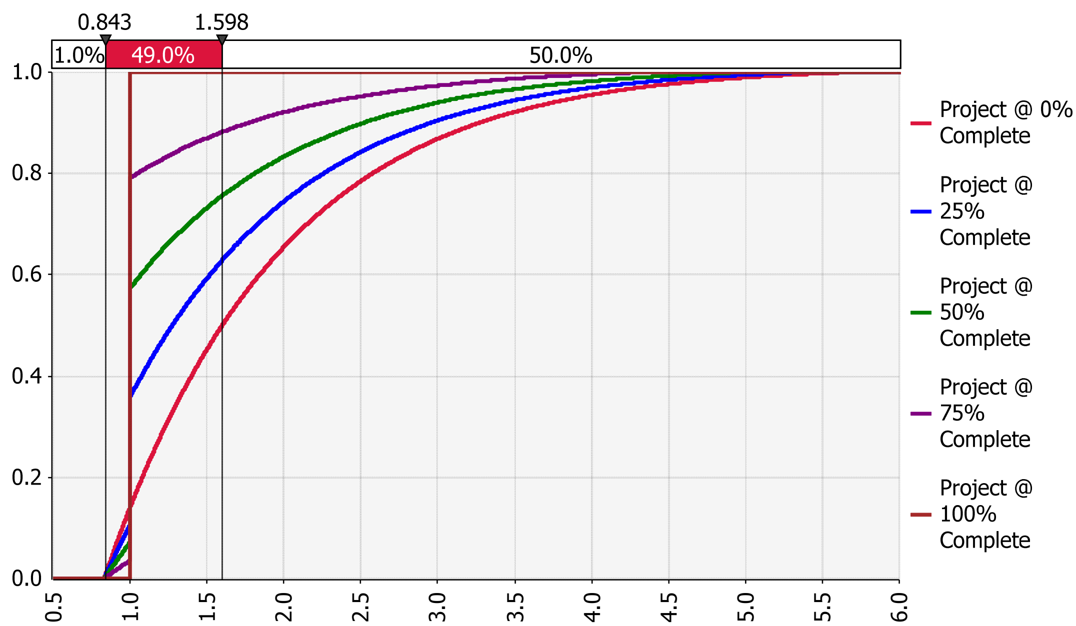


Figure 66: *– Example project with JCL-PC applied to typical point estimate*

Figure 68 shows the S-Curves for the same $1 million dollar project, but includes the JCL-PC optimism corrector and some minor project risk, through a more typical project life cycle with project scope creep causing final cost to increase to $1.66 million or 1.66 times the original estimate, (59% probability point for historical aerospace project growth). As the project evolves the S-Curve moves slightly to the right and becomes more and more vertical.

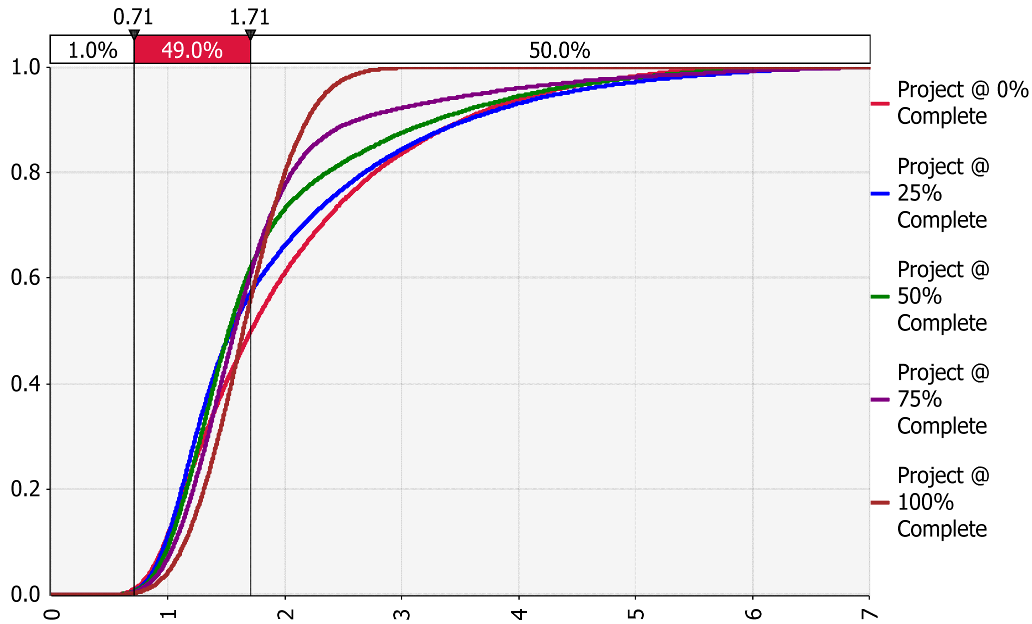


Figure 67: *– Example project with JCL-PC applied to typical Confidence Level estimate*

The notational method of accomplishing this is as follows.

Assumes no Unknown Risks Occur	Unknown Risk Distributions	% Project Comp	% Project Remaining	JCL-PC Multiplier
1.00	=RiskBetaGeneral(0.98679,26.007,-0.16733,29.928)+1	0%	100%	=RiskDiscrete(A9:B9,C9:D9)

Table 2: *- Notational method for JCL-PC applied to typical Confidence Level estimate*

JCL-PC = Project cost estimate x Discrete Risk Distribution

- Discrete Risk Inputs:
  - 1 - Project percent complete = Project percent remaining
  - NASA's historical cost growth
  - Constant of 1
- Probability of cost growth decreases as project progresses

Assumes no Unknown Risks Occur	Unknown Risk Distributions	% Project Comp	% Project Remaining	JCL-PC Multiplier
1.00	1.93	0%	100%	1.93
1.00	1.93	100%	0%	1.00

Table 3: *- JCL-PC multiplier at 0% and 100% project complete stages*

In actual practice it is difficult to ascertain the exact percentage of project completion. So it is recommended that the project percent complete be replaced by a uniform distribution with a range of completion percentages. For example if a project is between 10% and 20% complete

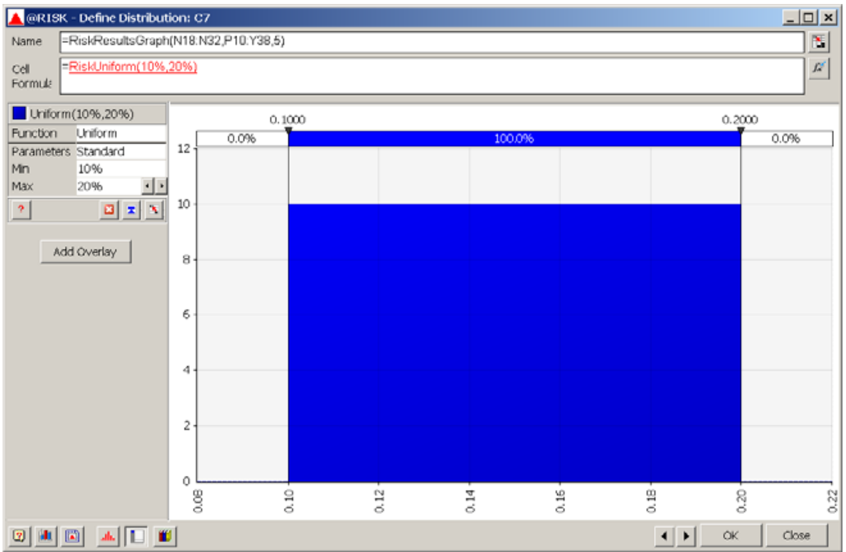


Figure 68: *– Uniform distribution, suggested input for project percent complete*

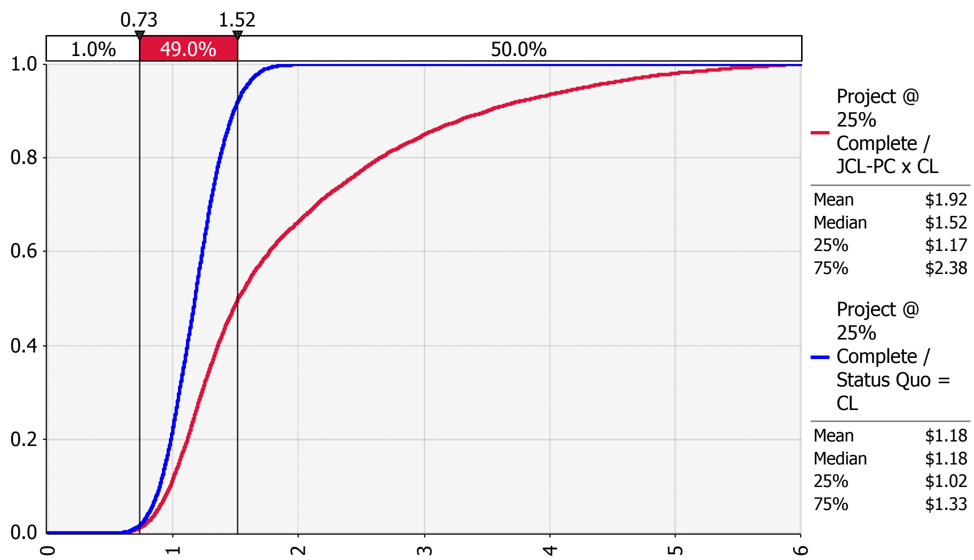


Figure 69: *– Comparison of Status Quo JCL method vs. JCL-PC method*

All examples of JCL-PC have been done using cost probabilities. The same method is applicable for schedule estimates as well, but for brevity purposes they are not presented in this paper.

Figure 68 displays the estimated cost of a one million dollar project at 50%, 60%, 70%, and 80% confidence levels at project completion marks ranging from 1% to 100% as derived using the Joint Confidence Level Probabilistic Calculator. There are some meaningful observations that can be made as we examine the chart.

Observation 1: At 0% complete, the numbers across the row to the right reveal varying financial requirements needed by management in order to feel progressively greater levels of confidence that the task at hand can be accomplished with the stated amount of funding.

Observation 2: When the project is 50% complete, you'll notice that a 50% confidence level suggests that the project can be completed for the anticipated $1,000,000. However, if we adhere to the NASA standard of a 70% confidence level, we see that another $400,000+ will likely be needed to complete the project. No matter how well a project is managed, it rarely compensates for ultra-optimistic budget estimates that sooner or later return with a vengeance and overcome the most skillful leaders.

Observation 3: The whole intent of the JCL-PC method is to scope "accurately" the lay-of-the-land in the program/project fulfillment world. The JCL-PC method does not "pad the budget" in any way. To the contrary, it strikes a fair and equitable balance for both the CBO (who has a need to know that supplied monies will actually accomplish the intended goals) and the NASA performing organization (who deserves sufficient resources to get the job done without cutting safety and quality corners.) The JCL-PC is the long awaited neutral facilitator who has the best interests of all parties at heart.

As bleak as the previous cost growth analysis is, it pales when compared to development cost growth for manned space flight projects. These projects are typically large, complex, long duration, and strive for leaps in technology innovation. Historically, all factors correlated with large cost growth percentages.

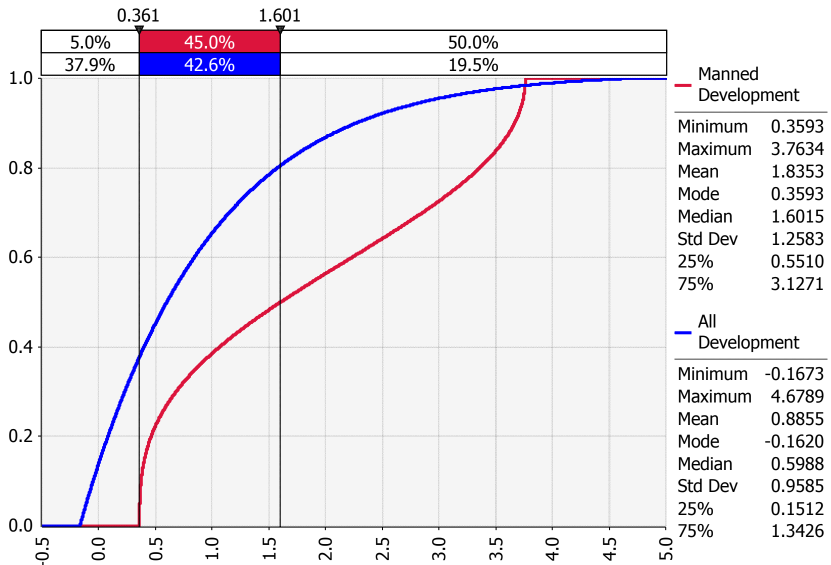


Figure 70: *– Manned space flight development project growth compared to all NASA development project growth*

The JCL-PC methodology should be employed at headquarters level to prevent project advocates from gaming the system and submitting an unrealistically low estimate or squandering essential reserves. Headquarters should be the holder of reserves and projects should be held accountable for overruns and be required to come to Headquarters to ask for additional funding above the initial request. Reserves should never be regarded as a slush-fund cushion that compensates for inefficiency or poor management - but should be available for valid and unforeseen working developments as intended.

"NASA needs to surgically remove many of our administrative processes & reports from off the shoulders of management. Through using the JCL-PC Method, optimism bias will become a thing of the past. Estimates will be credible, budgets will be respected and adhered to, and managers will genuinely be able to work their projects "as planned" notwithstanding unexpected events. Through using this approach, NASA will see the improvements it has been waiting for."

Glenn Butts - 2009

% Project Comp	50% Probability	60% Probability	70% Probability	80% Probability
0%	$ 1,609,066	$ 1,857,133	$ 2,174,399	$ 2,616,440
1%	$ 1,598,078	$ 1,846,323	$ 2,163,685	$ 2,605,307
2%	$ 1,585,663	$ 1,834,122	$ 2,152,228	$ 2,594,747
3%	$ 1,574,433	$ 1,822,371	$ 2,140,592	$ 2,583,494
4%	$ 1,563,509	$ 1,811,140	$ 2,129,614	$ 2,572,611
5%	$ 1,552,785	$ 1,801,310	$ 2,119,332	$ 2,561,769
6%	$ 1,541,261	$ 1,789,630	$ 2,108,168	$ 2,550,626
7%	$ 1,529,168	$ 1,777,058	$ 2,095,463	$ 2,537,132
8%	$ 1,516,338	$ 1,765,030	$ 2,082,426	$ 2,525,748
9%	$ 1,503,448	$ 1,751,744	$ 2,069,885	$ 2,513,173
10%	$ 1,489,706	$ 1,737,258	$ 2,055,196	$ 2,500,522
11%	$ 1,475,736	$ 1,724,750	$ 2,042,870	$ 2,484,315
12%	$ 1,465,601	$ 1,714,396	$ 2,032,325	$ 2,473,910
13%	$ 1,452,985	$ 1,702,363	$ 2,021,113	$ 2,463,222
14%	$ 1,440,544	$ 1,689,323	$ 2,009,071	$ 2,455,022
15%	$ 1,426,756	$ 1,676,526	$ 1,995,655	$ 2,441,035
16%	$ 1,412,468	$ 1,662,142	$ 1,980,270	$ 2,426,189
17%	$ 1,399,755	$ 1,648,626	$ 1,965,857	$ 2,410,808
18%	$ 1,386,037	$ 1,635,652	$ 1,954,296	$ 2,399,669
19%	$ 1,372,947	$ 1,621,448	$ 1,939,293	$ 2,382,456
20%	$ 1,360,167	$ 1,609,409	$ 1,928,335	$ 2,372,409
21%	$ 1,344,635	$ 1,593,364	$ 1,911,705	$ 2,357,853
22%	$ 1,333,685	$ 1,583,432	$ 1,902,295	$ 2,347,507
23%	$ 1,318,294	$ 1,567,763	$ 1,891,420	$ 2,336,302
24%	$ 1,303,174	$ 1,554,213	$ 1,871,708	$ 2,320,607
25%	$ 1,289,200	$ 1,537,384	$ 1,858,291	$ 2,305,082
26%	$ 1,272,705	$ 1,522,836	$ 1,845,361	$ 2,290,987
27%	$ 1,254,900	$ 1,505,320	$ 1,826,851	$ 2,279,456
28%	$ 1,241,265	$ 1,494,088	$ 1,813,336	$ 2,258,111
29%	$ 1,225,943	$ 1,476,599	$ 1,796,962	$ 2,246,298
30%	$ 1,208,380	$ 1,459,973	$ 1,782,621	$ 2,223,345
31%	$ 1,194,153	$ 1,445,453	$ 1,765,732	$ 2,211,968
32%	$ 1,180,633	$ 1,433,033	$ 1,753,182	$ 2,201,219
33%	$ 1,159,391	$ 1,415,927	$ 1,736,025	$ 2,180,268
34%	$ 1,145,376	$ 1,395,525	$ 1,718,317	$ 2,167,650
35%	$ 1,125,722	$ 1,377,224	$ 1,697,959	$ 2,152,046
36%	$ 1,109,768	$ 1,361,297	$ 1,681,585	$ 2,126,428
37%	$ 1,089,703	$ 1,340,298	$ 1,663,528	$ 2,111,215
38%	$ 1,073,074	$ 1,321,185	$ 1,644,121	$ 2,097,397
39%	$ 1,055,352	$ 1,307,108	$ 1,633,245	$ 2,082,129
40%	$ 1,036,021	$ 1,288,094	$ 1,612,696	$ 2,064,563
41%	$ 1,016,947	$ 1,266,124	$ 1,585,794	$ 2,038,385
42%	$ 1,000,000	$ 1,244,597	$ 1,566,420	$ 2,017,618
43%	$ 1,000,000	$ 1,231,943	$ 1,554,578	$ 2,001,107
44%	$ 1,000,000	$ 1,208,197	$ 1,531,093	$ 1,984,033
45%	$ 1,000,000	$ 1,188,041	$ 1,510,236	$ 1,960,073
46%	$ 1,000,000	$ 1,165,292	$ 1,485,487	$ 1,941,414
47%	$ 1,000,000	$ 1,150,335	$ 1,472,031	$ 1,923,773
48%	$ 1,000,000	$ 1,125,387	$ 1,450,458	$ 1,904,659
49%	$ 1,000,000	$ 1,105,308	$ 1,427,268	$ 1,881,346
50%	$ 1,000,000	$ 1,081,526	$ 1,402,738	$ 1,853,529

% Project Comp	50% Probability	60% Probability	70% Probability	80% Probability
51%	$ 1,000,000	$ 1,057,800	$ 1,385,759	$ 1,835,546
52%	$ 1,000,000	$ 1,036,906	$ 1,359,787	$ 1,811,089
53%	$ 1,000,000	$ 1,012,134	$ 1,335,648	$ 1,786,727
54%	$ 1,000,000	$ 1,000,000	$ 1,306,103	$ 1,763,228
55%	$ 1,000,000	$ 1,000,000	$ 1,290,673	$ 1,740,835
56%	$ 1,000,000	$ 1,000,000	$ 1,265,746	$ 1,718,179
57%	$ 1,000,000	$ 1,000,000	$ 1,232,599	$ 1,685,812
58%	$ 1,000,000	$ 1,000,000	$ 1,215,361	$ 1,668,453
59%	$ 1,000,000	$ 1,000,000	$ 1,184,725	$ 1,636,432
60%	$ 1,000,000	$ 1,000,000	$ 1,156,708	$ 1,605,007
61%	$ 1,000,000	$ 1,000,000	$ 1,123,590	$ 1,576,575
62%	$ 1,000,000	$ 1,000,000	$ 1,098,902	$ 1,554,492
63%	$ 1,000,000	$ 1,000,000	$ 1,067,209	$ 1,517,164
64%	$ 1,000,000	$ 1,000,000	$ 1,035,774	$ 1,485,793
65%	$ 1,000,000	$ 1,000,000	$ 1,003,519	$ 1,459,294
66%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,428,904
67%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,387,431
68%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,354,001
69%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,323,170
70%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,288,540
71%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,248,773
72%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,207,219
73%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,170,704
74%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,129,256
75%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,080,471
76%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,039,946
77%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
78%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
79%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
80%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
81%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
82%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
83%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
84%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
85%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
86%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
87%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
88%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
89%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
90%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
91%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
92%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
93%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
94%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
95%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
96%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
97%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
98%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
99%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
100%	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000

Figure 71: *– Numerical cost estimate output for a 1 million dollar project at four different JCL percentages and project completion stages ranging from 0% to 100% using the JCL-PC method.*

Specific Recommendations

If NASA ***really*** wants accurate joint cost and schedule confidence level results data, these are the things we must do.

- IN A POLICY STATEMENT:

  1) Clearly specify that all risks (internal and external) are to be included in JCL analysis. If a hundred risks each have a 1% probability of occurring – in theory there is a 100% chance that at least one of the risks will occur. If the low-likelihood risk impact is large enough, it can materially affect project outcome. One method is to use the JCL-PC estimating equation introduced in this paper.

2) Mandate precise criteria upon which we are being asked to provide JCL assessments. (i.e. X number of flights/launches or an arbitrary time period, etc.). The answers generated can be substantially different due to the criteria used.

3) Require all estimates to be created by a bonafide estimating department that has direct reporting to senior management, similar to SM&A organizations

4) Recognize that cost control is just as important as cost estimates, and require valid cost impacts of all changes to be estimated, and not allow them to be labeled as "no cost" changes. All changes cost something!

5) Require managers to identify and publicize all valid elements/components identified by qualified personnel even if those items are not admitted or baselined by the program and even if those elements cause funding distress.

6) Require cost estimates to be submitted in future year dollars reflecting historical long term escalation rates - never in base year dollars. Base year dollars compared to then year dollars, adds to the illusion of cost growth even if there is not any.

7) Require that the current development stage of the program be specified on the estimate. Providing project phase information is key to historical analysis integrity.

8) Disenfranchise the risk reward system that provides strong incentives for underestimation.

   - Specify procedures that will be implemented to cancel projects that exceed schedule and budget.
   - Designate evaluation criteria that will hold project managers accountable for their management actions/decisions.
   - Reward success for submitting realistic estimates and accomplishing them as advertised.
   - Punish failure, swiftly and publicly
   - Use fee incentives like cost plus (fixed fee) or cost plus (incentive fee) that penalizes the contractor for over-run – reward success, *not the appearance of effort.*
   - Remove incentives for contractors to spend more time and money in order to increase profits.
   - Define requirements and issue more firm fixed price contracts, and don't make changes to them. Contractors will then start providing realistic proposals if they know they will have to stick with them.

9) Remove the prevailing stigma that under-runs are unacceptable. In other words, reverse the policy metrics which mandate that all funding must be spent or that frugal spending is viewed as bad. If a project has any residual funding, the Monte Carlo concept, which allocates excess monies in the direction of over-runs on other projects, relies on underruns on some projects. As it now stands, NASA & congress are insisting that there "shall be no under-runs".

We are gratified that NASA is becoming more committed to joint cost-schedule confidence assessment. Yet, we feel the needed course correction is not yet where it needs to be. We affirm our conviction that throughout all levels of the NASA hierarchy we all must constantly engage in self evaluation and regularly ask ourselves the timely question: Are we meeting the intent of our former NASA Administrator? To wit:

> **"… initiate a pattern of honest dealing between Program and Project Managers, Head Quarters, the Congress, and the White House, and . . . avoid the pattern of finger-pointing for cost overruns and schedule slips that have plagued the industry in the past."**
>
> *Michael Griffin - NASA Administrator - 3/27/2006*

This can only be accomplished by 1) organizational frankness and individual honesty at every level of the budgeting process, 2) employing the use of sophisticated and intelligent assessment tools that result in estimate projections which history will validate as intuitive, timely, and accurate. To this end we submit for your consideration this paper and its recommendations.

Appendix

In an attempt to aid future researchers on this subject, here is the project cost data used in the analysis. Do to the prevailing difficulty in collecting accurate data, it is anticipated that some of the cost growth is understated. This is caused by project renaming, re-baselining, scope cuts and project cancelations.

For example the COSTR program was reported in a 2004 CBO analysis with an initial estimate of $221 million and a current estimate of $326 million and a cost growth of 48%. However a 1992 analysis by the GAO references the initial estimate as being $400 million and a current estimate of $673 million, with a cost growth of 68%. Our analysis takes the CBO's earliest estimate of $221 million and the GAO's latest estimate of $673 million for a true cost growth of 204.5%.

Others projects are possibly overstated due to apples and oranges comparisons - for example, comparing projects base year dollars to then year dollars. Although this is not a valid comparison, it is unfortunately the one often used in the court of public opinion when criticizing NASA's estimates. Numerous sources were used in search of credible earliest available and latest available estimates.

CBO - A Budgetary Analysis of NASA's New Vision for Space Exploration September 2004

GAO/NSIAD-93-97 NASA Program Costs

GAO-04-642 Lack of Disciplined Cost-Estimating Processes Hinders Effective Program Management

Various websites and news publications

Overall it is felt that project true cost growth is much larger than generally reported or acknowledged. A IG report on the SOFIA project illustrates the point.

Year of Projection	Projected Budget for Initial Program Development	Projected Date for Operational Readiness Review	Note
1997	$ 265 million	September 2001	1
2000	301 million	December 2002	1
2003	373 million	March 2005	1
2008	840 million*	August 2011	2

Note 1: Based on SOFIA Independent Cost, Schedule, and Management Review of October 2004.
Note 2: Dollar projection based on the NASA FY 2009 Budget Estimate; date is the Limited Operational Capability milestone.

* Does not include $35 million for formulation.

***Figure 72:** – 3/27/09 NASA IG report on SOFIA project cost history - our analysis used the $373 million cost numbers.*

NASA Historical Cost Growth – Used in Paper

This is the data used in the paper. Numerous sources were used in search of credible earliest available and latest available estimates. All data comes from reputable sources, however errors probably exist, and some projects are still in development, so values may continue to evolve. See last data set for best available information.

Table 4

Program	Earliest Available	Latest Available	Percent Change
Advanced Communications Technology Satellite (ACTS)	$ 354.00	$ 656.00	85.3%
Advanced Health Management System Ph I (AHMS Phase 1)	$ 55.00	$ 55.00	0.0%
Advanced Solid Rocket Motor (ASRM)	$ 1,699.00	$ 3,251.80	91.4%
Advanced X-ray Astrophysics Facility (AXAF)	$ 1,410.00	$ 6,022.00	327.1%
Aeroassist Flight Experiment (AFE)	$ 159.00	$ 387.00	143.4%
Alternate Turbopumps (ATP)	$ 372.00	$ 1,053.00	183.1%
Apollo	$ 7,000.00	$25,400.00	262.9%
Aqua	$ 762.50	$ 1,006.00	31.9%
Cassini	$ 1,436.40	$ 1,375.90	-4.2%
Checkout and Launch Control System (CLCS)	$ 175.00	$ 399.00	128.0%
Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)	$ 68.20	$ 133.90	96.3%
CloudSat Spacecraft	$ 80.20	$ 105.80	31.9%
Cockpit Avionics Upgrade (CAU)	$ 442.00	$ 454.00	2.7%
Collaborative Solar Terrestrial Research (COSTR)	$ 221.00	$ 673.00	204.5%
Comet Nucleus Tour	$ 69.10	$ 96.50	39.7%
Comet Rendezvous Asteroid Flyby (CRAF)/ Cassini (Mission to Saturn)	$ 3,593.00	$ 3,351.00	-6.7%
Cosmic Background Explorer	$ 97.50	$ 159.70	63.8%
Deep Space-1	$ 73.30	$ 94.80	29.3%
Earth Observing System, Aura Satellite	$ 524.00	$ 763.00	45.6%
Earth Observing System, Terra Satellite	$ 1,078.70	$ 1,226.50	13.7%
Earth Observing-1	$ 72.00	$ 158.00	119.4%
Earth System Science Pathfinder	$ 145.10	$ 171.80	18.4%
Environmental Research Aircraft & Sensor Technology	$ 181.30	$ 173.00	-4.6%
Extreme Ultraviolet Explorer (EUVE)	$ 107.40	$ 322.00	199.8%
Far Ultraviolet Spectroscopic Explorer	$ 85.90	$ 120.40	40.2%
Fast Auroral Snapshot Explorer	$ 32.50	$ 42.90	32.0%
Flight Telerobotic Servicer (FTS)	$ 317.00	$ 485.00	53.0%
Fluids and Combustion Facility (FCF)	$ 118.90	$ 114.10	-4.0%
Fourier Transform Spectrometer	$ 317.00	$ 453.20	43.0%
Freedom (Space Station)	$ 25.12	$ 28.94	15.2%
Galaxy Evolution Explorer	$ 41.10	$ 87.10	111.9%
Galileo	$ 276.20	$ 902.30	226.7%
Galileo (Mission to Jupiter)	$ 455.00	$ 1,639.00	260.2%
Gamma Ray Observatory (GRO)	$ 183.80	$ 677.00	268.3%
Genesis Spacecraft	$ 126.10	$ 151.50	20.1%
Geospatial Operational Environmental Satellite I-M	$ 554.60	$ 1,241.00	123.8%
Geostationary Operational Environmental Satellite (GOES)	$ 691.00	$ 1,787.00	158.6%
Global Geospace Science (GGS)	$ 334.00	$ 649.00	94.3%
Gravity Probe B (GP-B)	$ 529.60	$ 709.30	33.9%
High Energy Transient Explorer-II	$ 8.40	$ 23.50	179.8%
High Energy Solar Spectroscopic Imager	$ 39.50	$ 63.50	60.8%
Hubble Space Telescope (HST)	$ 435.00	$ 1,682.00	286.7%

Ice Cloud and Land Elevation Satellite	$ 121.30	$ 177.00	45.9%
Imager for Aurora to Magnetopause Global Exploration	$ 83.60	$ 89.20	6.7%
International Gamma-Ray Astrophysics Lab (INTEGRAL)	$ 8.20	$ 11.90	45.1%
Jason-1	$ 77.50	$ 87.80	13.3%
James Webb Space Telescope (JWST)	$ 900.00	$ 4,900.00	444.4%
Land Remote Sensing Satellite (LANDSAT-D)	$ 260.10	$ 538.00	106.8%
Landsat-7	$ 445.80	$ 508.80	14.1%
Large Throat Main Combustion Chamber	$ 87.10	$ 76.90	-11.7%
Lunar Prospector	$ 56.20	$ 56.20	0.0%
Magellan (Mission to Venus)	$ 322.80	$ 856.00	165.2%
Mars Climate Orbiter	$ 183.60	$ 189.70	3.3%
Mars Exploration Rovers (MERs) 2003	$ 499.40	$ 767.00	53.6%
Mars Global Surveyor	$ 140.20	$ 130.70	-6.8%
Mars Observer (Mission to Mars)	$ 306.00	$ 994.00	224.8%
Mars Odyssey	$ 267.20	$ 366.10	37.0%
Mars Pathfinder - Total Cost Including Launch Vehicle 265.4M	$ 150.00	$ 174.20	16.1%
Mars Science Laboratory	$ 650.00	$ 2,300.00	253.8%
Mercury Program	$ 196.92	$ 384.00	95.0%
Microwave Anisotropy Probe	$ 88.30	$ 94.20	6.7%
Multifunction Electronics Display Subsystem	$ 201.70	$ 210.10	4.2%
NASA Scatterometer (NSCAT)	$ 100.40	$ 255.00	154.0%
Near Earth Asteroid Rendezvous Mission (NEAR)	$ 150.00	$ 124.90	-16.7%
New Millennium Program Earth Observing-1 (NMP-EO-1)	$ 111.70	$ 176.40	57.9%
Ocean Topography Experiment (TOPEX)	$ 438.00	$ 520.00	18.7%
Orbital Maneuvering Vehicle (OMV)	$ 371.00	$ 814.00	119.4%
Rosetta	$ 28.40	$ 40.10	41.2%
SeaWinds	$ 130.20	$ 148.80	14.3%
Second Tracking and Data Relay Satellite Ground Terminal	$ 341.40	$ 532.00	55.8%
Solar Radiation and Climate Experiment	$ 68.00	$ 74.50	9.6%
Solar Terrestrial Relations Observatory (STEREO)	$ 150.00	$ 550.00	266.7%
Space Infrared Telescope Facility (SIRTF) Renamed Spitzer Space Telescope 12-03	$ 472.00	$ 712.00	50.8%
Space Shuttle	$ 5,800.00	$17,789.00	206.7%
Space Shuttle - With Reserves	$ 6,960.00	$17,789.00	155.6%
Space Shuttle Endeavour	$ 2,100.00	$ 1,800.00	-14.3%
Space Station	$ 9,446.24	$45,000.00	376.4%
Stardust Spacecraft	$ 117.80	$ 116.80	-0.8%
Stratospheric Observatory for Infrared Astronomy (SOFIA)	$ 234.80	$ 373.00	58.9%
Submillimeter Wave Astronomy Satellite/Transition Region and Coronal Explorer/Wide Field Infrared Explorer	$ 140.00	$ 212.70	51.9%
Terra	$ 1,309.10	$ 1,393.20	6.4%
Tethered Satellite Svstem (TSS)	$ 40.70	$ 263.00	546.2%
Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED)	$ 129.30	$ 176.20	36.3%
Topography Experiment	$ 321.30	$ 401.50	25.0%
Tracking and Data Relay Satellite replacement (TDRS-7)	$ 300.00	$ 532.00	77.3%
Tracking and Data Relay Satellite System Replenishment	$ 899.80	$ 803.10	-10.7%
Tracking and Data Relay Satellite-7	$ 269.00	$ 370.00	37.5%
Triana Spacecraft	$ 75.00	$ 96.90	29.2%
Tropical Rainfall Measuring Mission (TRMM)	$ 218.80	$ 468.00	113.9%
Ulysses (Mission to the Sun)	$ 196.00	$ 460.00	134.7%
Upper Atmosphere Research Satellite (UARS)	$ 575.30	$ 790.00	37.3%
X-33	$ 1,124.00	$ 1,789.70	59.2%
X-34	$ 171.00	$ 378.00	121.1%

X-38	$ 500.00	$ 1,500.00	200.0%
X-43 Hyper-X	$ 167.00	$ 227.00	35.9%
X-ray Timing Explorer (XTE)	$ 100.00	$ 373.00	273.0%

Manned Space Flight Appears Riskier

Manned space flight projects appear to experience on average substantially higher cost growth, with an average growth of 156% and a median growth of 128%.

Table 5

Program	Initial	Latest Available	Percent Change
Alt Turbopumps	$ 372.00	$ 1,053.00	183%
CLCS - Canceled	$ 175.00	$ 399.00	128%
Mercury Program	$ 196.92	$ 384.00	95%
Space Shuttle	$ 5,800.00	$17,789.00	207%
Space Station	$ 9,446.24	$45,000.00	376%
X-30 National Aero Space Plane – Canceled	$ 3,100.00	$10,000.00	223%
X-33 - Canceled	$ 1,124.00	$ 1,789.70	59%
X-34 - Canceled	$ 171.00	$ 378.00	121%
X-38 - Canceled	$ 500.00	$ 1,500.00	200%
X-43 Hyper-X - Canceled	$ 167.00	$ 227.00	36%
Advanced Solid Rocket Motor (ASRM) – Canceled	$ 1,699.00	$ 3,251.80	91%

Additional Cost & Schedule Growth Data Set #1

The following cost and schedule growth data was compiled by Mr. Christian Smart of SAIC, and is included for additional reference information. This data was not obtained until after paper was completed, so none was used in our analysis.

It is important to note that generally this data indicates much less cost growth, with a median cost growth of 24.9% and a average of 45.5%, and a median schedule growth of 17%, and an average schedule growth of 21.9%.

There are deltas between initial costs, and final costs on many of the projects. With some projects showing higher cost growth. The "correct" answer probably requires another scrub of the data compiling the lowest indicated estimate, and the highest indicated estimate for each project, which time did not allow.

Mission	Initial Budget	Final Budget	Cost Growth %	Initial Schedule (Months)	Final Schedule (Months)	Schedule Growth %
ACE	$ 141.1	$ 108.5	-23%	61.7	61.7	0%
Alt. Turbopump	$ 591.7	$ 993.0	68%			
ASRM	$ 1,506.7	$ 3,251.8	116%			
AURA	$ 660.5	$ 713.8	8%	113.6	133.4	17%
AXAF	$ 1,410.0	$ 1,617.8	15%			
CALIPSO	$ 68.2	$ 170.0	149%	51.0	89.5	75%
Cassini	$ 1,436.4	$ 1,375.9	-4%			
CLCS	$ 175.0	$ 390.1	123%			
CloudSat	$ 80.2	$ 144.0	80%	46.2	85.2	84%
CONTOUR	$ 77.9	$ 96.8	24%	39.6	39.6	0%
Deep Space 1	$ 88.2	$ 99.3	13%	33.5	37.3	11%

EO-1	$ 73.8	$ 158.1	114%	38.5	57.5	49%
ERAST	$ 181.3	$ 173.0	-5%			
ESSP (VCL/GRACE)	$ 145.1	$ 171.8	18%			
FAST	$ 36.1	$ 42.9	19%	74.6	88.5	19%
FUSE	$ 108.0	$ 120.4	11%	44.0	51.9	18%
GALEX	$ 45.6	$ 72.0	58%	39.6	59.7	51%
Genesis	$ 137.5	$ 162.9	18%	38.6	45.9	19%
GGS (Wind/Polar)	$ 334.0	$ 458.1	37%			
HESSI	$ 32.0	$ 46.6	46%	31.4	50.9	62%
HETE-II	$ 8.4	$ 14.4	71%	36.5	49.0	34%
ICESat	$ 121.3	$ 177.0	46%	60.9	73.4	21%
IMAGE	$ 83.6	$ 89.2	7%	46.7	48.5	4%
LTMCC	$ 87.1	$ 76.9	-12%			
Lunar Prospector	$ 56.2	$ 56.6	1%	30.5	33.7	10%
MAP	$ 88.3	$ 94.2	7%	55.8	63.9	15%
Mars Odyssey	$ 267.2	$ 366.1	37%			
Mars Pathfinder	$ 174.2	$ 174.2	0%	37.5	37.6	0%
MCO	$ 183.6	$ 189.7	3%	38.6	38.9	1%
MEDS	$ 201.7	$ 210.1	4%			
MER	$ 533.1	$ 618.9	16%	34.1	34.5	1%
MGS	$ 140.2	$ 130.7	-7%	33.7	33.7	0%
NEAR	$ 150.1	$ 124.9	-17%	29.0	29.0	0%
OMV	$ 466.0	$ 766.5	64%			
SIRTF	$ 472.7	$ 644.2	36%	67.0	88.0	31%
SLWT	$ 172.5	$ 129.0	-25%			
SOFIA	$ 239.4	$ 373.0	56%			
SORCE	$ 68.0	$ 74.5	10%	48.0	54.9	14%
STARDUST	$ 117.8	$ 116.8	-1%	38.8	38.8	0%
TDRSS replen	$ 899.8	$ 803.1	-11%			
Terra	$ 1,078.7	$ 1,226.5	14%			
TIMED	$ 129.2	$ 162.3	26%	42.6	67.2	58%
Triana	$ 75.0	$ 96.9	29%			
TRMM	$ 253.1	$ 246.0	-3%	83.2	87.1	5%
X-33	$ 1,075.2	$ 1,218.9	13%			
X-34	$ 70.0	$ 205.2	193%			
X-38	$ 80.0	$ 94.0	18%			
X-43	$ 167.0	$ 227.0	36%			
XTE	$ 109.2	$ 194.2	78%			
SWAS	$ 47.3	$ 78.9	67%	73.0	116.4	59%
Landsat-7	$ 387.1	$ 449.1	16%	75.1	79.6	6%
Aqua	$ 946.7	$ 884.1	-7%	89.3	106.6	19%
Gravity Probe B	$ 351.0	$ 499.9	42%	85.2	128.5	51%
TRACE	$ 35.6	$ 40.3	13%	48.2	52.3	8%
WIRE	$ 39.7	$ 50.7	28%	43.6	50.8	17%
ICESAT	$ 121.3	$ 177.0	46%	60.9	73.4	21%
GRACE	$ 79.3	$ 88.4	11%	50.7	60.4	19%
Deep Impact	$ 194.1	$ 252.0	30%	51.2	63.3	24%
Messenger	$ 191.5	$ 288.7	51%	51.7	56.9	10%
SWIFT	$ 102.4	$ 164.9	61%	44.6	59.5	33%
STEREO	$ 267.6	$ 351.3	31%	55.8	64.6	16%

MRO	$ 334.4	$ 359.0	7%	46.7	47.0	1%
THEMIS	$ 102.3	$ 107.6	5%	42.2	43.5	3%
Tether	$ 28.3	$ 115.7	309%			
HST-OTA	$ 115.8	$ 561.7	385%			
OMV	$ 236.0	$ 523.1	122%			
ET	$ 349.6	$ 961.7	175%			
SSME	$ 1,267.1	$ 3,051.5	141%			
SRM	$ 338.6	$ 706.7	109%			
AIM	$ 61.1	$ 81.2	33%	43.8	49.9	14%
Deep Impact	$ 194.1	$ 252.0	30%	51.2	63.3	24%
ST-5	$ 26.3	$ 24.7	-6%	56.0	78.0	39%

Christian's Sources
Shaffer
Rutkowski
REDSTAR 121-4955 <-FY92$
Freaner-Bitten

Additional Cost & Schedule Growth Data Set #2

The following cost and schedule growth data was compiled by Debra L. Emmons, Robert E. Bitten, Claude W. Freaner, for their paper titled "Using Historical NASA Cost and Schedule Growth to Set Future Program and Project Reserve Guidelines" and is included for additional reference information. This data was not obtained until after paper was completed, so none was used in our analysis.

Mission	Initial Cost Estimate	Final Cost	% Cost Growth	Initial Schedule Months	Final Schedule Months	% Schedule Growth
NEAR	$ 150.1	$ 124.9	-16.8%	29.0	29.0	0.0%
Lunar Prospector	$ 56.2	$ 56.6	0.7%	30.5	33.7	10.7%
Genesis	$ 137.5	$ 162.9	18.5%	38.6	45.9	18.9%
Messenger	$ 191.5	$ 288.7	50.8%	51.7	56.9	10.0%
Mars Pathfinder	$ 174.2	$ 174.2	0.0%	37.5	37.6	0.3%
Stardust	$ 127.4	$ 126.4	-0.8%	38.8	38.8	0.0%
Contour	$ 77.9	$ 96.8	24.3%	39.6	39.6	0.2%
Deep Impact	$ 194.1	$ 252.0	29.8%	51.2	63.3	23.6%
MGS	$ 140.2	$ 130.7	-6.8%	33.7	33.7	0.0%
MCO/MPL	$ 183.6	$ 189.7	3.3%	38.6	38.9	0.9%
MER	$ 533.1	$ 618.9	16.1%	34.1	34.5	1.1%
MRO	$ 394.4	$ 450.0	14.1%	46.7	46.7	0.0%
FAST	$ 36.1	$ 42.9	18.9%	74.6	88.5	18.6%
SWAS	$ 47.3	$ 78.9	66.8%	73.0	116.4	59.4%
TRACE	$ 35.6	$ 40.3	13.2%	48.2	52.3	8.4%
WIRE	$ 39.7	$ 50.7	27.7%	43.6	50.8	16.5%
ACE	$ 152.0	$ 119.4	-21.4%	61.7	61.7	0.0%
FUSE	$ 131.3	$ 143.7	9.4%	44.0	51.9	17.8%
IMAGE	$ 83.6	$ 89.2	6.7%	46.7	48.5	3.9%
MAP	$ 88.3	$ 94.2	6.7%	55.8	63.9	14.4%
HESSI	$ 32.0	$ 46.6	45.6%	31.4	50.9	61.9%
GALEX	$ 45.6	$ 72.0	57.9%	39.6	59.7	50.8%
SWIFT	$ 102.4	$ 164.9	61.0%	44.6	59.5	33.3%

GRACE	$ 79.3	$ 88.4	11.5%	50.7	60.4	19.0%
CLOUDSAT	$ 80.2	$ 144.0	79.6%	46.2	85.2	84.2%
CALIPSO	$ 68.2	$ 170.3	149.7%	51.0	89.5	75.4%
DS-1	$ 88.2	$99.3	12.6%	33.5	37.3	11.5%
EO-1	$ 73.8	$ 158.1	114.2%	38.5	57.5	49.3%
SIRTF	$ 472.7	$ 644.2	36.3%	67.0	88.0	31.5%
STEREO	$ 267.6	$ 351.3	31.3%	55.8	64.6	15.6%
EOS-Aqua	$ 946.7	$ 884.1	-6.6%	89.3	106.6	19.4%
EOS-Aura	$ 660.5	$ 713.8	8.1%	113.6	133.4	17.4%
Landsat-7	$ 387.1	$ 449.1	16.0%	75.1	79.6	6.0%
TRMM	$ 253.1	$ 246.0	-2.8%	83.2	87.1	4.7%
TIMED	$ 129.2	$ 162.3	25.6%	43.6	67.2	53.9%
Gravity Probe B	$ 351.0	$ 499.9	42.4%	85.2	127.8	50.0%
THEMIS	$ 102.3	$ 107.6	5.2%	42.2	43.5	3.1%
HETE-II	$8.4	$14.4	71.4%	36.5	49.0	34.2%
SORCE	$ 68.0	$74.5	9.6%	48.0	54.9	14.4%
ICESAT	$ 121.3	$ 177.0	45.9%	60.9	73.4	20.6%

Additional Cost & Schedule Growth Data Set #3

The following cost and schedule growth data was compiled by from Kelli McCoy's 2008 NASA Cost Symposium paper. and is included for additional reference information. This data was not used in our analysis.

Theme	Mission	Original Duration	Final Duration	Slip %	SRR year	Launch
Heliophysics	ACE	57	57	0%	1992	1997
Earth Sci	ACRIMSAT	43	45	5%	1996	1999
	ACTS	48	98	104%	1985	1993
Heliophysics	AIM	40	47	18%	2003	2007
Earth Sci	Aquarius	50	69	38%	2004	2010
Earth Sci	Aura (Chem-1) or Chemistry	41	60	46%	1999	2004
Earth Sci	CALIPSO	38	75	97%	2000	2006
Planetary	Cassini	92	110	20%	1988	1997
ASO	Chandra	69	79	14%	1992	1999
ASO	CHIPSAT	30	40	33%	1999	2003
Heliophysics	CINDI	41	95	132%	2000	2008
Earth Sci	CloudSat	36	74	106%	2000	2006
	Cluster	75	81	8%	1989	1996
Heliophysics	Cluster-2 (Salsa & Samba)	75	130	73%	1989	2000
ASO	COBE	68	88	29%	1982	1989
Planetary	CONTOUR	38	38	0%	1999	2002
Earth Sci	CRRES	38	86	126%	1983	1990
	DART	31	43	39%	2001	2005
Planetary	DAWN	37	53	43%	2003	2007
Planetary	Deep Impact	44	56	27%	2000	2005
Planetary	Deep Space 1	40	43	8%	1995	1998
Earth Sci	EO-1	33	53	61%	1996	2000
ASO	EUVE	48	58	21%	1987	1992
Heliophysics	FAST	44	67	52%	1991	1996
ASO	FUSE	100	107	7%	1990	1999

ASO	GALEX	37	56	51%	1998	2003
Planetary	Galileo Orbiter	43	136	216%	1978	1989
Planetary	Galileo Probe	43	136	216%	1978	1989
Earth Sci	Genesis	34	41	21%	1998	2001
Heliophysics	Geotail	58	58	0%	1987	1992
ASO	GLAST	66	93	41%	2000	2008
Earth Sci	Glory	88	106	20%	2000	2009
Earth Sci	GOES I	45	102	127%	1985	1994
Earth Sci	GOES J	53	115	117%	1985	1995
Earth Sci	GOES K	57	138	142%	1985	1997
Earth Sci	GOES L	65	175	169%	1985	2000
Earth Sci	GOES M	74	189	155%	1985	2001
Earth Sci	GOES N	41	96	134%	1998	2006
Earth Sci	GOES O	47	126	168%	1998	2008
Earth Sci	GOES P	83	137	65%	1998	2009
ASO	GPB (Gravity Probe B)	74	126	70%	1993	2004
Earth Sci	GPM	113	149	32%	2002	2014
Earth Sci	GRACE	42	51	21%	1997	2002
ASO	GRO - (Compton Gamma Ray Ob)	62	127	105%	1980	1991
ASO	HST OTA	70	146	109%	1978	1990
ASO	HST SI	64	140	119%	1978	1990
ASO	HST SSM	70	146	109%	1978	1990
Heliophysics	IBEX	33	36	9%	2005	2008
Earth Sci	ICESAT	43	55	28%	1998	2003
Heliophysics	IMAGE	42	44	5%	1996	2000
Earth Sci	JASON 1	70	94	34%	1994	2001
Planetary	JUNO	51	51	0%	2007	2011
ASO	JWST	92	114	24%	2003	2013
ASO	Kepler	48	64	33%	2003	2009
Earth Sci	Landsat 7	55	66	20%	1993	1999
	LCROSS	27	28	4%	2006	2008
Earth Sci	LDCM	38	38	0%	2008	2011
ASO	LISA	55	120	118%	2007	2017
Planetary	MAGELLAN	61	73	20%	1983	1989
ASO	MAP or WMAP	54	61	13%	1996	2001
Planetary	MARS Climate Orbiter - MCO	45	45	0%	1995	1998
Planetary	Mars Observer	100	126	26%	1982	1992
Planetary	Mars Odyssey 01	33	34	3%	1998	2001
Planetary	Mars Pathfinder	49	49	0%	1992	1996
Planetary	Mars Polar Lander (MPL)	45	46	2%	1995	1999
Planetary	MER-A or MER03 - SPIRIT)	35	35	0%	2000	2003
Planetary	MER-B (Opportunity)	35	36	3%	2000	2003
Planetary	MESSENGER	46	51	11%	2000	2004
Planetary	MGS -Mars Global Surveyor	31	31	0%	1994	1996
Planetary	MMM (M3) on Chandrayaan-1	31	35	13%	2005	2008
Heliophysics	MMS	85	85	0%	2007	2014
Planetary	MRO	43	43	0%	2002	2005
Planetary	MSL	45	45	0%	2005	2009

Planetary	New Horizons	44	44	0%	2002	2006
Earth Sci	NPP	79	123	56%	2000	2010
Earth Sci	OCO	52	67	29%	2003	2009
Earth Sci	OSTM	72	74	3%	2002	2008
Planetary	Phoenix/Scout 7	41	41	0%	2004	2007
Earth Sci	QUICKSCAT	14	21	50%	1997	1999
Heliophysics	RHESSI was HESSI	31	53	71%	1997	2002
Heliophysics	Sampex	37	38	3%	1989	1992
Heliophysics	SDO	52	68	31%	2003	2008
Heliophysics	SET-1	39	89	128%	2003	2011
ASO	SIM	73	191	162%	2003	2019
ASO	SIRTF or Spitzer	55	78	42%	1997	2003
Heliophysics	SNOE	23	35	52%	1995	1998
Heliophysics	SoHO	63	72	14%	1989	1995
Heliophysics	Solar B or HINODE	58	83	43%	1999	2006
Earth Sci	SORCE	32	44	38%	1999	2003
Heliophysics	ST-5	48	70	46%	2000	2006
ASO	ST-7	47	89	89%	2002	2009
Heliophysics	ST-8	37	32	-14%	2006	2008
Planetary	STARDUST	35	35	0%	1996	1999
Heliophysics	STEREO	49	77	57%	2000	2006
ASO	SWAS	57	102	79%	1990	1998
ASO	SWIFT	41	54	32%	2000	2004
	TDRS-H	41	52	27%	1996	2000
	TDRS-I	47	73	55%	1996	2002
	TDRS-J	53	82	55%	1996	2002
Earth Sci	Terriers	31	56	81%	1994	1999
Heliophysics	THEMIS	37	43	16%	2003	2007
Heliophysics	TIMED	63	86	37%	1994	2001
Earth Sci	Topex/Poseidon	105	151	44%	1980	1992
Heliophysics	TRACE	26	32	23%	1995	1998
Earth Sci	TRMM	72	81	13%	1991	1997
Earth Sci	UARS	73	95	30%	1983	1991
Heliophysics	Ulysses	40	132	230%	1979	1990
Heliophysics	WIND	48	71	48%	1988	1994
ASO	WIRE	52	57	10%	1994	1999
ASO	WISE	42	59	40%	2004	2009
ASO	XTE or RXTE	53	48	-9%	1991	1995

Compiled Cost & Schedule Growth Data Set

The following cost and schedule growth data is a combined list of the earliest available and latest available data for 188 projects. Some of the names are the same, but supplementary data led us to believe they were separate projects. In fact they may not be, renaming, rebaselineing, and whitewashing make this type of data mining and analysis very difficult. All data comes from reputable sources, however errors probably exist, and some projects are still in development, so values may continue to evolve.

It shows an average cost growth of 98.2%, a median cost growth of 53.3%, and average schedule growth of 56.8%, and a median schedule growth of 34.9%. This is abysmal to say the least and exceeds many of the recently published papers values. **This data was not obtained until after paper was completed, so none was used in our analysis, but is included in an attempt to aide future researchers.**

Theme	Name	Initial	Latest Available	Percent change	Initial Schedule	Final Schedule	Percent Change
Heliophysics	ACE	$ 141.10	$ 108.50	-23.1%	57	62	8.2%
Earth Sci	ACRIMSAT				43	45	4.7%
	ACTS	$ 354.00	$ 656.00	85.3%	48	98	104.2%
	AFE	$ 159.00	$ 387.00	143.4%	Canceled		
	AHMS	$ 55.00	$ 55.00	0.0%			
Heliophysics	AIM	$ 61.10	$ 81.20	32.9%	40	50	24.7%
	Apollo	$7,000.00	$ 25,400.00	262.9%			
Earth Sci	Aqua	$ 762.50	$ 1,006.00	31.9%	89	107	19.4%
Earth Sci	Aquarius				50	69	38.0%
Manned	ASRM	$1,506.70	$ 3,251.80	115.8%	Canceled		
Manned	ATP	$ 372.00	$ 1,053.00	183.1%			
	AURA	$ 524.00	$ 763.00	45.6%	114	133	17.4%
Earth Sci	Aura (Chem-1) or Chemistry				41	60	46.3%
	AXAF	$1,410.00	$ 6,022.00	327.1%			
Heliophysics	BARREL					54	
Earth Sci	CALIPSO	$ 68.20	$ 170.3	149.7%	38	89	135.4%
Planetary	Cassini	$1,436.40	$ 1,375.90	-4.2%	92	110	19.6%
Manned	CAU	$ 442.00	$ 454.00	2.7%			
ASO	Chandra				69	79	14.5%
ASO	CHIPSAT				30	40	33.3%
Heliophysics	CINDI				41	95	131.7%
Manned	CLCS	$ 175.00	$ 399.00	128.0%	Canceled		
	Clementine					19	
Earth Sci	CloudSat	$ 80.20	$ 144.00	79.6%	36	85	136.6%
	Cluster				75	81	8.0%
Heliophysics	Cluster-2 (Rumba & Tengo)					131	
Heliophysics	Cluster-2 (Salsa & Samba)				75	130	73.3%
ASO	COBE				68	88	29.4%
Planetary	CONTOUR	$ 69.10	$ 96.80	40.1%	38	40	4.2%
	Cosmic Background Explorer	$ 97.50	$ 159.70	63.8%			
	COSTR	$ 221.00	$ 673.00	204.5%			
	CRAF	$3,593.00	$ 3,351.00	-6.7%	Canceled/ Development		
Earth Sci	CRRES				38	86	126.3%
	DART				31	43	38.7%
Planetary	DAWN	202.8	287.1	41.6%	37	53	43.2%
	Deep Impact	$ 194.10	$ 252.00	29.8%	44	63	43.9%
Planetary	Deep Space 1	$ 73.30	$ 99.30	35.5%	33	43	28.5%
	DSMS					36	
Earth Sci	EO-1	$ 72.00	$ 158.1	119.6%	33	58	74.2%
	ERAST	$ 181.30	$ 173.00	-4.6%			
	ESSP	$ 145.10	$ 171.80	18.4%			

	ET	$ 349.60	$ 961.70	175.1%			
ASO	EUVE	$ 107.40	$ 322.00	199.8%	48	58	20.8%
Heliophysics	FAST	$ 32.50	$ 42.90	32.0%	44	89	101.1%
	FCF	$ 118.90	$ 114.10	-4.0%			
	FTS	$ 317.00	$ 485.00	53.0%	Canceled		
	FTS	$ 317.00	$ 453.20	43.0%			
ASO	FUSE	$ 85.90	$ 143.7	67.3%	44	107	143.2%
ASO	GALEX	$ 41.10	$ 87.10	111.9%	37	60	61.4%
Planetary	Galileo Orbiter				43	136	216.3%
Planetary	Galileo Probe				43	136	216.3%
Planetary	Galilleo	$ 276.20	$ 1,639.00	493.4%			
Earth Sci	Genesis	$ 126.10	$ 162.90	29.2%	34	46	34.9%
Heliophysics	Geospace RBSP					44	
Heliophysics	Geotail				58	58	0.0%
	GGS	$ 334.00	$ 649.00	94.3%			
ASO	GLAST				66	93	40.9%
Earth Sci	Glory				88	106	20.5%
	GOES	$ 554.60	$ 1,241.00	123.8%			
	GOES	$ 691.00	$ 1,787.00	158.6%			
Earth Sci	GOES I				45	102	126.7%
Earth Sci	GOES J				53	115	117.0%
Earth Sci	GOES K				57	138	142.1%
Earth Sci	GOES L				65	175	169.2%
Earth Sci	GOES M				74	189	155.4%
Earth Sci	GOES N				41	96	134.1%
Earth Sci	GOES O				47	126	168.1%
Earth Sci	GOES P				83	137	65.1%
ASO	GP-B	$ 351.00	$ 709.30	102.1%	74	128	72.7%
Earth Sci	GPM				113	149	31.9%
Earth Sci	GRACE	$ 79.30	$ 88.40	11.5%	42	60	43.8%
Planetary	GRAIL				8	44	450.0%
	GRO	$ 183.80	$ 677.00	268.3%			
ASO	GRO - (Compton Gamma Ray Ob)				62	127	104.8%
	HESSI	$ 32.00	$ 63.50	98.4%	31	51	61.9%
ASO	HETE	$ 8.40	$ 23.50	179.8%	37	49	34.2%
	HST	$ 435.00	$ 1,682.00	286.7%			
ASO	HST SI				64	140	118.8%
ASO	HST SSM				70	146	108.6%
ASO	HST-OTA	$ 115.80	$ 561.70	385.1%	70	146	108.6%
Heliophysics	IBEX				33	36	9.1%
Earth Sci	ICESAT	$ 121.30	$ 177.00	45.9%	43	73	70.7%
Heliophysics	IMAGE	$ 83.60	$ 89.20	6.7%	42	49	15.5%
ASO	INTEGRAL	$ 8.20	$ 11.90	45.1%			
Earth Sci	JASON	$ 77.50	$ 87.80	13.3%	70	94	34.3%
Planetary	JUNO				51	51	0.0%
ASO	JWST	$ 900.00	$ 4,900.00	444.4%	92	114	23.9%
ASO	Kepler				48	64	33.3%
	LADEE					38	
Earth Sci	Landsat 7	$ 387.10	$ 508.80	31.4%	55	80	44.7%
	LANDSAT-D	$ 260.10	$ 538.00	106.8%			

	LCROSS				27	28	3.7%
Earth Sci	LDCM				38	38	0.0%
ASO	LISA				55	120	118.2%
SSE	LRO				38	39	2.6%
Manned	LTMCC	$ 87.10	$ 76.90	-11.7%			
Planetary	Lunar	$ 56.20	$ 56.60	0.7%	30	34	10.7%
Planetary	MAGELLAN	$ 322.80	$ 856.00	165.2%	61	73	19.7%
	MAP	$ 88.30	$ 94.20	6.7%	56	64	14.4%
ASO	MAP or WMAP				54	61	13.0%
Planetary	MPL				45	46	2.2%
Planetary	MCO	$ 183.60	$ 189.70	3.3%	39	45	16.6%
	MEDS	$ 201.70	$ 210.10	4.2%			
Planetary	MER	$ 499.40	$ 767.00	53.6%	34	34	1.1%
Planetary	MER-A or MER03 - SPIRIT)				35	35	0.0%
Planetary	MER-B (Opportunity)				35	36	2.9%
Manned	MERCURY	$ 196.92	$ 384.00	95.0%			
Planetary	Messenger	$ 191.50	$ 288.70	50.8%	46	57	23.7%
Planetary	MGS	$ 140.20	$ 130.70	-6.8%	31	34	8.7%
Planetary	MMM				31	35	12.9%
Heliophysics	MMS				85	85	0.0%
Planetary	MRO	$ 334.40	$ 450.0	34.6%	43	47	9.4%
Planetary	MSL	$ 650.00	$ 2,300.00	253.8%	45		
Planetary	NEAR	$ 150.00	$ 124.90	-16.7%	29	29	0.0%
Planetary	New Horizons				44	44	0.0%
	NMP	$ 111.70	$ 176.40	57.9%			
Earth Sci	NPP				79	123	55.7%
	NSCAT	$ 100.40	$ 255.00	154.0%			
ASO	NuStar					37	
Planetary	Mars Observer	$ 306.00	$ 994.00	224.8%	100	126	26.0%
Earth Sci	OCO				52	67	28.8%
Planetary	ODYSSEY	$ 267.20	$ 366.10	37.0%	33	34	3.0%
Manned	OMV	$ 236.00	$ 814.00	244.9%	Canceled		
Earth Sci	OSTM				72	74	2.8%
Planetary	PATHFINDER	$ 150.00	$ 174.20	16.1%	38	49	30.6%
Planetary	Phoenix/Scout 7				41	41	0.0%
Earth Sci	QUICKSCAT				14	21	50.0%
Heliophysics	RHESSI was HESSI				31	53	71.0%
	Rosetta	$ 28.40	$ 40.10	41.2%			
Heliophysics	Sampex				37	38	2.7%
Heliophysics	SDO				52	68	30.8%
	SeaWinds	$ 130.20	$ 148.80	14.3%			
Heliophysics	SET-1				39	89	128.2%
ASO	SIM				73	191	161.6%
Manned	SLWT	$ 172.50	$ 129.00	-25.2%			
Heliophysics	SNOE				23	35	52.2%
ASO	SOFIA	$ 234.80	$ 840.00	257.8%	48	207	331.3%
Heliophysics	SoHO				63	72	14.3%
	Solar Orbiter					84	
Heliophysics	Solar B or HINODE	$ 99.30	$ 80.40	-19.0%	58	83	43.1%
Earth Sci	SORCE	$ 68.00	$ 74.50	9.6%	32	55	71.6%

Manned	Shuttle	$5,800.00	$ 17,789.00	206.7%			
Manned	Shuttle – With Reserves	$6,960.00	$ 17,789.00	155.6%			
Manned	Shuttle – Endeavor	$2,100.00	$ 1,800.00	-14.3%			
Manned	SSME	$1,267.10	$ 3,051.50	140.8%			
Manned	Space Station	$9,446.24	$ 45,000.00	376.4%			
ASO	SIRTF or Spitzer	$ 472.00	$ 712.00	50.8%	55	88	60.1%
Manned	SRM	$ 338.60	$ 706.70	108.7%			
Manned	SS	$ 25.12	$ 28.94	15.2%			
Heliophysics	ST-5	$ 26.30	48.7	85.2%	48	78	62.5%
Heliophysics	ST-6					56	
ASO	ST-7				47	89	89.4%
Heliophysics	ST-8				37	32	-13.5%
CT	ST-9				42	42	0.0%
Planetary	STARDUST	$ 117.80	$ 126.4	7.3%	35	39	10.9%
	STDRS	$ 341.40	$ 532.00	55.8%			
Heliophysics	STEREO	$ 150.00	$ 550.00	266.7%	49	77	57.1%
ASO	SWAS	$ 47.30	$ 78.90	66.8%	57	116	104.2%
	SWASTR	$ 140.00	$ 212.70	51.9%			
ASO	SWIFT	$ 102.40	$ 164.90	61.0%	41	60	45.1%
	TDRS7	$ 269.00	$ 532.00	97.8%			
	TDRS-H				41	52	26.8%
	TDRS-I				47	73	55.3%
	TDRS-J				53	82	54.7%
	TE	$ 321.30	$ 401.50	25.0%			
Earth Sci	TERRA	$1,078.70	$ 1,393.20	29.2%			
Earth Sci	Terriers				31	56	80.6%
	Tether	$ 28.30	$ 115.70	308.8%			
Heliophysics	THEMIS	$ 102.30	$ 107.60	5.2%	37	44	17.6%
Heliophysics	TIMED	$ 129.20	$ 176.20	36.4%	44	86	97.1%
	TOPEX	$ 438.00	$ 520.00	18.7%			
Earth Sci	Topex/Poseidon				105	151	43.8%
Heliophysics	TRACE	$ 35.60	$ 40.30	13.2%	26	52	101.2%
	TRDS	$ 899.80	$ 803.10	-10.7%			
	Triana Spacecraft	$ 75.00	$ 96.90	29.2%			
Earth Sci	TRMM	$ 218.80	$ 468.00	113.9%	72	87	21.0%
	TSS	$ 40.70	$ 263.00	546.2%			
Earth Sci	UARS	$ 575.30	$ 790.00	37.3%	73	95	30.1%
Heliophysics	Ulysses	$ 196.00	$ 460.00	134.7%	40	132	230.0%
Heliophysics	WIND				48	71	47.9%
ASO	WIRE	$ 39.70	$ 50.70	27.7%	44	57	30.7%
ASO	WISE				42	59	40.5%
Manned	X-30	$3,100.00	$ 10,000.00	222.6%	Canceled		
Manned	X-33 - Canceled	$1,075.20	$ 1,789.70	66.5%	Canceled		
Manned	X-34 - Canceled	$ 70.00	$ 378.00	440.0%	Canceled		
Manned	X-38 - Canceled	$ 500.00	$ 1,500.00	200.0%	Canceled		
Manned	X-43 Hyper-X Canceled	$ 167.00	$ 227.00	35.9%	Canceled		
ASO	XTE or RXTE	$ 100.00	$ 373.00	273.0%	53	48	-9.4%