But What Will It Cost?
The Evolution of NASA Cost Estimating

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Within two years of being chartered in 1958 as an independent agency to conduct civilian pursuits in aeronautics and space, NASA absorbed either wholly or partially the people, facilities and equipment of several existing organizations. These included, most notably, the laboratories of the National Advisory Committee for Aeronautics (NACA) at Langley Research Center in Virginia, Ames Research Center in California, and Lewis Research Center in Ohio; the Army Ballistic Missile Agency (ABMA) at Redstone Arsenal Alabama, for which the team of Wernher von Braun worked; and the Department of Defense Advanced Research Projects Agency (ARPA) and their ongoing work on big boosters.[1]

These were especially valuable resources to jump start the new agency in light of the shocking success of the Soviet space probe Sputnik in the autumn of the previous year and the corresponding pressure from an impatient American public to produce some response. Along with these inheritances, there came some existing systems engineering and management practices, including project cost estimating methodologies. This paper will briefly trace the origins of those methods and how they evolved within the Agency over the past three decades.

The Origins of the Art

World War II had caused a demand for military aircraft in numbers and in models that far exceeded anything the aircraft industry had even imagined before. While there had been some rudimentary work from time to time[2] to develop parametric techniques for predicting cost, there was certainly no widespread use of any kind of cost estimating beyond a laborious build-up of work hours and materials. A type of statistical estimating had been suggested in 1936 by T. P. Wright in the Journal of Aeronautical Science.[3] Wright provided equations which could be used to predict the cost of airplanes over long production runs, a theory which came to be called the learning curve. By the time the demand for airplanes had exploded in the early years of World War II, industrial engineers were happily using Wright's learning curve to predict the unit cost of airplanes when thousands were to be built (and it's still used today though the quantities involved are more likely to be hundreds instead of thousands).

In the late 1940s the Department of Defense and especially the U.S. Air Force were studying multiple scenarios of how the country should proceed into the new age of jet aircraft, missiles and rockets. The Air Force saw a need for a stable, highly skilled cadre of analysts to help with the evaluation of these alternatives and established the Rand Corporation in Santa Monica, California, as a civilian "think tank" to which it could turn for independent analysis. Rand's work represents some of the earliest and most systematic published studies of cost estimating in the airplane industry.

Among the first assignments given to Rand were studies of first and second generation ICBMs, jet fighters and jet bombers. While the learning curve was still very useful for predicting the behavior of recurring cost, there were still no techniques other than detailed work-hour and material estimating for projecting what the first unit cost might be (a key input to the learning curve equation). Worse still, no quick methods were available for estimating the nonrecurring cost associated with research, development, testing and evaluation (RDT&E). In the defense business in the early to mid-1950s, RDT&E had sud-

Center (GSFC) as another development center. GSFC was assigned responsibility for Earth orbital science satellites and soon had on the drawing board a number of spacecraft for which cost estimates were needed. The Orbiting Astronomical Observatory, the Orbiting Geophysical Observatory and the Nimbus programs were all started early in the 1959-60 period and, like most other projects in the Agency at the time, experienced significant cost growth. GSFC organized a cost group to improve the estimates, first under Bill Mecca, and later managed by Paul Villone. In 1967 Werner Gruhl joined the office where he implemented numerous improvements to the GSFC methods. In later years he joined the Comptroller's office at NASA Headquarters as NASA's chief estimator.

Among the improvements creditable to GSFC during the late 1960s and early 1970s were: 1) spacecraft cost models that were sensitive to the number of complete and partial test units and the quality of the test units; 2) models devoted to estimating spacecraft instruments; and 3) the expansion of the database through the practice of contracting with the prime contractor to document the cost in accordance with NASA standard parametric work breakdown structures (WBS) and approaches.[14]

By 1965 most of NASA's contractors were revising their traditional approach to cost estimating, which had relied upon the design engineers to estimate costs, replacing it with an approach that created a new job position–that of trained parametric cost estimators whose job it was to obtain data from the design engineers and translate this information into cost estimates using established procedures.[15] At essentially the same time, cost estimating was being elevated to a separate discipline within NASA Headquarters and at the NASA field centers. This trend toward cost estimating as a specialization was caused by several factors. First, it was unrealistic to expect that the design engineers had the interest, skills and resources necessary to put together good cost estimates. Second, during the preceding three years, the pace of the Gemini and Apollo programs had so accelerated that the Requests for Proposals issued by the government typically gave the contractors only 30 days to respond–only parametricians had any hope of preparing a response in this short amount of time. Third, because of growing cost overrun problems, NASA cost reviews had increased notably and the reviewers were looking for costs with some basis in historical actuals–essentially a prescription for parametric cost estimating.

At both MSC and MSFC, the cost estimating function was placed in an advanced mission planning organization. At MSC, it was embodied within Max Faget's Engineering and Development Directorate,[16] and at MSFC it was within the Future Projects Office headed by Herman Koelle.[17] Faget, an incredibly gifted engineer, had already left his imprint on the Mercury, Gemini and Apollo programs, and was a strong believer in an advanced planning function with strong cost analysis. Koelle, a German engineer who, though not a member of the original team, had later joined von Braun, was also extremely competent and very interested in cost. Koelle had, in fact, along with his deputy William G. Huber, assembled the very first NASA cost methodology in 1960, published first in an inhouse report[18] and then in 1961 as a handbook that Koelle edited for budding space engineers.[19]

Out of the eye of the Apollo hurricane for the moment, both the MSFC and the MSC cost personnel now sought to regroup and attempt to make improvements in capability. In 1964 MSFC contracted with Lockheed and General Dynamics[20] to develop a more rigorous and sophisticated cost modeling capability for launch vehicle life cycle cost modeling. This effort was led by Terry Sharpe of MSFC's Future Projects Office. Sharpe, an Operations Research specialist interested in improving the rigor of the estimating process, led the MSFC estimating group as they managed the contractor's development of the model and then brought it in-house and installed the model on MSFC mainframe computers.

Through about 1965 the only computational support in use by NASA estimators was the Freidan mechanical calculator. By the mid-1960s mainframe time was generally available, and by the late 1960s the miracle of hand-held, four-function electronic calculators could be had for $400 apiece–one per office was the general rule. Throughout the early 1970s the hand-held calculator ruled supreme. By the middle 1970s IMSAI 8080 8-bit microcomputers made their appearance. Finally, by the late 1970s the age of the personal computer had dawned. Estimators, probably more than any other breed, immediately saw the genius of the Apple II, the IBM PC and the amazing spreadsheets: Visicalc, Supercalc and Lotus 1-2-3. Civilization had begun.

The resulting capability was extremely ambitious for the time, taking into account a multitude of variables affecting launch vehicle life cycle cost. The model received significant notoriety, and once the CIA inquired if the MSFC estimators might make a series of runs on a set of Soviet launch vehicles. Busy with their own work, the estimators demurred. The CIA pressed the case to a higher level manager, a retired Air Force colonel. Suddenly the MSFC estimators discovered that they had been mistaken about priorities. The runs were made and the CIA analysts went away happy.

Later in 1964 after a reorganization, management of the MSFC cost office was taken over by Bill Rutledge who went on to lead the MSFC cost group for more than 20 years. Rutledge steadily built the MSFC cost group's strength until it was generally recognized in the late 1960s as the strongest cost organization within the Agency. One of Rutledge's more outstanding innovations was the acquisition of a contractor to expand and maintain an Agency-wide cost database and develop new models. The REDSTAR (Resource Data Storage and Retrieval) database was begun in 1971 and is still operational today, supporting Agency-wide cost activities. The contract was originally awarded to PRC and, under Rutledge's management, developed numerous models throughout the 1970s and 1980s.

MSFC also established a grassroots cost estimating organization within the MSFC Science and Engineering laboratories. This group was managed by Rod Stewart for a number of years. After his retirement from NASA, Stewart, along with his wife Annie, authored an outstanding series of cost estimating books.[21] In 1966, MSC, working in parallel to the MSFC activities, contracted with General Dynamics[22] and Rand[23] to improve their spacecraft estimating capability. The MSC cost group also significantly improved their capabilities during this period under the very able management of Humboldt Mandell, who was later to play a leading role in the Shuttle, Space Station and Space Exploration Initiative cost estimating activities.

By 1967 both the MSC and MSFC cost estimating organizations were beginning to obtain the first historical data from the flight hardware of the Apollo program. This included cost data on the Saturn IB and Saturn V launch vehicles by stage, and on the Command and Service Module (CSM) and the Lunar Excursion Module (LEM) at the major subsystem level. Fairly shallow data by today's standards, it was considered somewhat of a windfall to the NASA estimators who had been struggling along with two- and three-data point CERs at the total system level. The Project Offices at MSC and MSFC compiled the data between 1967 and 1969 and documented the results in the unpublished "Apollo Cost Study" (preserved today in the JSC and MSFC cost group databases). Eventually this was supplemented by paying the CSM prime contractor to retroactively compile the data in a WBS format useful for parametric cost estimating.[24] Despite these improvements, one Rand report in 1967 laments that the number of data points for cost estimating was "depressingly low. . . only one

1972 under contract to the winning prime contractor, North American–though this did not end the debate over the worthiness of the project.[33] All through 1973 NASA was very involved in extensive "capture/cost" analyses to produce data to answer Congressional, GAO and OMB inquiries about the Shuttle's economic forecasts. These analyses were NASA inhouse extensions of the work done by Mathematica, Lockheed and Aerospace. The studies consumed most of the resources of the MSFC and JSC cost groups as well as Headquarters program office personnel. They compared the discounted life cycle costs of "capturing" the NASA and DOD payloads with the Shuttle versus expendable launch vehicles. The Shuttle case was finally determined to yield a 14 percent internal rate of return and $14 billion of benefits (in 1972 dollars). This data was used as the final reinforcement of the Shuttle program commitment.

Declining Budgets, Rising Costs

Once Shuttle development was safely underway by 1974, most of the estimating talent of the Agency was turned to various kinds of scientific satellite estimating. As NASA's budget declined in the 1970s, both JPL and GSFC pioneered such economies as the use of the protoflight concept in spacecraft development. Before the 1970s NASA had prototyped most spacecraft (i.e., built one or more prototypes which served as ground test articles) before building the flight article. In the protoflight approach, only one complete spacecraft is built, which serves first as the ground test article and is then refurbished as the flight article. The protoflight approach theoretically saves money. However, these savings must be balanced against the cost of refurbishing the test article into a state ready for flight, the cost of maintaining more rigid configuration control of the ground test article to insure its eventual flight worthiness, and the increased risk of having less hardware.

Other attempts were made to lower cost without much success. Low estimates based on wishful thinking concerning off-the-shelf hardware and reduced complexity proved unrealistic, and overruns began to breed more overruns as projects underway ate up the funds other projects had expected.

Meanwhile, as NASA Headquarters continued to guide the overall programs, handle the political interfaces, foster other external relations, and integrate and defend the Agency budget, a need was seen to strengthen the Washington cost analysis function.[34] Having moved to the Headquarters Comptroller's Office from GSFC in 1970, Werner Gruhl set up an independent review capability under Mal Peterson, an assistant to the Comptroller. Gruhl aggressively championed the constant improvement of the database. Gruhl and Peterson's greatest contribution was probably their relentless urging for realistic estimates. They also initiated an annual symposium for all NASA estimators and were instrumental in helping to establish a process for Non-Advocate Reviews (NARs) for potential new projects.

The NAR was instituted as a required milestone in which each major new project had to prove its maturity to an impartial panel of technical, management and cost experts before going forward. As part of the NAR process, Peterson and Gruhl, working with a relatively small staff of one to three analysts, undertook to perform independent estimates of most of the major new candidates for authorization. Peterson largely devoted himself to penetrating reviews of the technical and programmatic readiness, the underpinning of the cost estimate. Gruhl, using mostly models of his own developed from the REDSTAR database, generated his own estimates. Together they were a formidable team and undoubtedly reduced the cost overrun problem from what it would have been without the NAR.

Another significant milestone in cost estimating that occurred during the 1970s was the emergence of the Price Model. First developed within RCA by Frank Freiman, the model began to be marketed in 1975 by RCA as a commercially available model. Freiman's brainchild was arguably the single most innovative occurrence in parametric cost estimating ever. His genius was to see hardware development and production costs as a process governed by logical interrelationships between a handful of key variables. Probably feeling his way with intuition and engineering experience more than hard data, Freiman derived a set of algorithms that modeled these relationships. The resulting model could then be calibrated to a particular organization's historical track record by essentially running the model backward to discover what settings for the variables gave the known cost. Once calibrated, the model could be run forward using a rich set of technical and programmatic factors to predict the cost of future projects. While the Price models are applicable to a wide range of industries in addition to aerospace, the model first found use in the aerospace industry. NASA encouraged Freiman to market his invention, and actually provided him with data for calibrating the model after observing its potential in Shuttle cost estimating.[35] The success of the Price model inspired the development of several other commercial cost models with application to hardware, software and the life cycle.

By the late 1970s and into the mid-1980s, the cost of NASA projects was a serious problem. It was now obvious that Shuttle payloads cost more, not less, than payloads on unmanned vehicles. Overruns were worse than ever despite better databases, better models, better estimators, and more stringent Headquarters reviews. It seemed that NASA was in danger of pricing itself right out of business.[36] At JSC, Hum Mandell, assisted by Richard Whitlock and Kelly Cyr, initiated analyses of this problem. Making imaginative use of the Price model,[37] they found that NASA's culture drives cost and that the complexity of NASA projects had been steadily increasing, an idea also advanced by Gruhl. Mandell argued persuasively to NASA management for a change in culture from the exotically expensive to the affordable. At the same time, he argued that estimates of future projects needed to account for the steadily increasing complexity of NASA projects.

Recent Years

Once the Space Shuttle had begun operations, NASA turned its attention once again to defining a Space Station. After Pre-Phase A and Phase A studies had analyzed several configurations, in 1983 NASA ran a Washington-based, multi-center team called the Configuration Development Group (CDG) to lead the Phase B studies. The CDG was led by Luther Powell, an experienced MSFC project manager. For his chief estimator, Powell chose O'Keefe Sullivan, a senior estimator from the MSFC cost group. Sullivan had just completed managing the development of the PRC Space Station Cost Model,[38] an innovative model that created a Space Station WBS by cleverly combining historical data points from parts of the Shuttle Orbiter, Apollo modules, unmanned spacecraft and other projects. This model was distributed and used by all four of the Work Package Centers and was probably the most satisfactory parametric cost model ever developed by NASA. Work Package 1 (WP-1) was at MSFC, with responsibility for the Station modules; WP-2 was at JSC with responsibility for truss structures, RCS and C&DH; WP-3 was at LeRC with responsibility for power; and WP-4 was at GSFC with responsibility for platforms. Sullivan used the model to estimate the project at between $11.8 and $14 billion (in 1984 dollars). The content of this estimate included the initial capability, eight-person, 75-kilowatt station and space platforms at two different orbital locations, with additional dollars required later to grow the program to full capability.[39]

Meanwhile, NASA Administrator Jim Beggs had been negotiating with the OMB for support to start the project. Under pressure to propose something affordable, Beggs committed to Congress in September 1983 that a Station could be constructed for $8 billion, a rather random number in light of the known estimates and the fact that the conceptual design had never settled down to an extent necessary for a solid definition and cost estimate. Nevertheless, the Agency pushed ahead with the Phase B studies and by fall 1987, needing to narrow the options in configurations still being debated between the Centers, established a group called the Critical Evaluation Task Force (CETF), quartered at LaRC and led by LaRC manager Ray Hook. Hook brought Bill Rutledge in from MSFC to lead the cost analysis effort, and Rutledge assembled a team made up of estimators representing the Work Package Centers and Headquarters (Bill Hicks, Richard Whitlock, Tom LaCroix, and Dave Bates). Over a period of a few intense weeks, they generated the cost of the new baseline, which, even after significant requirements had been cut, still totaled at least $14 billion.

NASA reluctantly took this cost to the OMB. Seeking to inspire a can-do attitude among the CETF team, NASA management passed out buttons containing the slogan "We Can Do It!" One senior estimator, who had seen it all before, modified his button to read "We Can Do It For $20 Billion!"[40] Amid great political turmoil, the Space Station was finally given a go-ahead. Despite contractor proposed costs that were more unrealistically optimistic than usual, the source evaluations were completed and contracts were awarded for the four work packages. The project managed to survive several close calls in the FY 1988 through FY 1991 budgets, though with steadily escalating costs and several iterations of requirements cutbacks and redesigns. Like the purchase of a car, the sticker price includes nonrecurring cost only, and this is the cost NASA had always quoted Congress for new projects, including the Space Station. During the long and winding road of gaining Congressional authority for the Station, NASA was asked to include other costs such as Station growth, Shuttle launch costs, operations costs, and various other costs, which led to confusion and charges of even more cost growth than actually occurred.

As this is being written, NASA is actively designing and estimating the cost of several major future programs including the Earth Observation System, the National Launch System and the Space Exploration Initiative, among others. Each of these programs, like most NASA programs before them, is unique unto itself and presents a new set of cost estimating challenges. At the same time, the recent years of growth in budget resources that NASA has enjoyed seems to have run its course. In an era of relatively level budget authority, NASA is seeking ways to maximize the amount of program obtainable. New ideas on this topic abound. Total Quality Management, Design to Cost, Concurrent Engineering and a number of other cultural changes are being suggested as a solution to the problems of high cost. As usual, the NASA estimating community is in the middle. Armed with data from the past, which somehow must be adapted to estimate the future, they attempt to answer the all important question: *But what will it cost?*

So brief a treatment of the history of NASA cost estimating leaves so much unsaid that apologies are in order. Nothing was mentioned of the aeronautical side of NASA, yet they estimate the cost of projects that are no less important to the nation than the space projects focused upon here. The Kennedy Space Center facilities and operations costing was not mentioned, though nothing NASA has sent to space could have been sent without them. Whole projects from which much was learned about cost estimating (Viking, Skylab, Spacelab, Centaur-G, Hubble Space Telescope, Galileo, Magellan, Ulysses and many others) had to be left unexplored. Even when touched upon, many subjects were given only the barest of treatments, the expansion left for other studies. Finally, and worst of all, while this paper unfairly singles out a dozen or so individuals, another few score men and women who have labored hard in the crucial and controversial business of NASA cost estimating will not see their names here. They are saluted anyway.

References

1 See Roger E. Bilstein, *Stages To Saturn, A Technological History Of The Apollo/Saturn Launch Vehicles*, NASA, Washington D.C., 1980, Chapter 2, for a discussion of how NASA was formed from these and other organizations.

2 Keith Burbridge, *A Touch of History*, Mountain View, CA: BFH Parametrics, 1984, *passim.*

3 T. P. Wright, "Factors Affecting the Cost of Airplanes," *Journal of Aeronautical Science*, Vol. 3, No. 2, 1936.

4 David Novick, "A History of Military Cost Analysis: 1950-1961," in *National Estimator*, Journal of the National Estimating Society, Spring 1981, p. 18.

5 Humboldt C. Mandell, Jr., "Assessment of Space Shuttle, Program Cost Estimating Methods" (Ph.D. dissertation, University of Colorado Graduate School of Public Affairs, 1983), pp. 315-328. This is a particularly good listing of the aerospace cost analysis literature through 1983.

6 For the earliest treatment of the new methods, see: David Novick, *Weapon System Cost Analysis*, The Rand Corporation, Santa Monica, CA, January 24, 1956.

7 Mandell, p. 93.

8 Bilstein, *Stages To Saturn*, p. 25.

9 Author's interview with Terry H. Sharpe, NASA MSFC, November 19, 1991.

10 Bilstein, *Stages To Saturn*, pp. 38-42.

11 Bilstein, Roger E., *Orders Of Magnitude: A History of the NACA and NASA, 1915-1990*, NASA, Washington D.C., 1989, p. 49.

12 *Space Planners Guide*, United States Air Force, Air Force Systems Command, July 1965.

13 Author's interview of Bill Ruhland, NASA JPL, November 27, 1991.

14 Author's interview of Werner Gruhl, NASA Headquarters (retired), November 21, 1991.

15 *Estimator's Cost Analysis Handbook*, The Boeing Company, Seattle, WA, Numbered 2-81254-1, Revision F, 1965, p. 2.

16 Mandell, pp. 30-31.

17 Sharpe.

18 Herman H. Koelle and William G. Huber, *Economy of Space Flight*, NASA MSFC, October 28, 1960.

19 Koelle, Herman Heinz, *Handbook of Astronautical Engineering*, NY, 1961.

20 General Dynamics Corporation, *Launch Vehicle Systems Cost Model*, Contract NAS8-11283, Fort Worth, TX, May 5, 1964.

21 See, for example, the following books, all by Stewart, Rodney D., and published by John Wiley & Sons, NY: *Cost Estimating* (1982), *Cost Estimator's Reference Manual* (1987), *Proposal Preparation* (1984) and *Managing Millions* (1988).

22 Brents, T., *Manned Spacecraft Cost Model*, General Dynamics, TX, July 18, 1966.

23 Campbell, Harry G. and D. J. Dreyfuss, *Manned Spacecraft Cost Estimating Relationships*, The Rand Corporation, Santa Monica, CA, March 1967.

24 Rockwell Space Division, *CSM Cost, Schedule and Technical Characteristics Study*, Downey, CA, April 30, 1971.

25 *Manned Spacecraft Cost Estimating Relationships*, The Rand Corporation, Santa Monica, CA, March 1967.

26 *NASA Space Shuttle Task Group Report*, NASA (Washington, July 31, 1969).

27 Mandell, p. 48.

28 Mandell, p. 33.

29 Mandell, p. 49 and *passim* for a complete description of the design and cost iterations during the Shuttle Phase A and B studies.

30 *Economic Analysis of Space Transportation Systems*, NASA Contract No. NASW-2081, May 1971.

31 *Payload Effects Analysis Study*, Lockheed Missiles and Space Company, Report No. LMSC-A990556, June 1971.

32 *Integrated Operations/Payload/Fleet Analysis Final Report*, Aerospace Corporation, Report No. ATR72(7231)-1, August 1971.

33 Nor is the debate over today. For an insightful analysis of the decision to build the Shuttle, see: John M. Logsdon, "The Space Shuttle Program: A Policy Failure?", *Science*, May 30, 1986.

34 Gruhl.

35 Author's interview of Frank Gray and Bob Breiling, RCA Price, November 21, 1984.

36 Author's interview of Tom Newman, NASA Headquarters (retired), November 21, 1991.

37 RCA Price Systems Division, *Equipment Specification Cost Effects Study*, Cherry Hill, NJ, November 30, 1976.

38 *Space Station Cost Model*, Planning Research Corporation, NASA MSFC, 1984.

39 Author's interview of O'Keefe Sullivan, NASA MSFC, November 21, 1991.

40 Author's interview with Bill Rutledge, NASA MSFC (retired), November 27, 1991, and author's interview with Bill Hicks, NASA MSFC, November 29, 1991.