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BUT WHAT WILL IT COST? THE HISTORY 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 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 its 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 suddenly become a much more important consideration for two reasons. First, a shrinking defense budget (between World War II and the Korean War) had cut the number of production units of most Air Force programs. Second, the cost of new technology had greatly magnified the cost of development. The inability to nimbly estimate RDT&E and first unit production costs was a distinct problem.

Fortunately, within Rand a cost analysis department had been founded in 1950[4] under David Novick, who was drafted into the job because he was the only one around with any cost experience. This group at Rand proved to be prolific contributors to the art and science of cost analysis so much so that the literature of aerospace cost estimating of the 1950s and 1960s is dominated by the scores of Rand cost studies that were published.[5] Novick and others at Rand deserve credit for developing and improving the most basic tool of the cost estimating discipline, the cost estimating relationship (CER), and merging the CER with the learning curve to form the foundation of aerospace estimating, which stands today.[6]

By 1951, Rand was devising CERs for aircraft cost as a function of such variables as speed, range, altitude, etc. Acceptable statistical correlations were observed at least acceptable enough for the high-level comparisons between alternatives that Rand was doing at the time. When the data was segregated by aircraft types (e.g., fighters, bombers, cargo aircraft), families of curves were discovered. Since each curve corresponded to different levels of complexity, the stratification helped clarify the development cost trends. Eventually, a usable set of predictive equations was derived that was quickly put to use in Air Force future planning activities.

The use of the CERs and stratification were basic breakthroughs in cost estimating, especially for RDT&E and first unit costs. For the first time, cost analysts saw the promise of being able to estimate relatively quickly and accurately the cost of proposed new systems. Rand extended the methods throughout the 1950s and by the early 1960s the techniques were being acceptably applied to all phases of aerospace systems.[7]

The Early NASA Years

In the spring of 1957 the Army Ballistic Missile Arsenal (ABMA) in Huntsville, under the direction of Wernher von Braun, initiated design studies on a large and advanced rocket booster that could be used for large DoD payloads then being conceptualized.[8] Numerous design options were under consideration and all of the most promising needed cost projections. Von Braun's team had long been flying experimental rockets, but precious little cost data existed, and none existed for the scale of the rockets that were coming off the drawing boards. Nevertheless, estimates were being demanded. With the procedures that Rand had used on aircraft, data was pieced together and plotted against gross liftoff weight because this performance variable was known both for the historical data points and for the concepts being estimated. The resulting CERs were at the total rocket level (engines being added separately based mainly on contractor estimates) and often did not inspire much confidence either by their correlation or their number of data points.[9]

Suddenly, in the fall of 1957 the Soviets launched Sputnik I and then, four weeks later, Sputnik II (carrying a dog), and the Army's big booster work took on an entirely new importance. While vehicle configuration studies inspired by the Soviet success continued at a rapid pace through 1958 and 1959, some momentous programmatic decisions were made regarding the ultimate management relationships between ABMA, the Army Redstone Project Arsenal (ARPA) and NASA. ABMA and von Braun, under ARPA sponsorship, were designing a massive rocket called Saturn. The DoD, however, as ARPA's parent organization, was coming to the conclusion that they did not need such a super booster and was beginning to withdraw support over the objections of both ARPA and ABMA. In the end, by autumn of 1959, both the Secretary of Defense and President Eisenhower had concluded that ABMA and the Saturn should be transferred to NASA.[10] In addition, a new home was found for the von Braun team by setting aside a complex within the borders of Redstone Arsenal in Huntsville.

By early fall of 1960, the Marshall Space Flight Center (MSFC) was operational.

NASA's first 10-year plan had been submitted to Congress in February 1960; it called for a broad program of Earth orbital satellites, lunar and planetary probes, larger launch vehicles and manned flights to Earth orbit and around the moon. The cost, estimated by analogies, intuition and guesses, was given as $1 billion to $1.5 billion per year.[11]

With the Kennedy Administration in office by early 1961, planning for a manned lunar landing project continued. President Kennedy and Vice President Johnson were both interested in options for moving ahead of the Soviets, and NASA was working on plans that could place an American on the lunar surface shortly after the turn of the decade.

The orbiting of Yuri Gagarin in April 1961 caused immediate questions from the Administration and Congress about the costs of accelerating the plans. Jim Webb, the NASA Administrator, had been briefed on $10 billion cost estimates associated with the moon project. Prudently, he decided to give himself some rope and gave Congress a $20 to $40 billion range. (The program was to cost about $20 billion ultimately.)

Despite the magnitude of the cost projections, in his State of the Union address in May 1961, President Kennedy established his famous goal of a lunar mission before the end of the decade. NASA was off and running. MSFC took responsibility for the Saturn launch vehicles, and the new Manned Spacecraft Center (MSC) in Houston, created in mid-1962 but operating before that out of Langley, was given responsibility for the payload—in this case the modules that would take the astronauts to the moon's surface and back.

While MSFC was being organized, the Jet Propulsion Laboratory (JPL) in California, in business as an Army research organization since the 1930s, was transferred to NASA from the Army. JPL had already built the Explorer satellite that had ridden an ABMA rocket into orbit as the country's first successful response to Sputnik. JPL began its association with NASA by being assigned the lead center role for Agency planetary projects. As JPL began designing several planetary probes, including the Ranger series of lunar spacecraft, the planetary series of Mariner spacecraft and the Lunar Surveyor spacecraft, they were dependent primarily upon contractor quotes for purchased hardware and their own work-hour and material estimates for inhouse work.

As the pace of planning picked up, they began to use an Air Force tool, the *Space Planner's Guide*,[12] a chapter of which is devoted to weight-based CERs for space project estimating. In 1967, Bill Ruhland, a former Chrysler Saturn I-C manager, went to work at JPL and contracted with a new company called Planning Research Corporation (which had been started by some former analysts who had worked on the *Space Planner's Guide*) to improve the CERs.[13] Ruhland stuck with estimating, and went on to become NASA's preeminent estimator for planetary spacecraft throughout the 1970s and 1980s. PRC leveraged its early relationship with JPL and Ruhland by establishing cost modeling contracts with most of the other NASA centers and dominating the development of NASA cost models for the next 25 years.

In March 1961, with launch vehicles, manned capsules and planetary spacecraft work underway, NASA dedicated the Goddard Space Flight 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 contractors' development of the model and then brought it inhouse and installed it 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 Agencywide cost database and develop new models. The REDSTAR (Resource Data Storage and Retrieval) database was begun in 1971 and is still operational today, supporting Agencywide 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 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 subsystem contains more than four data points and this paucity of data precludes the application of statistical techniques either in the development of the CERs themselves, or in the establishment of confidence levels for the predictive values generated by the CERs."[25]

While most of the science programs were managed out of JPL and GSFC, the research centers (Ames, Langley, and Lewis) were also given development projects from time to time. Ames managed the Pioneer planetary probes, Langley managed the Lunar Orbiter and the Viking Mars mission, and LeRC managed the Centaur project. Generally, the costs were estimated using models from the other Centers.

The Shuttle Era: Promise of Low Cost

By 1968 the nation was immersed in social and political turmoil, the Vietnam War and the attempt to build the Great Society. Though the accomplishment of the first manned lunar landing was not to occur until the following year, the budget that NASA received was lower than the previous year and broke the trend of ever increasing flows of money that the Agency had enjoyed since its creation a decade before. NASA realized that the dream of building directly on the expendable Saturn launch vehicle technology, building Earth orbital and lunar orbital space stations, continuing exploration of the lunar surface and mounting an expedition to Mars were not in the immediate plans.

By early 1969, while the ongoing Apollo program prepared for the Apollo 11 mission to the moon on which humans would land for the first time, future planning activities within NASA had been scaled back from the overly ambitious, broad set of space activities to focus on the crucial next step. Space stations, moon bases and Mars missions all needed low-cost, routine transportation from the Earth's surface to low Earth orbit. If the budget realities precluded doing everything at once, then the next thrust would be in low Earth orbit transportation as a first building block to all the rest.

A task force was assigned in March 1969 to study the problem and recommend options for further study.[26] This report called for the development of a new space shuttle system that could meet certain performance and cost-per-flight objectives. Many options were examined, but the fully reusable two-stage was the preferred choice because it seemed to offer the lowest recurring cost. Concurrently with these inhouse assessments, four parallel Phase A (i.e., conceptual design) studies had been awarded to General Dynamics, Lockheed, McDonnell Douglas and North American (today's Rockwell International). For most of 1969 these studies proceeded apace, churning out massive stacks of paper designs, along with cost numbers that gave the impression that all was well. For around $10 billion in development costs, the most reusable Shuttle configurations offered recurring costs of only a few million dollars per flight.

As the Phase A studies neared completion in late 1969, however, two cost-related problems began to emerge. First, NASA's communications with the Office of Management and Budget (OMB) revealed that the outlook for the NASA budget was not good. The projections showed that continued reductions in NASA's funding were inevitable; the lower budget numbers did not match the amount needed to fund the favored Shuttle designs.

Second, as NASA reviewed the contractors cost estimates for the Shuttle and compared the numbers to their own estimates, it became clear that no one in the industry or the government had a good handle on what the Shuttle could be expected to cost.[27]

The problem with the estimates was analogous data. A winged, reusable spaceship had never been built before and all the cost estimates were being based on extrapolations from large aircraft such as the C-5, B-52, B-70 (for wings, fuselage, landing gear, etc.), from the Saturn (for tanks, thrust structure, etc.) and from the Apollo capsules (for crew systems). The problem was compounded by the scope of the estimating job. All the various designs being contemplated overloaded the estimating resources that NASA had at the time. The entire complement of NASA estimators at the two lead Centers (JSC and MSFC) numbered only eight people, yet cost was to be one of the most key variables in the decision making process concerning the Shuttle.[28]

Because the magnitude of the upfront costs of the fully reusable systems had not yet been adequately estimated, NASA proceeded into Phase B in mid-1970 with the intent of putting more meat on the bones of the skeletal designs. Meanwhile, negotiations with the Office of Management and Budget continued concerning the budget outlook, and the numbers got lower and lower. Slowly, the cost estimates became more realistic just as the Phase B studies were nearing completion in the summer of 1971.

The studies were extended so that cost cutting measures could be investigated. First, expendable drop tanks were substituted for reusable interior tanks. Then the flyback booster was scrapped, first for expendable liquid rocket boosters, then for expendable solid rocket boosters. Taken together, these reductions made it possible to barely fit the Shuttle's development within the OMB guidelines, but each change had added to the recurring cost per flight.[29]

But the Shuttle peak year funding versus the OMB budget cap was not the only cost question dogging the Shuttle. For the mandated Mercury, Gemini and Apollo programs, money had flowed without any requirement for the Agency to show economic justification for the projects. When the idea of a Shuttle system was floated in 1969 as part of NASA's plans after Apollo, the OMB decided that such an expensive undertaking ought to show some economic benefits that outweighed the costs. Because the analytical skills for an economic justification did not exist inhouse and NASA thought it wise to have independent support for the Shuttle, the Agency hired the Aerospace Corporation, Lockheed and economist Oskar Morgenstern and his company Mathematica to develop the data OMB wanted to see. Morgenstern turned the economic analysis over to a young protege named Klaus Heiss. Heiss put together an impressive study[30] that compared the life cycle costs of the Shuttle with the costs of the equally capable expendable launch vehicles.

One of the more important arguments for the Shuttle case was that payloads on the Shuttle would cost considerably less than payloads on expendables, a notion that was based on an extensive cost estimating study done for NASA by Lockheed.[31] This study, a classic for its scope, originality and methodology, nevertheless reached an exactly wrong conclusion.

It is known now that Shuttle payloads actually cost more than those that fly on expendable launch vehicles due to the strenuous safety review process for a manned vehicle. But Lockheed forecasted that the payload developers would save about 40 percent of their costs from the advantages offered by the Shuttle. The advantages were thought to be that: 1) the relatively high weight lifting performance and payload bay volume offered by the Shuttle would allow payloads to ease up on lightweighting and miniaturization, which are cost drivers; 2) the Shuttle would allow retrieval and refurbishment of satellites instead of buying additional copies as was necessary with expendable rockets; and 3) a single national launch system such as the Shuttle would allow standardization of payloads instead of multiple designs configured for the plethora of expendable vehicle interfaces. Finally, it was Aerospace's job to determine the payload requirements and produce traffic models, and they ultimately forecasted the need for 60 Shuttle flights per year.[32] While the Shuttle payload benefits and flight rates were both flawed assumptions, Klaus Heiss constructed a discounted cost benefit analysis that asserted savings in the billions. At the least, the Aerospace, Lockheed, Mathematica work sent the OMB accountants to murmuring.

President Nixon finally gave the nod, and the Shuttle's detailed design began in the summer of 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 Kelley 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 FY1988 through FY1991 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, 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

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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.

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IMPROVING COST EFFICIENCY IN LARGE PROGRAMS

by John D. Hodge

This paper examines the question of cost, from the birth of a program to its conclusion, particularly from the point of view of large multi-center programs, and suggests how to avoid some of the traps and pitfalls. Emphasis is given to cost in the systems engineering process, but there is an inevitable overlap with program management. (The terms systems engineering and program management have never been clearly defined.) In these days of vast Federal budget deficits and increasing overseas competition, it is imperative that we get more for each research and development dollar. This is the only way we will retain our leadership in high technology and, in the long run, our way of life.

One of the most vexing aspects of managing large programs within NASA (or any other high technology government programs) is how to allocate program funds in a way that is best for the program. One of the major reasons is that the role of cost changes throughout the phases of the program. Another reason is that total cost is not all that easy to define; yet another is that funding, which is based on annual appropriations, is almost never consistent with fiscally efficient program spending rates. The net result is that program costs almost always escalate and inordinate time is spent controlling costs at the expense of maintaining performance or schedule.

Many studies have tried to address this problem. They show that program costs will escalate by at least a factor of three, from approval to completion. The studies suggest a number of guidelines that should be followed if costs are to be kept down, including clear definition of requirements, stable management and strong central control. Unfortunately, these factors are not always under the control of the program manager.

The principles are simple. First, define very carefully what it is you are trying to do. Check everything you do against that baseline, even if it has to be changed, and resist change once the decisions have been made. Second, break up the program into manageably sized deliverables that can be measured in terms of cost, schedule and performance, and define the interfaces between them. Third, continuously assess the risks to success as the program proceeds, and modify only as necessary.

Requirements Traceability

Most studies have shown that the primary reason for cost escalation is that not enough time or resources are spent in defining the program. It is clear that you cannot control what you have not or cannot define. It is during this period that some of the most elegant systems engineering should be performed, especially in understanding the cost of every requirement and its systems implication. Even if the definition is adequate during the early phases of the program, it is imperative that great vigilance be exercised in maintaining the baseline definition of the program and the fundamental reasons for doing the program.

This process establishes a small but influential part of the program office, preferably within the systems engineering organization. The program office must be dedicated to the traceability of requirements and to ensuring that a clear path exists from program rationale to program requirements to systems requirements to systems design. Too often, once a design has been established, changes are proposed and enacted that bear little relationship to the original premises of the program. As will be discussed later in this paper, there are many reasons for change, but where possible, changes should