Life Cycle Cost Growth Study
for the
Discovery and New Frontiers Program Office

Final Report

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Improving the Life Cycle Cost Management of Planetary Missions

Results from the Life Cycle Cost Growth Study performed by the Discovery and New Frontiers Program Office at NASA Marshall Space Flight Center

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Executive Summary

In order to improve cost and schedule performance, the Discovery and New Frontiers (D&NF) Program Office studied life cycle cost (LCC) and schedule growth for five missions. The goal was to identify the underlying causes for the cost overruns and schedule delays, and to develop practical mitigations to assist D&NF projects in identifying potential risks and controlling the associated impacts to proposed mission costs and schedules. The study found nine systemic issues involving project management and systems engineering that were the primary contributors to LCC and schedule growth:

1. Optimistic hardware/software inheritance and technology readiness assumptions caused cost and schedule growth in the detailed design and development phases (phases C/D) for all five missions studied.
2. Insufficient project management and technical insight into contractor performance resulted in poor communications, schedule delays, and technical problems that were manifested as cost overruns in three missions.
3. Inadequate planning for operations (phase E) resulted in significant LCC impacts in four missions.
4. Mission replans were inadequate, and significant changes to mission scope, schedule, or funding profiles were not sufficiently understood or analyzed, resulting in unexpected cost increases and schedule delays in three missions.
5. Projects demonstrated problems developing and maintaining Integrated Master Schedules (IMSs); problems stemming from inadequate IMSs were seen in four missions.
6. The complexity drivers for fault protection and autonomy (FPA) capabilities are not well understood and projects underestimated the time and effort required to complete FPA development in four missions.
7. Ineffective management structure and unclear roles and responsibilities resulted in cost and schedule impacts to three of the five missions studied. Issues resulting from the management structure compounded the effects of other project issues, such as overly optimistic heritage or technology assumptions, inadequate project schedules, and inadequate planning or replans. The management structure issues were exacerbated by project team member inexperience.
8. Team players with limited experience in planetary mission development were a significant contributor to project management issues resulting in cost over-runs. Project team inexperience was a direct factor in only two of the missions studied, however it also contributed to other problems cited within this study.
9. Many of the technical and project management drivers for LCC escapes were identified as issues (weaknesses, risks, concerns, or findings) during one or more of the mandated NASA project reviews, but there was insufficient follow-through to address (mitigate or refute) the panel's conclusions and recommendations.

The study also noted three observations:

1. The collection, analysis, and synthesis of the study data was much more intensive than anticipated, primarily due to the lack of official, formal program and project historical documentation.

2. The D&NF programs, as well as NASA as a whole, need to address the credibility of project cost estimates, including independent cost evaluations.

3. The majority of the underlying causes are embedded in the project approach during the concept study (phase A) and preliminary design (phase B) phases, but the actual cost or schedule impacts typically are not experienced until late in the development or operations phases (phases D and E).

The most surprising result is that none of these findings are new. All of the findings have been reported over the years as project management and systems engineering issues; good project management and systems engineering practices have been identified addressing each of the findings. However, the study concludes that problems remain and additional attention is required to control or eliminate these problems and contain the resulting impacts to D&NF project costs and schedules.

Background

The Discovery Program (DP) is a science program of frequent, mid-class spacecraft missions that perform high-quality focused scientific investigations. Initiated in 1992, the DP was defined to ensure frequent access to space for planetary system(s) science investigations, emphasizing missions that can be accomplished under the leadership of the scientific research community. The DP comprises a long-term series of space science missions that are independent and uncoupled, but share a common funding and management structure. Since its inception, DP has successfully completed missions to study the Moon, inner planets, asteroids, comets, and solar wind. Missions or missions of opportunity currently in development or operations will continue exploration of the inner and outer planets, asteroids, comets, and the Moon.

The New Frontiers Program (NFP) is a science program of medium-size spacecraft missions that perform high-quality focused scientific investigations. Initiated in 2003, the NFP was defined to pursue planetary missions that require resources beyond those available in the DP. The NFP comprises a long-term series of space science missions that are independent and uncoupled, but share a common funding and management structure. The NFP currently comprises two missions to study outer and dwarf planets.

Both programs include two classes of projects: missions of opportunity (MOs) and full missions. MOs are characterized by being an element (for example, a science instrument) of another mission of any size not associated with either program, or by reusing existing NASA space assets in phase E. MOs have a not-to-exceed total cost to NASA as specified in the Announcement of Opportunity (AO), which at the time of this study was $35M. Given the smaller size and lower complexity of the effort, MOs were not included in the D&NF LCC study.

Full missions for both programs are selected through an open science competition and can include any science investigation involving solar system objects except for the Earth and the Sun, which are currently covered by other programs. D&NF missions are Principal Investigator (PI)-led, complete, self-standing, and uncoupled Science Mission Directorate (SMD) investigations. The total cost to the National Aeronautics and Space Administration (NASA) for each mission has a not-to-exceed cost cap specified in the AO for the competition. At the time of this study, the Discovery mission cost cap was $425M and the New Frontiers mission cost cap was $700M. The mission cost cap covers the complete mission, including spacecraft development, mission operations, data analysis, and education and public outreach. Typically, the launch vehicle costs for past missions have been included in the mission cost cap, although the current trend for both programs is to exclude these costs from the project-controlled cap.

D&NF missions are ultimately defined in terms of the science return from the mission. Level I requirements include the baseline science mission: the full set of scientific requirements identified for the mission, and the threshold science mission: the minimum set of science requirements below which the mission is not considered justifiable for the proposed cost. The delta between the baseline and threshold science requirements is used to define specific project de-scopes that can, with authorization from the program, be used to offset cost or schedule overruns. The use of de-scopes as a risk mitigation technique is built into the D&NF program approach to managing low-cost, cost-capped missions.

Each PI is held responsible for proper execution of all aspects of the mission, including cost and schedule. PIs team with a NASA center, or an institution such as the Jet Propulsion Laboratory or the Johns Hopkins University Applied Physics Laboratory, to lead implementation of the mission. This home institution in turn assigns a project manager to lead the day-to-day activities. Development of one or more elements of the mission may be held in house at the home institution, or more often is delegated to a prime contractor, with additional subcontractors as required. Thus, the project management structure and lines of communication for each project include the PI, the Project Manager at the home institution, a project manager at a prime contractor, and any subcontractor management.

The D&NF programs are managed by a single program office at Marshall Space Flight Center. The program office goal is to enhance the probability of mission success of D&NF projects through independent oversight and insight throughout all phases of the mission life cycle utilizing a knowledgeable and efficient team. From this perspective, success is defined as:

- Delivering mission science to the PI (meeting the Level I requirements)
- Ensuring the implementing organization’s success in delivering the spacecraft on cost and schedule (meeting the launch date and cost cap)
- Meeting the program launch frequency requirement for science missions

Study Impetus & Approach

As uncoupled, multi-mission programs emphasizing cost-capped PI-led missions, the ability of the D&NF programs to meet their launch frequency requirements is driven by the ability of each individual project to meet its proposed and confirmed LCC and schedule. Looking at the missions over the history of the D&NF programs showed an increased frequency of cost overruns and schedule delays (see **Figures 1 and 2**).

While there was a trend of increasing life cycle cost growth even in the earliest D&NF missions, the growth was contained in the early missions, showing an average cost growth of ~5% and a maximum of 15% for one mission. In contrast, the five recent missions selected for the study showed an average cost growth of 31%, with one mission reaching 50%.[1]

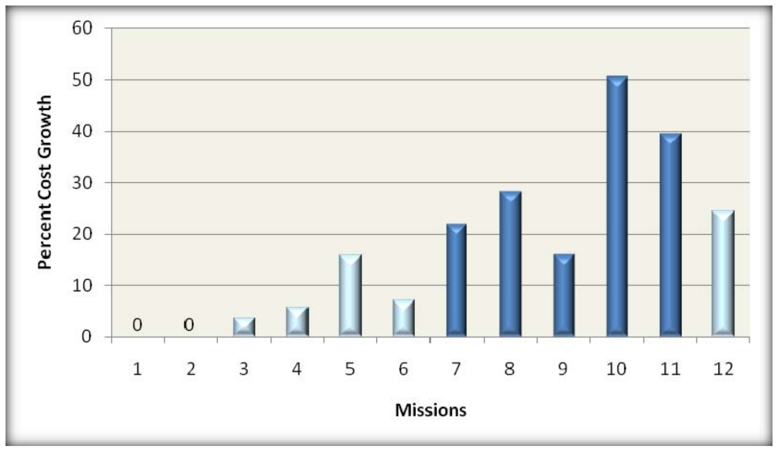

Figure 1. D&NF Life Cycle Cost Growth

Likewise, the average schedule growth for the D&NF missions increased from about 6% (20% for one mission) to 55%, with one missions showing a schedule growth of 153%. Note that schedule growth is shown in **Figure 2** for only nine of the D&NF missions because the available documentation does not include the original proposed launch dates for the remaining two missions (see Observation 1: Poor Program Documentation)

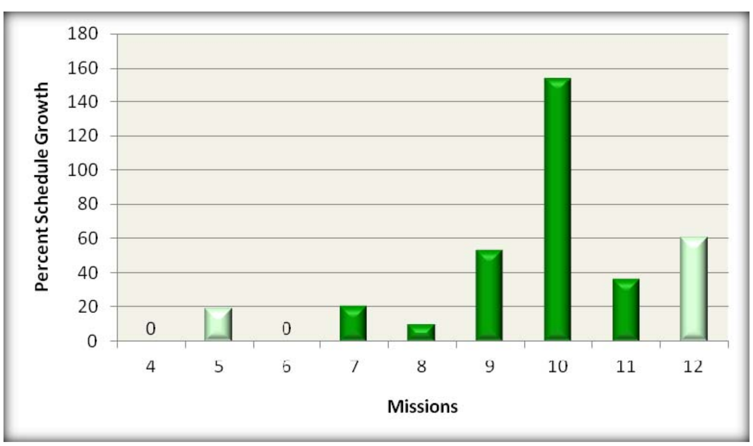

Figure 2. D&NF Schedule Growth (Launch Date Slip)

At a very high level, some of the cost and schedule growth was known to be attributed to changes in NASA philosophy regarding project risk, and the subsequent imposition of additional systems engineering and management processes that had not been included in the original mission proposals. However, the

[1] Study was executed prior to implementation of NASA guidelines to budget missions at the 70% confidence level.

trend has continued for missions that were proposed and accepted after this transitional period.

Some of the cost growth may also be attributed to the selection of missions that are more complex and therefore missions that are inherently more difficult to accurately estimate than earlier missions implementing the “low hanging fruit”. However, these cost escapes directly affect the programs’ ability to fund new mission starts and meet their objectives to provide opportunities for the science community to propose and execute solar system exploration missions. Therefore, the D&NF Program Manager chartered a study to assess the cost escapes that have occurred on recent D&NF missions, determine how the cost escapes are making it through the institutional and D&NF evaluation and review processes, and determine what *reasonable* things could be done as a program to either prevent the cost escapes or manage them better.

Study Objectives

The objectives of the study were to:

- Assess mission development process irrespective of organizational responsibility
- Assess LCC growth at decision gates throughout the mission development process
- Identify factors that contribute to the occurrence of unplanned costs and significant mission cost cap overruns
- Provide specific recommendations and implementation plans based on the findings to improve current processes and provide a greater level of insight to make better-informed decisions throughout the mission life cycle

Study Process

To execute the study, five missions were selected from the two programs based on a recent history of exceeding proposed or confirmed costs. Those missions are highlighted in dark blue in **Figure 1** and dark green in **Figure 2**. The selected missions covered a spectrum of complexity, cost growth, and maturity. All missions were well into or past the detailed design (phase C); two missions were already in operations, and one had completed its primary mission.

The study process is illustrated in **Figure 3**. Decision gates (see **Table 1**) are mission milestones at which NASA makes decisions that authorize a project to proceed and commit funding to a project’s LCC. Each decision gate is associated with a detailed review of the project plans and proposed schedule and costs by a source evaluation board or a review board to ensure that the project can be executed within the proposed cost and schedule and to identify any risks against successful completion. The study looked at the reviews and products associated with each decision gate and compiled a preliminary timeline of the evolution of the project milestones and the total LCC for each mission. In addition to the decision gate data, the study looked at cost analysis data requirement (CADRe) results, milestone review products (Critical Design Review (CDR), System

Implementation Review (SIR), Operations Readiness Review (ORR), and Mission Readiness Review (MRR)), project status reports, and program budget exercises, in order to understand the drivers underlying the cost changes at each decision.

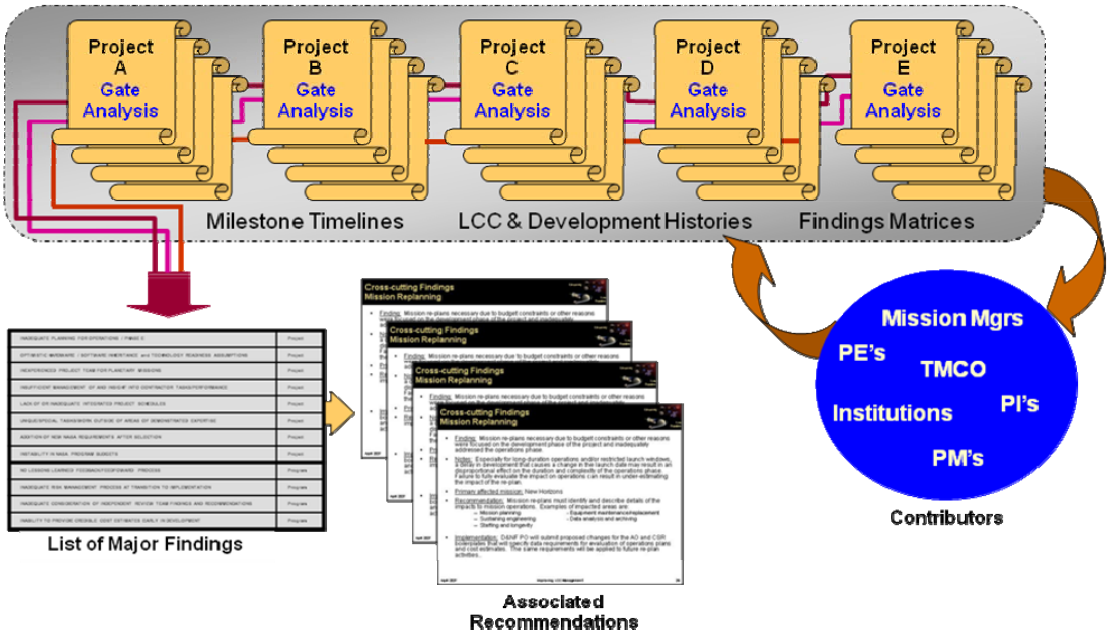

Figure 3. D&NF Life Cycle Cost Study Process

Table 1. Decision Gates

Decision Gate	**Associated Products or Reviews**	**Timeline Event**
Proposal Selection	AO Proposal	Phase A Start
Project Selection	Concept Study Report (CSR)	Phase B Start
Project Confirmation	Preliminary Design Review (PDR); Confirmation Review (CR)	Project Confirmation; Phase C Start

Members of the study team then met in person with program and project representatives to develop an accepted historical timeline of cost increases and schedule changes over the life cycle of each selected mission. Program representatives included the program office mission managers (MMs) and Headquarters (HQ) program executives (PEs) assigned to the missions selected for study, budget analysts, and representatives from the Technical, Management, Cost, and Other (TMCO) source selection process. Project representatives included mission PIs, Project Managers, budget analysts, and representatives of the home institution.

Considerable effort was required to reconcile the cost history with the underlying drivers. In no case did a complete documented history of the cost and schedule changes exist for a mission. Instead, the cost and schedule changes had to be reconstructed from an inconsistent and sometimes contradictory set of documents held at the project, program, and HQ levels, as well as the memory of members of the project teams and program management. The results of this analysis were documented in a consistent set of products for each mission:

- A detailed spreadsheet summarizing the discussions with the program and project representatives

- A project development timeline identifying the original life cycle phase boundaries, and any changes to the proposed major milestones

- A cost history breakdown, including the factors contributing to the cost increases at each decision gate

- A narrative summary of the driving changes to the mission cost and schedule of the full mission life cycle

Note that during this process, the study focus was on the primary cost and schedule drivers and their relative potential for impact, not the pinpoint accuracy of the associated cost estimates. As will be discussed later, it was very difficult to trace the detailed cost and schedule history for each of the missions. Even after discussions with the project, it was often impossible, given the passage of time, to accurately break out individual costs between multiple items included in a single line in a budget submit. However, while frustrating, these were not found to invalidate the study approach nor to interfere with the identification of the primary drivers for the cost and schedule impacts.

Finally, the detailed mission timelines and cost breakdowns were used to identify the overarching drivers for project cost overruns and schedule delays. In general, the drivers affected multiple missions. However, the final set of findings also included drivers that resulted in a significant cost or schedule impact for only one or two missions, if they represented a significant potential risk to future D&NF missions. Also, the emphasis of the study was on cost and schedule risks that could be directly affected by D&NF program or project management. Thus, the findings do not include cost drivers that were outside the control of the project or program. Cost or schedule drivers resulting from NASA policy or budget decisions are noted in the data, but are included in the study results only as they contribute to the nine findings of the study.

Results

The final trace of the cost growth from the CSR (start of phase B) across the five missions studied is shown in **Figure 4**. The percent growth is shown for three data points: the end of preliminary design at the PDR, the subsequent CR, and the final project estimate at the time of the study. The final project cost growth shown in **Figure 4**

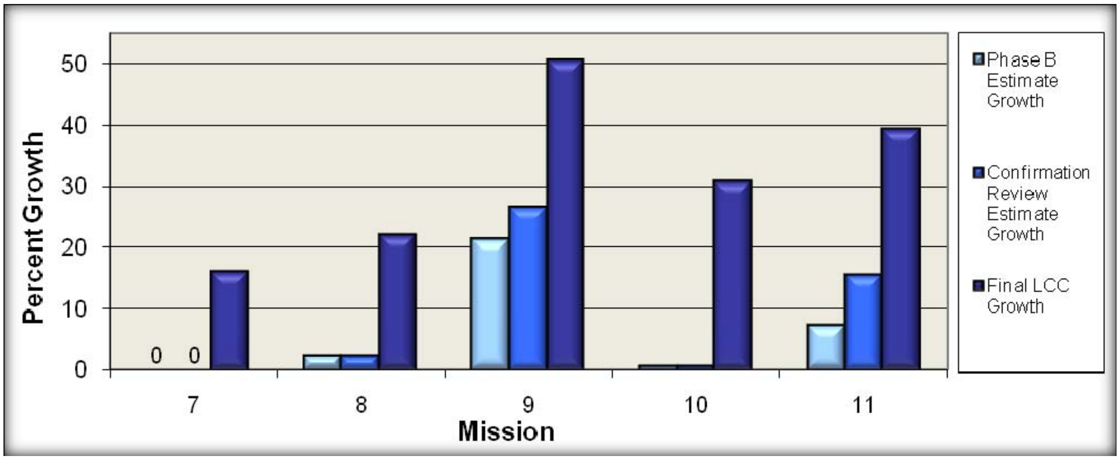

Figure 4. Recent Mission Life Cycle Cost Growth

may not represent the total project LCC, as only one of the missions studied had completed its primary science mission at the time of the study. As seen in other cost growth studies, the largest cost growth in all cases occurred after project confirmation.

Figure 5 traces the schedule growth in terms of launch delays from the dates proposed in

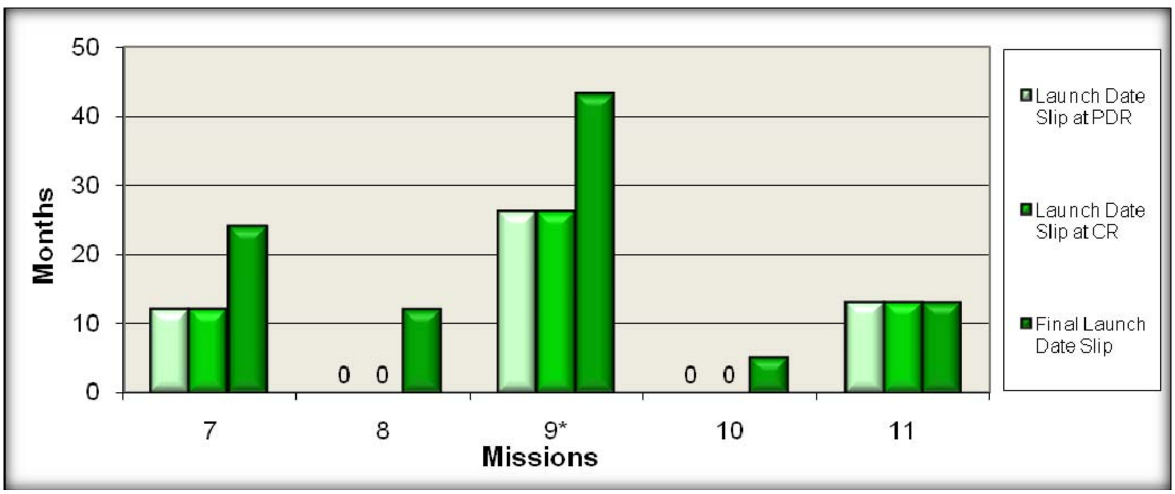

Figure 5. Recent Mission Project Schedule Growth (Launch Date Slip)

the CSR for the five missions studied. Similar to the project cost growth, the schedule shown for three data points: the end of preliminary design at the PDR, the subsequent CR, and the actual or proposed launch date at the time of the study. Thus, the schedule growth does not include increases to the overall mission duration due to changes in encounter (e.g., fly-by) or orbit insertion date resulting from a launch delay. The accompanying increases in operations (phase E) duration ranged up to two years for the missions studied. It should also be noted that at the time of the study, one mission (mission 3, indicated by an asterisk in **Figure 5**) had not launched, so the schedule growth shown may not represent the full launch delay experienced by the project.

As expected, not all cost and schedule growth could be traced to factors under the control of the program or the project. Several projects experienced cost growth when additional NASA requirements that were not costed in the original mission proposal were passed on to the projects. Some examples of these included recommendations from the NASA Integrated Action Team (NIAT), increasing reserves to a mandated level, or implementation of full cost accounting within NASA. In addition, three projects experienced both cost and schedule growth as the result of a stand-down imposed by NASA due to budget issues. Although noted as cost drivers during the study, these were not included in the findings in order to concentrate on the issues within the control of the program or the project.

Major Findings

The study returned nine major findings covering multiple aspects of program and project management, and project systems engineering (see **Table 2**) that are under the control of the program or project. There is no implied ranking to the order of the findings based on potential impact to a specific mission, or the number of potential missions experiencing an impact.

Table 2. Major Findings

1	**Heritage and Technology Assumptions**
2	**Insufficient Project Insight**
3	**Inadequate Planning for Operations**
4	**Inadequate Mission Replans**
5	**Integrated Project Schedules**
6	**Fault Protection and Autonomy**
7	**Ineffective Management Structure**
8	**Project Team Inexperience**
9	**Consideration of Review Team Findings**

The most surprising result of this study is that none of these findings are new. All of these have been identified by practitioners and researchers as areas of project management or system engineering risk. Institutional standards or best practices have been developed in these areas; all are routinely covered in project management or system engineering training courses. However, the study indicates that management and engineering processes in these areas are not yet fully mature nor consistently and routinely implemented across NASA projects. Despite the years of experience in executing spacecraft missions, the development of institutional standards, and the implementation of training programs, NASA projects still experience cost overruns resulting from basic project management and systems engineering issues.

Finding 1: Heritage and Technology Assumptions

Optimistic hardware/software inheritance and technology readiness assumptions caused cost and schedule growth during detailed design (phase C) and development (phase D) for all five missions studied. Missions frequently assume the use of advanced technology systems or heritage in their proposals to enable a mission or reduce the overall mission risk and cost. However, the missions studied failed to achieve the proposed reduction in cost and/or schedule duration, and all experienced significant cost and schedule growth during the development and test.

The cost and schedule growth was not found to be the result of technical issues. Institutional inheritance and technology readiness processes appear to adequately prevent technical issues from impacting mission operational success. However, a combination of overly optimistic assumptions regarding technology readiness or the potential savings associated with inheritance and institutional inheritance and technology readiness processes allowed cost/schedule escapes to impact phases C/D. In general, the overruns could be traced back to:

- Inadequate understanding of the heritage system's performance within the proposed project design or mission environment
- Project personnel with insufficient experience with the heritage system
- Inadequate scoping of impacts to implement a new technology for space flight

During the proposal development, projects assume the use of various instruments, sensors, or spacecraft buses and cite heritage from previous missions as the basis for cost or schedule savings. However, typically little or no allowance is made for structural, mechanical, electrical, or thermal redesign required to use the item within the constraints of the new spacecraft. Studies to mitigate common risks such as internal electrostatic discharge (IESD), cross-talk, or thermal stability may not be included in early design costs for heritage hardware. Likewise, insufficient analysis is performed in formulation (phases A and B) to accurately determine redesign that might be necessary or identify additional testing for recertification of heritage hardware for use in a new thermal or radiation environment.

In addition, the schedule and cost savings achievable from the use of heritage hardware are highly dependent on the extent to which the personnel working on the spacecraft have previous experience with the heritage hardware. The study data showed that projects failed to sufficiently account for the learning curve required to bring an inexperienced team up to speed on heritage hardware. The impact resulting from a lack of accurate, up-to-date documentation on heritage hardware also was not identified or adequately compensated for in schedules and cost estimates.

Similarly, project estimates of the effort required to incorporate a new technology into the space system were under-scoped. Programmatic issues, such as launch approval for nuclear systems, were not adequately understood and therefore were underestimated. Ancillary support, such as required equipment for development and ground testing were inadequately defined in early design and therefore were inadequately covered in the proposed mission costs. Finally, impacts to other spacecraft systems (e.g., additional shielding for other spacecraft systems after the introduction of a nuclear component) may not be identified during proposal development or preliminary design and therefore not included in the proposed and confirmed costs for the mission.

Project management needs to realistically assess both the benefits and risks associated with heritage and new technology, and ensure appropriate mitigations are identified and implemented. Proposals and early design products should clearly demonstrate the relationship between heritage/technology rankings and cost/reserve estimates. This relationship should form the basis of a living reference between heritage/technology rankings and cost/reserve estimates, updated throughout formulation and implementation. High risk heritage/technology assumptions should be captured as project risks, tracked against mitigation actions, and assigned cost liens or threats that are updated at each project review.

Standing Review Board (SRB) or review team members need to be selected to ensure that members possess current expertise in applicable areas, including not just the heritage or new technology but the operational environments encountered during the mission. Heritage and technology assumptions, proposed and completed mitigation activities, and the associated cost liens or threats need to be independently and rigorously reviewed at each major milestone.

Finding 2: Insufficient Project Insight

Insufficient project management and technical insight into contractor performance resulted in poor communications, schedule delays, and technical problems that manifested as cost overruns. This was a significant contributor to cost overruns on three of the five missions studied.

As uncoupled programs of independent, PI-led missions, the D&NF programs rely on the processes and procedures of the home institution to meet NASA-imposed standards. Cost overruns occurred when insufficient insight or oversight by the project resulted in contractor specifications, processes, and procedures that did not meet the home institution’s expectations. This can result from a new teaming relationship, perhaps created to provide an unusual mission-enabling technology or to support reuse of a technology in a new or different manner. This can also result from transfers between business units of project personnel with significant experience in other methodologies, but with insufficient training in NASA’s standards, processes, and procedures. In each case, organization “cultural” differences and insufficient flow down of detailed requirements led to products that did not meet institutional standards.

In some cases, the result was "gaps" in processes, where each side was expecting the other to routinely perform specific activities (e.g., test). In other cases, the result was a part that could not be certified for use according to NASA standards. In turn, the process gaps and uncertified products led to rework and retest of both hardware and software before the product could be accepted. In addition, waivers were sometimes required and approved in order to limit cost and schedule increases, resulting in an increase to the overall mission risk accepted by project and NASA. Cost overruns also resulted from hardware mishaps stemming from processes that did not meet NASA standards, as well as from adding personnel to oversee a process to mitigate the risk of a mishap during a critical process.

During the early formulation of a project, all parties need to work together to clearly communicate requirements and standards down the organization chain to all levels, including contractors and subcontractors. Likewise, institution or corporate practices need to be clearly and concisely communicated up the organization chain. Even with this communication, the parent organization(s) need to implement a sufficient level of insight to ensure that the communication does occur, that all levels are in agreement, and that the delivered products will meet home institution requirements and standards. This is critical for all teaming arrangements, even organizations that have a long and very successful teaming relationship on multiple projects, as changes in personnel can introduce differences in expectations.

Finding 3: Inadequate Planning for Operations

Mission selection, review, and management processes are heavily focused on hardware development schedules and costs. Operations costs are typically small compared to the spacecraft development and test costs. This, combined with the long lead time for realizing phase E costs, can lead to de-emphasis of phase E support requirements during proposal and preliminary design cost exercises. However, even moderate yearly underestimates can present significant LCC impacts for missions with long phase E durations, becoming a significant contributor to cost overruns on four of the five missions studied.

Underestimation of the proposed mission operations costs was seen to result from:

- Underestimating the complexity of mission operations
- Inadequate planning for sustaining engineering
- Ignoring special requirements for long duration missions, e.g., knowledge retention, software and hardware refresh, technology evolution, institutional staffing considerations

An additional factor, underestimating the ground system support requirements leading to delaying development of operational capabilities into phase E was also a significant contributor to cost increases during this time frame.

Insufficient resources and effort are assigned to defining an operations concept and estimating operations costs during the proposal and phase B activities. Missions are often proposed, staffed, and estimated as "routine operations," ignoring drivers in the spacecraft and mission design that require additional ground system tool capabilities or additional operational staffing support. In addition, changes to the spacecraft design are not always adequately assessed for their effect on operations, particularly increases in operational complexity, as part of system engineering trade studies. This could be the result of processes that failed to include the full LCC impact during system design trade studies, insufficient information available to the operations team to allow a realistic assessment of the effect on operations, or insufficient experience in the operations team to understand the full ramifications of a spacecraft design change.

Even for straightforward missions, phase E costs can be underestimated due to inadequate planning for sustaining engineering. Overly optimistic assumptions about operational savings due to lessons learned from previous projects are often not realized due to spacecraft "idiosyncrasies" that are not identified until after launch. Overly optimistic assumptions are also made about the need for flight software maintenance after launch or general engineering support during cruise phase for monitoring spacecraft health and safety or responding to spacecraft anomalies.

In addition, projects typically ignore one or more of the special requirements for long duration missions. For deep space missions, the requirement for minimal staffing during cruise phase in order to control total phase E costs competes with the need to retain critical staff knowledge and a skill base to support engineering activities during critical milestones such as planet flybys, as well as science operations at the science target. The staffing plan is then found to be unworkable during detailed planning for engineering activities before launch, or when the detailed science planning begins during cruise. Likewise, special considerations applying to long duration deep space missions, such as routine software and hardware refresh and the incorporation of evolving technologies, are inadequately represented in the confirmed mission costs. While it might be the initial intent of the project to control costs by rejecting hardware or operating system upgrades, this may be found to be unworkable when vendors suspend maintenance on certain hardware or software product lines, requiring projects to upgrade or face unsupported hardware failures.

Finally, inadequate planning for the development of operational tools often results in software development being delayed in phase E. This is most common for fault management software (see Finding 6: Fault Protection and Autonomy) and science operations tools, but was seen to occur in many areas, including flight software, mission design, scheduling, and spacecraft analysis tools. While the actual development should be covered by unspent phase C/D funding held over into phase E, in practice this is rarely sufficient. Not only was work delayed into phase E, but staffing was increased during phase C/D causing most, if not all, of the planned development costs to be spent in phase C/D, and requiring additional funding for development during phase E. In addition, the unexpected development typically levies additional effort on the operations teams for testing, parallel (shadow) operations, reprocessing, and, potentially, procedure and command product development. This additional work is rarely covered by the original phase E costs estimated during formulation.

Project management should emphasize the need for a full and accurate LCC estimate from the earliest stages of proposal development. This should include a phase E staffing estimate by primary operations functional area that can clearly be traced to and supported by the proposed operations concept. Early design activities need to emphasize the importance of an increasingly detailed operations concept developed in parallel with the spacecraft that identifies, for example, plans for equipment maintenance/replacement and parts obsolescence, and longevity plans for retaining/replacing key personnel.

If circumstances force a project replan, project management needs to reassess key elements of the operations concept and consider the potential impact to mission life time, complexity, and operations staffing. In the event that significant phase D work must be deferred into phase E, project management should rigorously assess the impact on operations personnel and manage the deferred phase D work as a formal development effort, including all the appropriate schedules and metrics.

Review teams should independently assess the operations staffing and cost estimates and the phase E reserve plans against the mission operations concept. The Confirmation Review out-brief should specifically address the operations concept and the assessment of the project phase E plan, including any potential risks to the plan based on the operations concept.

Finding 4: Inadequate Mission Replans

The impact of significant changes to mission scope, schedule, or funding profiles were not sufficiently understood, resulting in unexpected cost increases and schedule delays. Not all replans were initiated as the direct result of project issues; several of the projects studied experienced delays or replans as the result of NASA-initiated changes. Other project replans were the result of project issues stemming from one or more of the findings identified in this study. In either case, project replans are often time constrained in order to maintain project schedules or meet NASA budget cycle deadlines. Insufficient analysis of the full implications of the changes to the total mission life cycle resulted in additional unanticipated cost and schedule growth in three of the five missions studied.

For NASA-driven changes (excluding directed launch delays), the most common cause for an inadequate replan was a lack of understanding of the change to the scope or process requirements. As one example, the system engineering and test processes resulting from additional risk reduction activities (in response to NIAT recommendations) were not well understood at the time of the original replan assessment. As the full impact on project resources became apparent, the project was forced to replan, adding additional resources (cost) to meet schedule commitments.

Similar to the issues noted in Finding 3, above, impacts to phase E resources were typically missed or underestimated in replans that resulted in launch delays. The realities of deep space missions are often brushed over given the time available to replan, assuming (correctly) that the spacecraft can still be operated. However, in one case a 3 month launch delay added 2 years to the operational lifetime, as well as increasing the number of critical activities by ~50%. The total effect on operations of the overall increase in mission complexity, including the density of critical activities, was not fully realized until two years into phase E.

Likewise, effects of a launch delay on heritage hardware or technology assumptions are often not completely analyzed during a replan. A launch delay can change the assumptions under which the original environmental analyses were performed (e.g., mission delayed to solar maximum). A new mission design resulting from the launch delay can completely alter the spacecraft thermal environment or the mission lifetime. The impacts from these types of issues are often not fully realized until the replan is complete and approved, and the engineering team revisits the original analyses.

Finally, any replan that defers phase C/D work (software and ground segment hardware) into phase E, needs to be carefully assessed to ensure that all operational considerations have been included. This includes not only the development work and any associated ground or in-flight testing, but also interim operational support for workarounds; hardware and personnel requirements for training, scenario tests, and data reprocessing; and documentation updates.

In order to ensure an accurate and complete mission replan, the program and project need to work together to clearly define the goals and scope of the replan and ensure sufficient time is allocated to perform a detailed assessment. Projects need to carefully consider ancillary effects such as heritage assumptions (see Finding 1: Heritage and Technology Assumptions), as well as specifically address any operational considerations (see Finding 3: Inadequate Planning for Operations). The project should then develop a detailed revised baseline, including not only the cost and schedule impacts but also the underlying assumptions and any risks associated with the revised baseline. The replan should be confirmed by a complete and independent evaluation of the assumptions and risks and the resulting impacts to project LCC and schedule. In the event that time constraints do not permit a full evaluation prior to submitting revised cost and schedule data, the full process including independent review still should be completed as soon as possible after submitting the revised data.

Finding 5: Integrated Project Schedules

The lack of a comprehensive, integrated project schedule resulted in uncoordinated activities, inefficiencies in resource management, and increased costs. A valid, comprehensive IMS is required for earned value management (EVM), which is an accepted and required tool for measuring project progress and controlling project costs. Yet, projects continue to experience problems developing and maintaining IMSs. Schedule delays and the resulting cost overruns stemming from inadequate IMSs were seen in 4 out of 5 of the missions studied.

In the missions studied, every home institution required and set standards for an IMS, and every project had implemented one. In spite of this, the study identified IMS inadequacies that could be directly traced to cost overruns and schedule delays, including:

- Missing critical milestones and major events
- Missing logical relationships (interdependencies), or unidentified or incomplete critical paths
- Over-specified and unmanageably large number of tasks
- Multiple separate, uncoordinated schedules

The lack of a comprehensive, usable IMS resulted in uncoordinated activities, inefficiencies in resource management, late identification of risks to the critical path, and increased costs.

One of the most common problems relating to IMS inadequacies over the missions studied was missing critical milestones and major events. In at least one case, events were missing even though the IMS was extremely detailed, extending to a low level of detail in all areas. In fact, the very size of the IMS was a likely contributor to the missing milestones and events, in that it was too large for a meaningful review of all the events and relationships. The missing events resulted in resources being underestimated for completing critical tasks, and meant that management had insufficient or confusing data for tracking performance across the project.

Most IMSs also had missing logical relationships (interdependencies) or unidentified or incomplete critical paths. These were a common cause for underestimating resources, poor decision-making, and resulting schedule delays, with the added expense of additional resources for replans.

Finally, both of the above issues were compounded by the existence of multiple separate, uncoordinated schedules that needed to be rolled together to understand the project status, rather than one true IMS. Although considerable effort was expended by projects on merging, or building automated processes to merge, the schedules, the mere existence of multiple independent and uncoordinated schedules compounded the difficulties in reviewing the schedule and ensuring that all critical milestones, major events, logical relationship, and critical paths had been identified and were being tracked. This in turn increased the likelihood of problems in tracking performance and the early identification of risks to the critical path.

The importance of a usable IMS as a routine project management tool cannot be over emphasized. Project management must ensure that a valid, comprehensive IMS is in place and forms the basis of and facilitates EVM reporting. More importantly, project management must ensure that the IMS can be used easily as a routine part of monthly, weekly, and, at times, daily assessment of project performance and status across all elements and levels of the project.

The Integrated Baseline Review (IBR) should be used to confirm the content of the schedule and the processes for maintaining the schedule, as well as the ability of the schedule to support weekly and monthly planning and annual reviews. The actual integrated schedule and associated processes should be reviewed as part of project milestone reviews (PDR, CDR, and SIR) and periodically throughout the life cycle.

Finding 6: Fault Protection and Autonomy

The study also found that missions underestimate the time and effort required to complete FPA development. Four of the five missions studied experienced cost overruns, schedule delays, and even launch delays in order to complete the required FPA capabilities.

Underestimation of FPA complexity resulted from difficulties:

- Defining the appropriate autonomy requirements and the proper level of fault protection
- Evaluating overall FPA complexity, including all hardware, software, and operations components
- Estimating test requirements, including hardware and software fidelity and test coverage
- Estimating required resources, including subsystem and operations personnel support, hardware simulation facilities (test beds)

In general, FPA requirements tend to be defined late in development. This means that the full complexity of the FPA subsystem is not well understood during formulation, and the resources required for FPA development, test, and execution are not completely covered in the cost estimates prior to confirmation. In addition, FPA may not be clearly defined as an distinct engineering discipline. Instead, it is often included as an added responsibility of the system engineering team, and given a lower priority than critical systems engineering issues involving power or mass margins. Even when FPA is staffed as a separate engineering discipline, the staffing level may not be sufficient to allow the engineer(s) to follow the hardware and software trades and decisions closely enough to understand their impact on FPA complexity. This limits the project’s ability to mitigate increasing FPA complexity by appropriate system trades.

Initial underestimation of FPA requirements and complexity, coupled with the growth in FPA complexity during development, requires projects to add additional resources to FPA development and testing in phase D in an attempt to maintain schedules. However, this may not be sufficient, and launch constraints can result in development work being held over to phase E. Not only does the delayed FPA work represent an impact to phase E funding, but it typically also requires additional operations personnel support for workarounds and changes to databases, documentation, and procedures while the FPA development is completed. The need for additional support can also be seen in the subsystem and system engineering areas, as additional subject matter experts are required to deal with analysis and anomalies until the FPA capabilities are complete and tested operationally. Incomplete implementation at launch also represents an additional risk to mission success until the FPA capabilities can be completed and fully tested in flight.

NASA as a whole, including the program, institutions, and projects need to develop a better understanding of the detailed cost drivers associated with FPA, in order to improve the initial estimate of the resources required. [2] Project management needs to ensure that FPA is treated as a separate and equal engineering discipline, with the resources and processes required to ensure that FPA complexity is considered as a factor in system trades and design decisions. Finally, project management needs to ensure that FPA development and testing is incorporated into the master schedule at a sufficient level to allow management to accurately track progress and plan for changes in resource requirements before issues reach a critical mass.

Finding 7: Ineffective Management Structure

Ineffective management structure and unclear roles and responsibilities resulted in cost and schedule impacts to three of the five missions studied. Issues with management structure occurred primarily within projects involving multiple organizations, and were exacerbated by project team member inexperience (see Finding 8: Project Team Inexperience). Ineffective management structure also served to compound the effects of other embedded project issues such as overly optimistic heritage or technology assumptions (see Finding 1: Heritage and Technology Assumptions), inadequate project schedules (see Finding 5: Integrated Project Schedules), and inadequate planning or replans (see Finding 3: Inadequate Planning for Operations and Finding 4: Inadequate Mission Replans).

The problem areas noted during the study included:

- Inconsistent project reporting and decision-making
- Unclear lines of technical authority
- Unconnected systems engineering across multiple organizations
- Unclear responsibility for system integration

In some cases, these resulted in changes to scope and commitment of reserves without adequate review and appropriate controls. In some cases, they resulted in “gaps” in definition and coverage of critical tasks. While in others, they resulted in a lack of clear authority and accountability for decisions and activities.

During the early formulation of a project, all parties need to work together to clearly define and communicate roles and responsibilities to all levels, including contractors and

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[2] Since this study, the D&NF Program Office, on behalf of NASA’s Planetary Science Division, sponsored a Fault Management Workshop to bring subject matter experts from across NASA together and begin to understand the issues and drivers affecting FPA cost overruns. The results from this workshop are documented in the report: *Spacecraft Fault Management Workshop Results for the Science Mission Directorate, Planetary Sciences Division.*

subcontractors. This definition needs to include clear paths for communication, even among teams with experience working together. Based on their experiences, review teams should specifically assess the project's:

- Management structure for clear reporting and decision authority
- System engineering and integration responsibilities for gaps and overlap
- Technical authority structure

In addition, they should assess the team understanding of and the on-going effectiveness of the management structure.

Finding 8: Project Team Inexperience

Teams that include major players with limited experience in planetary mission development are a major contributor to project management issues resulting in cost over-runs. Project team inexperience was a direct factor in only two of the missions studied; however, it contributed to problems in a number of other areas cited within this study. The inexperience was manifested in many ways:

- Complex or poorly-defined management structure, roles and responsibilities, and communications
- Inadequate development schedules and implementation of performance measuring techniques
- Inadequate performance oversight and configuration management: institute to prime and prime to subs
- Incorrect or inadequate heritage or technology evaluations
- Inaccurate cost estimates, inadequate cost control and management of reserves

Given there may be strategic benefits to selecting "new" team members, the project and program should assume a greater cost risk and operate with increased insight/oversight for less experienced team members. Both projects and the review teams should:

- Assess the relevant experience for major partners and identify associated risks
- Develop mitigation plans, including mentoring and active sharing of lessons learned from more experienced partners
- Identify and carry a cost threat, adjusted to reflect continuing team performance

Review teams should independently assess the overall effectiveness of the management structure and any mitigation activities at the major milestone reviews.

Finding 9: Consideration of Review Team Findings

One of the more surprising findings of the study was that many of the technical and project management drivers for LCC escapes were identified as issues (weaknesses, risks, concerns, or findings) during one or more of the mandated NASA project reviews. In other words, NASA commissions senior-level expert review panels, but does not always follow through and address (mitigate or refute) the panel's conclusions and recommendations.

There was little evidence indicating a consistent approach to responding to the findings and recommendations of a review team. At the time of the study, there was little evidence of formal documentation of findings and recommendations, and there was no indication that risks, budget adjustments, or cost threats were created to follow through on the board results. In many instances, the issues identified by a review team but not addressed, significantly affected a project's cost and schedule and the program budget.

The changes to the formation of SRBs implemented in NPR 7120.5D, *NASA Space Flight Program and Project Management Requirements*, are one step toward providing the continuity to ensure issues raised by review teams are addressed. However, project managers must allocate sufficient time and resources as part of the review schedule to seriously consider, analyze, and respond to issues raised by review panels. For each issue, project managers should carefully trade the cost of early mitigation versus the potential cost if the issue worsens or is realized (see Observation 3: Embedding vs. Realization of Impacts). If no immediate action is taken to resolve or mitigate each issue, the project should create and track a risk and associated threat to the project reserves to maintain visibility into the issue by management as the project matures.

Observations

In addition to the findings discussed above, the study returned three observations covering issues that are primarily programmatic in nature (see **Table 3**). There is no implied ranking to the observations. These observations were seen during the analysis of the mission data for all of the missions studied.

Table 3. Observations

1	**Poor Program Documentation**
2	**Cost Credibility**
3	**Embedding versus Realization of Impacts**

Observation 1: Poor Program Documentation

The collection, analysis, and synthesis of the study data were much more intensive than anticipated. This was primarily due to the lack of official, formal program and project documentation. There was little traceability of cost or schedule impacts to program-level decisions or direction (e.g., official letters, documents). Cost or schedule changes were often "grouped" into high-level categories, making it difficult to trace the changes to detailed cost drivers. Records of year-to-year or life cycle-phased cost commitments and obligations to projects were often inconsistent and different players (project, program office, HQ) disagreed on the details of the project timelines, cost increases, and scope changes.

Given that the study concentrated on identifying the largest drivers, the data were still valid for identifying driving issues. However, programs and the projects need to be diligent in documenting decisions and project direction. Significant programmatic direction to a project should be documented in a NASA memorandum. Project budget adjustments should be documented with sufficient detail to understand the cause and any effects of the change; this should include documented feedback to projects regarding the results of the planning, programming, budgeting, and execution (PPBE) process. Finally, significant project meeting decisions should be documented in official minutes (management council, Program Control Board (PCB), etc.) that are sent to key program and project attendees.

Observation 2: Cost Credibility

Both D&NF programs, as well as NASA as a whole, need to address the credibility of project cost estimates, including independent cost evaluations. Even when technical and programmatic risks were identified early, the associated cost estimates did not adequately cover the identified risk. In many cases, more than one cost increase was seen for a given technical or programmatic issue, due to inadequately scoping the costs to analyze and resolve an issue or implement a new NASA-required process. In addition, even though reviewed by technical, scheduling, and cost experts, the underestimates were not identified and therefore were subsequently approved by NASA management. As noted above, in some cases this was directly related to the time allocated for a replan. However, in other cases, there was no observable correlation to a tight replan schedule. Rather, the cost increases appeared to result from inadequate understanding of the issues, required processes, and potential impacts on the mission.

Observation 3: Embedding versus Realization of Impacts

The third observation addresses an overarching issue affecting all the missions studied. It is predicted to be a fundamental issue that needs to be addressed in any plan to mitigate the findings identified by this study.

Figure 6 shows the timing associated with the cost and schedule impacts addressed by the findings of this study. The time period during which each issue was embedded into the assumptions or design of the appropriate missions is shown in blue on the diagram, while the time period during which each issues was realized as an actual cost impact or schedule change is identified in red. With one exception, the impacts associated with replanning (Finding 4: Inadequate Mission Replans), all impacts are embedded (but not yet recognized) within the project cost and schedule plans by project confirmation at the end of phase B. However, the majority of the cost and schedule impacts are not realized as a request for increased project funding or a replan of the project schedule until well into phase D.

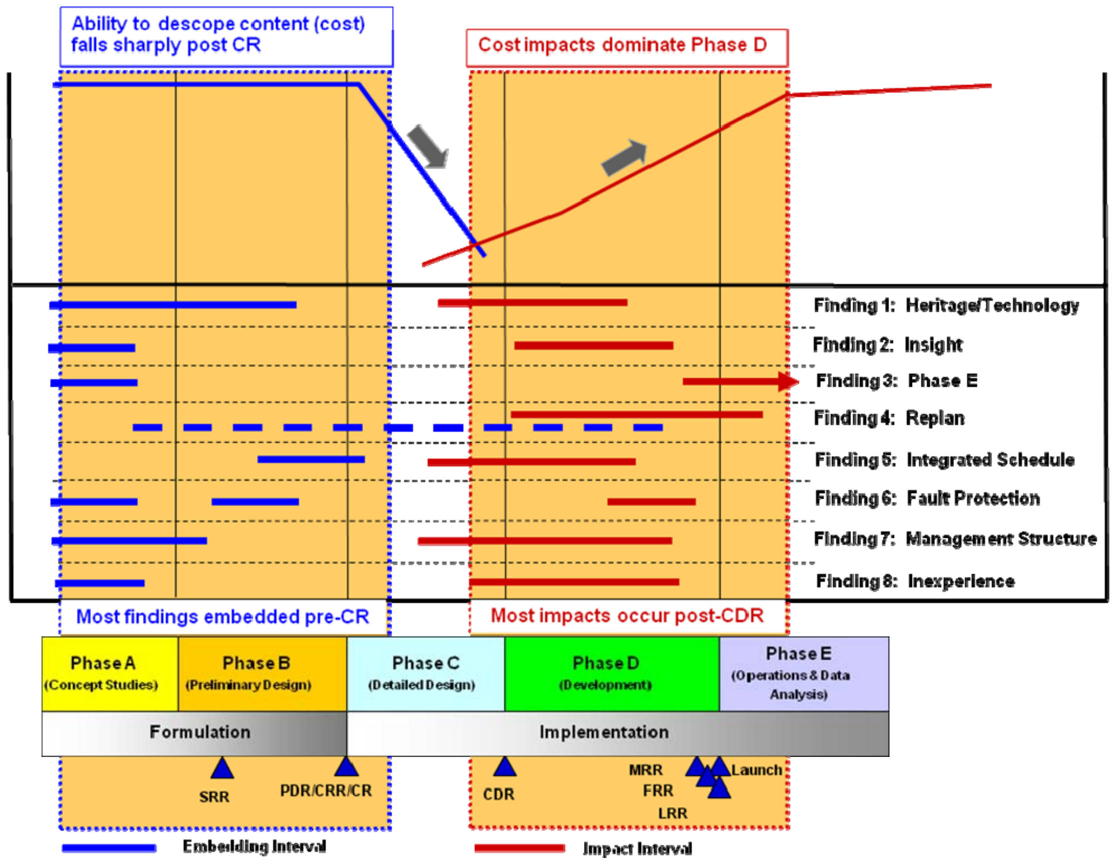

Figure 6. Embedding versus Realization of Cost & Schedule Impacts

At the same time, the ability to descope content in order to control project cost falls sharply after the end of phase B. This is primarily due to the maturity of hardware and software designs, which are at a sufficient level that the cost of redesign to omit a piece of hardware, or select an alternative, equals or exceeds the savings associated with the descope. Thus, although both of the D&NF Programs require descopes as mitigation for the inherent risk in low-cost, cost-capped missions, descopes in and of themselves do not provide sufficient protection against the risk of schedule replans and cost overruns embedded within the project plans.

Summary

The D&NF Program Office LCC Management Study provides a detailed look at the drivers underlying cost overruns and schedule delays for five D&NF missions. While none of the findings are new, the study underlines the importance of continued emphasis on sound project management techniques: a clean project management structure with a clear definition of roles and responsibilities across the various partners in a project, an understanding of institutional standards and procedures and any differences among the partners, and the critical need for a comprehensive IMS that can be used easily and routinely to identify potential threats to the critical path. The study also highlights the continuing need for realistic estimates of the total LCC. Sufficient time and resources must be allocated early in a project to ensure that the appropriate trade studies and analyses are performed across all aspects of a mission: spacecraft, ground system, operations concept, and fault management, to ensure that proposed and confirmed costs truly reflect the resource requirements over the entire mission life cycle. These studies need to include a realistic review of the assumptions underlying the use of new technologies, the integration of heritage and new hardware and software into the total mission environment, and any development and test savings based on heritage technology and lessons learned. Finally, the LCC Management Study stresses the need to listen to, carefully consider, and take positive action regarding the issues raised during reviews by the expert review teams.

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The Discovery & New Frontiers Program Office Life Cycle Cost Study was performed under the direction of Paul Gilbert/MSFC, led by Bryan Barley/MSFC, and supported by Kenny Mitchell/MSFC(Retired) and Marilyn Newhouse/CSC.

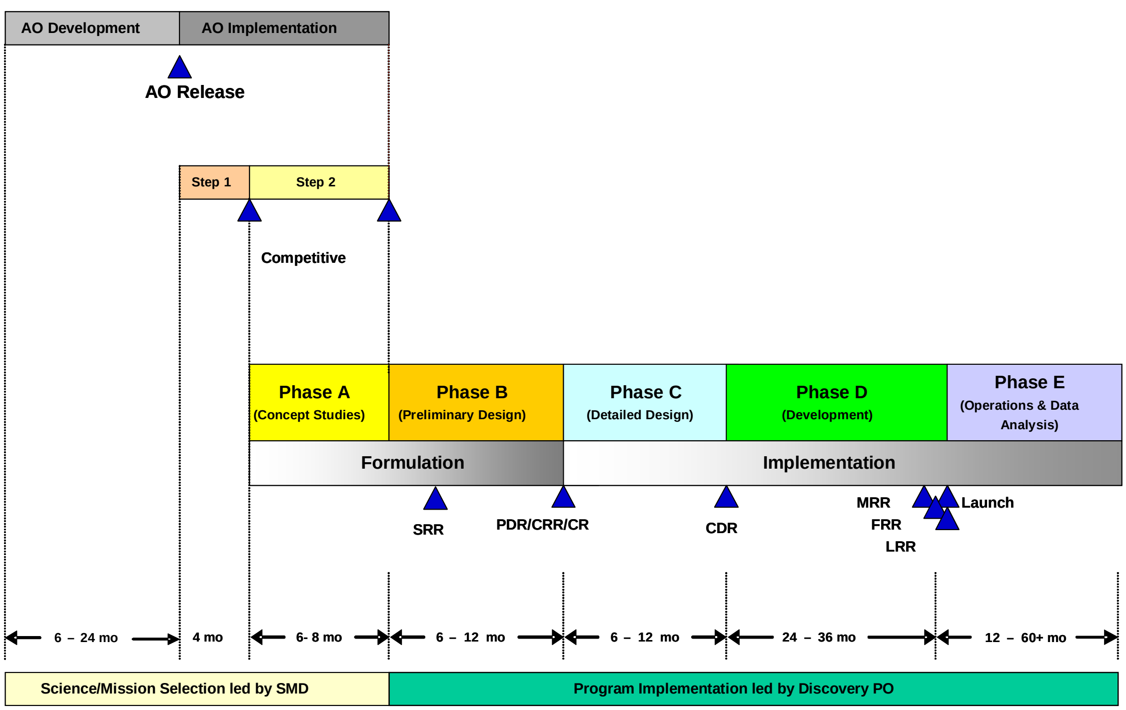
Appendix A. Terminology

Autonomy: The ability of the spacecraft to operate without intervention from ground operations. Together with fault protection, it defines the capability of a spacecraft to execute a critical science activity in deep space (e.g., encounter) without real-time intervention.

Baseline Science Requirements: That mission which, if fully implemented, accomplishes the entire set of scientific objectives identified at the initiation of the mission.

Confirmation: Authorization of a project to begin implementation; the culmination of PDR, CR, and Key Decision Point C (KDP-C).

Decision Gates: Mission milestones at which NASA reviews project plans and makes decisions that commit funding to a project's LCC. The decision gates used for this study were the selection of proposals (start of phase A), selection of a project for development (start of phase B), PDR/CR (start of phase C).



Fault Protection: The detection of and response to in-flight anomalies. The response may be "layered," some occurring autonomously onboard, others requiring intervention from the ground.

Heritage Systems: Hardware, software, and procedures with previous flight history that are reused for a new mission in order to enable a mission capability or reduce overall mission cost, schedule, or risk.

Inheritance: The process of evaluating the compatibility and benefits of heritage systems to the requirements of a new project, and validating the level of reuse or rework (design, fabrication or coding, process or procedure development, documentation) required to use the heritage system in the new mission environment.

Minimum Science: See Threshold Science.

Mission Manager (MM): A D&NF program office role that provides the primary day-to-day interface between the program and the project. MMs have a detailed knowledge of the cost and schedule history, and are cognizant of the technical and programmatic issues for their missions.

Mission Program Executive (PE): The Mission PEs at NASA/HQ support the Associate Administrator (AA) for the SMD and the Program Director in defining, integrating, and assessing the activities of D&NF Projects. The mission PEs are cognizant of project technical, schedule, and cost performance and provide course correction recommendations to the Program Director and directorate management.

Principal Investigator (PI): The programmatic lead for D&NF missions. As PI-led missions, the PI retains ultimate authority and responsibility for the cost, schedule, technical, and science performance for their mission.

Science Floor: See Threshold Science.

Technology Development: .

Threshold Science: The minimum scientific requirements below which the mission is not considered justifiable for the proposed cost. Also referred to as **Minimum Science** and **Science Floor**.

Appendix B. Acronyms

AA	Associate Administrator
AO	Announcement of Opportunity
CDR	Critical Design Review
CR	Confirmation Review
CSR	Concept Study Report
D&NF	Discovery and New Frontiers
DP	Discovery Program
DPI	Deputy Principal Investigator
EVM	Earned Value Management
FPA	fault protection and autonomy
FRR	Flight Readiness Review
HQ	Headquarters
IBR	Integrated Baseline Review
IESD	internal electrostatic discharge
IMS	Integrated Master Schedule
LCC	life cycle cost
LRR	Launch Readiness Review
MM	Mission Manager
MRR	Mission Readiness Review
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NFP	New Frontiers Program
NIAT	NASA Integrated Action Team
NPR	NASA Procedural Requirements
PCB	Program Control Board
PDR	Preliminary Design Review
PE	Program Executive
PI	Principal Investigator
PPBE	Planning, Programming, Budgeting, and Execution
RM	Resource Manager
SIR	System Implementation Review
SMD	Science Mission Directorate
SRB	Standing Review Board
SRR	Systems Requirements Review
TMCO	technical, management, cost, and other