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Constellation Program

Lessons Learned

Volume I: Executive Summary

LESSONS LEARNED

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Constellation Program Lessons Learned
Volume I: Executive Summary

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FOREWORD

The Constellation Program, as a national-level undertaking, had multiple purposes. These can and will be described from many points of view.

To us Constellation was born of the charred debris, scattered in the Piney Woods of East Texas, that were reverently collected as the last remains of that delicate machine Columbia, she that failed to preserve the lives of our friends and colleagues due to our own very human errors. The painful acknowledgement of those errors became foundational principles for what later emerged as the nation's new space exploration program: Constellation.

For those of us who worked it, the program bound us by a common belief that America's future lies in the Final Frontier; indeed that America must lead the way there. We joyfully dedicated our working lives and careers to building the ships that would sail those treacherous seas. We had prepared ourselves for this challenge, having learned from the best and honed our skills in the unique arena of human space flight. We were driven by the hope that America would one day step beyond the known, and were blessed when, for a moment, the national will bent towards our dreams. It was a privilege and an honor to have a hand in this endeavor. Perhaps our greatest shared joy and satisfaction came from the recognition that amid the inherent tumult of a program of this size and scope, we bore the challenges with teammates of superior skill and dedication. We understood that another generation would explore using what we had conceived and built. We rejoiced at our successes, but we also knew faults and failures. This, the summation of what we have learned, is our final expression of that cherished hope.

To our families, we beg your forgiveness for the long hours away and too many distracted conversations. Thank you for indulging our passion.

And, to our generational forebears in human space flight, our hope is that our efforts honor you.

CONTENTS

Foreword....iv

Contents....v

Preface....vii

1.0 Introduction....1

2.0 Context — "WHERE YOU STAND DEPENDS ON WHERE YOU SIT"....2

2.1 A Brief Description of the Program....2

2.2 The Program Environment — Key to Understanding the Lessons Learned....4

2.2.1 Program Scope....4

2.2.2 Program Funding....4

2.2.3 The Mosaic of NASA Participation....8

2.2.4 Phasing of Project/Program Start-up....9

3.0 Key Findings....11

4.0 Lessons Learned....12

4.1 Robust vs. Optimal Planning — The Only Certainty Is that the Funding Will Not Match the Plan....12

4.2 Schedule Creep and the Fixed Base — The Law of Diminishing Returns....12

4.3 Tailoring and the Design and Construction Standards — Drinking from a Fire Hose....13

4.4 Tailoring Process Simplification —The Law of Unexpected Consequences....14

4.5 Risk-informed Design — Risk as a Commodity....15

4.6 In-house Tasks — Sustaining the NASA Institutional Base vs. Affordably Supporting the Programs — Getting from "or" to "and"....16

4.7 Roles, Responsibility, and Authority — a Non-thermodynamic Application of Entropy....17

4.8 Decision Making — Only as Efficient as Roles, Responsibilities, and Authorities Are Clear and Understood....19

4.9 Organization Is Organic — You'll Never Get It Right, But You Can Make It Better....21

4.10 Communication Among a Far-flung Team — Interpersonal Networks and Information Techology Applications Can Improve Bandwidth.....22

4.11 Flight Tests — Learning by Doing 23

5.0 Development Process, Knowledge Capture, and Contributors 25

Appendix A. PAPER ON PROGRAM FORMULATION 26

Appendix B. ACRONYMS 41

PREFACE

"Experience keeps a dear school, but fools will learn in no other."—Benjamin Franklin

Learning from experience is irreplaceable. Learning from the experience of others is the next best thing. Both are an exercise in judgment. Sifting the useful kernels in a chaos of chaff requires perception and oftentimes detachment. We have attempted to present these lessons in a manner that allows this, and a format that can enable rapid learning in this context.

This document (Volume I) provides an executive summary of the lessons learned from the Constellation Program. A companion document (Volume II) provides more detailed analyses for those seeking further insight and information.

In this volume, Section 1.0 introduces the approach in preparing and organizing the content to enable rapid assimilation of the lessons. Section 2.0 describes the contextual framework in which the Constellation Program was formulated and functioned, which is necessary to understand most of the lessons. Context of a former program may seem irrelevant in the heady days of new program formulation. However, readers should take some time to understand the context. Many of the lessons would be different in a different context, so the reader should reflect on the similarities and differences in his or her current circumstances. Section 3.0 summarizes key findings, at the program level, developed from the significant lessons learned that appear in Section 4.0. Readers can use the key findings in Section 3.0 to peruse for particular topics, and will find more supporting detail and analyses in a topical format in Section 4.0. Appendix A contains a white paper describing the Constellation Program formulation that may be of use to readers wanting more context or background information.

The reader will no doubt recognize some very similar themes from previous lessons learned, blue-ribbon committee reviews, National Academy reviews, and advisory panel reviews for this and other large-scale human space flight programs; including Apollo, Space Shuttle, Shuttle/Mir, and the International Space Station. This could signal an inability to learn lessons from previous generations; however, it is more likely that similar challenges persist in the Agency structure and approach to program formulation, budget advocacy, and management. Perhaps the greatest value of these Constellation lessons learned can be found in viewing them in context with these previous efforts to guide and advise the Agency and its stakeholders.

1.0 INTRODUCTION

These lessons learned are part of a suite of hardware, software, test results, designs, knowledge base, and documentation that comprises the legacy of the Constellation Program.

The context, summary information, and lessons learned are presented in a factual format, as known and described at the time. While our opinions might be discernable in context, we have avoided all but factually sustainable statements. Statements should not be viewed as either positive or negative; their value lies in what we did and what we learned that is worthy of passing on.

The lessons include both “dos” and “don’ts.” In many cases, one person’s “do” can be viewed as another person’s “don’t”; therefore, we have attempted to capture both perspectives when applicable and useful.

The lessons have been formatted with a description together with supporting information, a succinct statement of the lesson learned, and recommendations for future programs and projects that may be placed in similar circumstances.

Supporting information, along with more detail on the Constellation Program, can be found in Appendix A and the companion Volume II.

2.0 CONTEXT — "WHERE YOU STAND DEPENDS ON WHERE YOU SIT"

2.1 A Brief Description of the Program

NASA formed the Constellation Program in 2005 to achieve the objectives of maintaining American presence in low-Earth orbit, returning to the moon for purposes of establishing an outpost, and laying the foundation to explore Mars and beyond in the first half of the 21st century. The Constellation Program's heritage rested on the successes and lessons learned from NASA's previous human space flight programs: Mercury, Gemini, Apollo, Space Shuttle, and the International Space Station (ISS).

Following the loss of *Columbia*, NASA established the *Columbia* Accident Investigation Board (CAIB) to perform an in-depth review of the Space Shuttle Program. As a result of this review, the CAIB concluded that it was in the best interest of the U.S. to develop a replacement for the space shuttle. The CAIB concluded that it should be possible, using past and future investments in technology, to develop the basis for a system "significantly improved over one designed 40 years earlier, for carrying humans to orbit and enabling their work in space."

In January 2004, The White House issued a new exploration initiative to return humans to the moon by 2020 in preparation for the human exploration of Mars and beyond. As part of this initiative, NASA would continue to use the space shuttle to fulfill its obligation to complete assembly of the ISS and then retire the space shuttle by 2010. NASA would also build and fly a new Crew Exploration Vehicle (since named *Orion*) by 2014. In 2005, Congress expressly endorsed the President's exploration initiative and authorized NASA to "…establish a program to develop a sustained human presence on the moon, including a robust precursor program to promote exploration, science, commerce and U.S. preeminence in space, and as a stepping stone to future exploration of Mars and other destinations."

In response to the Presidential direction, the Agency formed the Exploration Systems Mission Directorate (ESMD) at NASA Headquarters in 2004 to oversee development of exploration programs. The Constellation Systems Division was initiated to oversee the human exploration mission development.

In May 2005, the NASA Administrator commissioned the Exploration Systems Architecture Study (ESAS), a 60-day study to perform the task of defining the top-level requirements and configurations for crew and cargo launch systems to support exploration objectives. The study concluded that the launch vehicles should be derived from existing technologies, leveraging the lessons learned from past programs. The ESAS recommended an architecture that formed the basis of the Constellation Program.

For those interested, Appendix A contains a paper that describes in more detail the rationale behind the formulation of the Constellation Program, including organizational structure and workforce structure, as well as the approaches to requirements generation, budget formulation, operational philosophies, and procurement strategies.

Since exploration of the moon and beyond was the overarching goal of the Constellation Program, all elements were designed to perform the lunar missions, while also being capable of performing missions to the ISS. The program was phased as a stepwise capability buildup that was largely based on space shuttle heritage components. The Initial Capability (IC) comprised elements necessary to service the ISS by 2015 with crew rotations: including the *Orion* Crew Exploration Vehicle, the *Ares I* Crew Launch Vehicle, and the supporting ground and mission infrastructure to enable these missions. The Constellation Lunar Capability (LC) added the *Ares V* Cargo Launch Vehicle, the *Altair* Lunar Lander, and spacesuits designed for partial-gravity exploration. Lunar Outpost elements and capabilities were to follow, including mobility elements such as rovers, permanent or semipermanent habitats, and power and communication elements to support a sustained exploration presence.

The Constellation Program was managed at the Johnson Space Center (JSC), with the following seven "hardware development" project offices:

- Crew Exploration Vehicle Project (the *Orion* spacecraft), at JSC
- Exploration Launch Projects (the *Ares I* and *Ares V* launch vehicles), at the Marshall Space Flight Center (MSFC)
- Ground Operations Project (development of launch and recovery facilities) at the Kennedy Space Center (KSC)
- Mission Operations Project (development of flight and mission control facilities) at JSC
- Extravehicular Activity (EVA) Systems Project (spacesuit and tool development) at JSC
- Lunar Lander Project (the *Altair* lunar descent and ascent module) at JSC
- Lunar Surface Systems Pre-project (advanced planning for lunar habitats and surface support systems) at JSC

Orion, *Ares I*, Ground Operations, Mission Operations, and EVA comprised the IC projects. *Ares V*, the *Altair* and Lunar Surface Systems, along with upgrades to the IC to meet lunar interfaces and requirements, comprised the LC projects.

By 2010, all elements of the IC had achieved Preliminary Design Review (PDR), and test flights were under way, with the successful launches of *Ares I*-X and the *Orion* Pad Abort-1 tests. The White House announced the cancellation of the program on Feb. 1, 2010, on the seventh anniversary of the loss of *Columbia* and her crew.

According to the NASA Authorization Act of 2010 (PL 111-267, Oct. 11, 2010), elements of the Constellation Program will continue in NASA's current planning. The *Orion* vehicle is redesigned as the Multi-Purpose Crewed Vechicle (MPCV) and will likely enable crew launch on a variety of launch vehicles. The Space Launch System (SLS), intended as the vehicle to launch crews and cargo beyond Low Earth Orbit (LEO), has various configurations under consideration including options based on space shuttle and *Ares* heritage designs and hardware. The Ground

Operations infrastructure at KSC, developed for Constellation, will be adapted to the SLS and new commercial launch capabilities.

2.2 The Program Environment — Key to Understanding the Lessons Learned

2.2.1 Program Scope

The Constellation Program was conceived as a multi-decadal undertaking, with the primary goal of enabling human exploration beyond LEO. It was to serve as the space shuttle's successor not only in function but also in utilization of facilities and work force. It was to provide the primary mode of delivery of crews to the ISS, enable the construction and operation of an outpost on the moon, and enable human exploration of Mars. Constellation, as the Agency's flagship program, spanned all 10 NASA centers and multiple large-scale acquisitions. It required modernizing an infrastructure that had been designed and sized largely for the Apollo Program in the 1960s. Moreover, it required leading a work force that was generationally removed from the previous human spacecraft launch and entry development challenges.

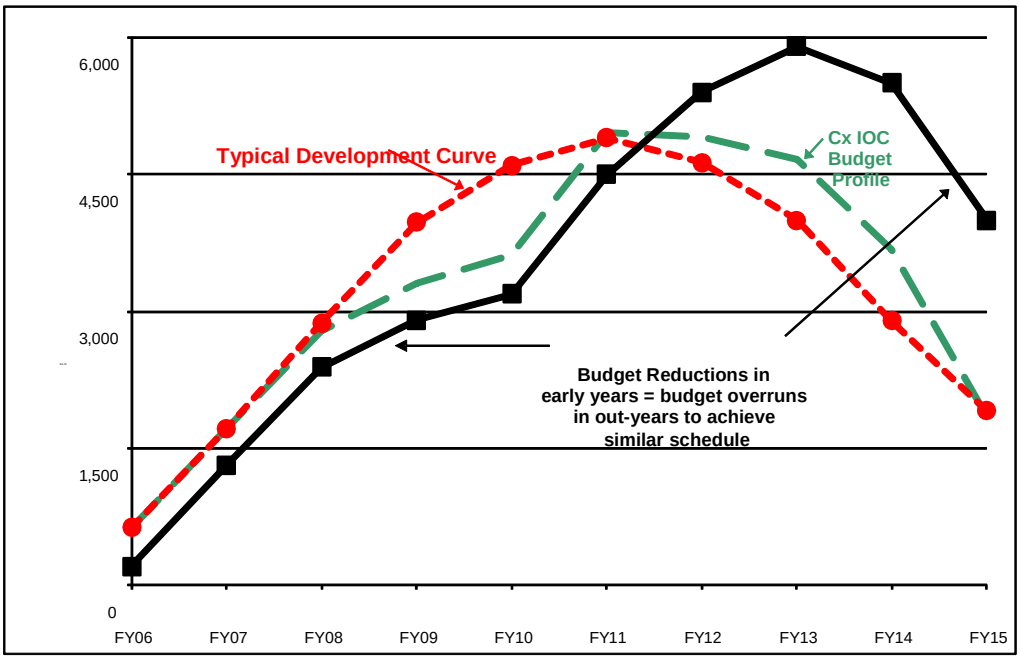
While the near-term focus of the program was providing crew transport to the ISS via the IC, the capability to go beyond LEO drove many of the technical and programmatic decisions. These decisions were suboptimal when viewed with only near-term objectives in mind, while they were necessary to support the LC phases of the program. They also, in some cases, increased risk to the IC through incorporation of newer technologies with less flight heritage. The need for commonality to decrease life-cycle cost and complexity drove many decisions. For example, the *Ares I* design used a five-segment, solid-chemical first stage along with the J2-X upper stage engine. Other simpler, less-costly designs could have been used to optimize development for the *Ares I* alone, but, in context with the *Ares V* development, these elements lowered the overall program design complexity, risk, and cost.

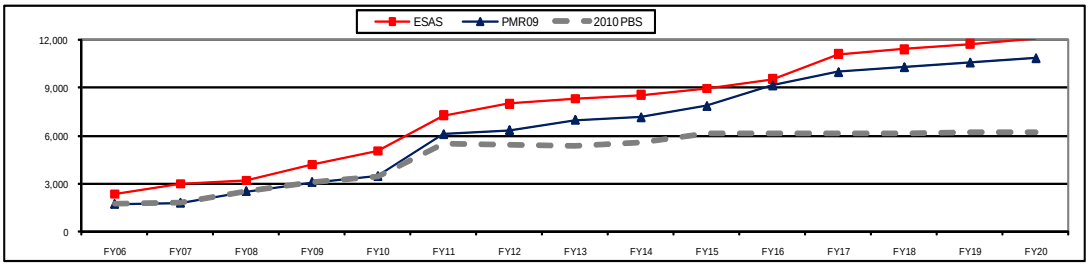
Optimization for the long-term program drove not only design decisions but also infrastructure needs, standards, organizational structure, units of measure (SI), data architecture, etc., that would not have been necessary for the IC alone. The primary objective of stepping beyond LEO with the LC was optimized at the expense of having an IC that was more costly and complex than necessary as a stand-alone development.

2.2.2 Program Funding

Funding for the Constellation Program was inconsistent and unreliable from its initial formulation through its cancellation. Indeed, this inconsistency became the chronic constraint that aggravated all other constraints. Figure 1 illustrates this persistent problem. The program experienced a 10% budget cut prior to PDR. The "profile" was far less than optimal for a development project. The funding "notch" in fiscal year 2010 (FY10) was a result of Agency funding limitations due to space shuttle retirement. While Constellation was expected to transport crews to and from ISS soon after space shuttle retirement, the funding ramp-up needed for development was not available until *after* the space shuttle was retired. This, of

course, put pressure on the program content, schedule, and rationale for the ISS crew rotation mission (Initial Operational Capability [IOC]).





RY$ In M	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20	Total
ESAS	2,333	2,976	3,195	4,202	5,034	7,273	7,994	8,324	8,558	8,948	9,547	11,107	11,422	11,744	12,073	114730
PMR09	1707	1779	2514	3085	3454	6085	6346	6991	7145	7856	9145	9983	10294	10582	10854	97820
2010 PBS	1707	1779	2514	3085	3454	5524	5444	5376	5570	6153	6161	6170	6178	6186	6195	71496
PMR09 vs. ESAS Delta	(626)	(1197)	(681)	(1117)	(1580)	(1188)	(1648)	(1333)	(1413)	(1092)	(402)	(1124)	(1128)	(1162)	(1219)	(16910)
Passback vs. ESAS Delta	(626)	(1197)	(681)	(1117)	(1580)	(1749)	(2550)	(2948)	(2988)	(2795)	(3386)	(4937)	(5244)	(5558)	(5878)	(43234)

Fig. 1: Constellation budget profiles before and after budget reductions (ESAS=the initial program budget baseline; PMR=Program Manager's Recommendation; PBS=President's Budget Submittal)

Figure 2 illustrates the result of the budget pressure on major schedule milestones (PDR, Critical Design Review [CDR], IOC, and human lunar return [HLR]). IOC moved 2 years (2012 to 2014) due to the first budget cut. The program was able to recapture 1 year of that loss by replanning (at greater risk). Subsequent budget cuts pushed IOC further, into 2015. The program was required to hold the IOC schedule commitment to 2015, since this was the "no later than" date that was committed to Congress.

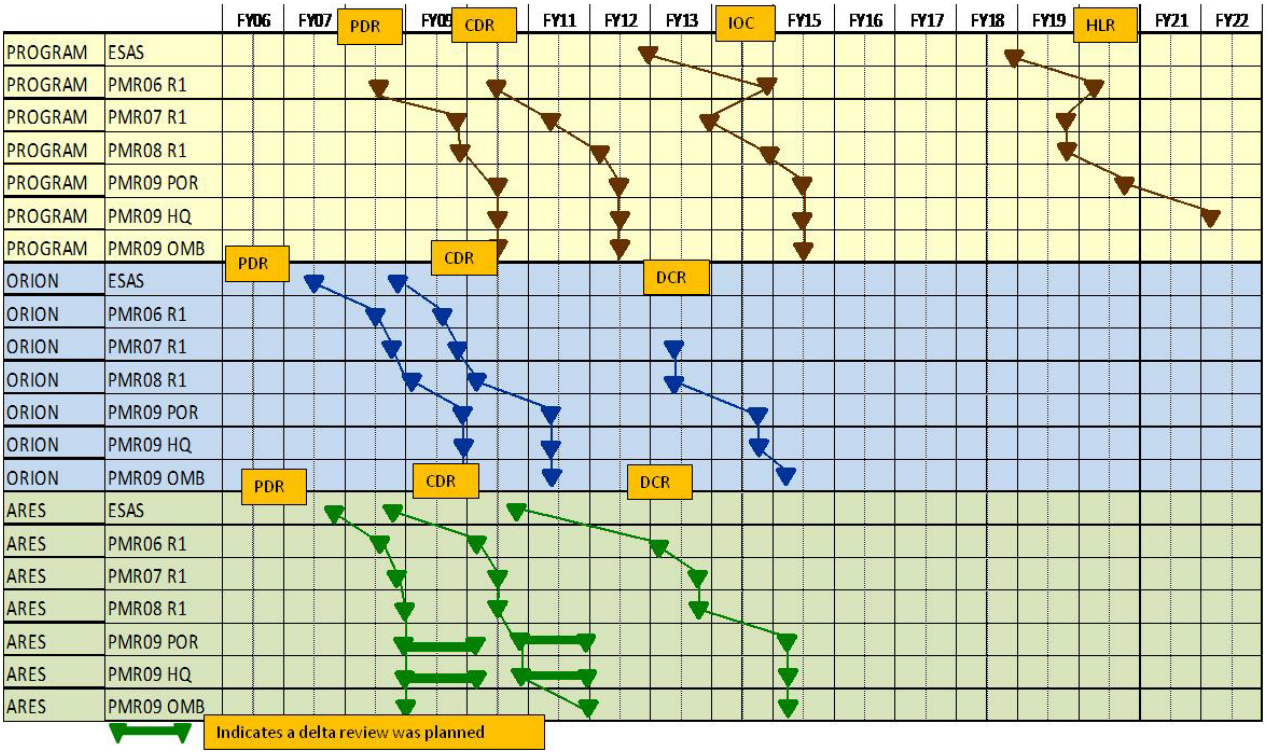


Fig. 2: Consequences of funding cuts on Constellation major milestones

The phasing of the program exacerbated the funding challenges, in a “rob Peter to pay Paul” fashion. The viability of the lunar program phase was under constant threat, as it was the only souce to supplement shortfalls in the IC when schedule slips had been exhausted (see effect of the fixed-base costs, below). The lunar phase of the program (e.g., HLR in Fig. 2) bore the brunt of the cuts that could be accommodated in out-years and was pushed even further than the IOC milestones. This is illustrated in Fig. 2 (observe that IOC was “held” in 2015 while HLR slipped almost 2 years).

Constellation was planned with adequate budget reserves, although these reserves were not phased to be most useful to the program (i.e., much of the reserve was phased later in the program schedule rather than earlier). An unfortunately prevalent perspective on program reserves in the federal government is that reserves are seen as “over funding” that can be depleted to address other issues or drawn back to the Treasury if unused within 1 fiscal year. Agency reserves (i.e., allowance for program adjustment [APA] funds) had been long ago eliminated. Constellation reserves were intially planned to fund risk mitigation efforts. Reserves were rapidly depleted due to the combined effects of budget cuts, Agency “taxes,” and efforts to hold schedule without sacrificing content. Subsequently, risk mitigations were reduced and then eliminated, leaving little recourse to resolve the typical technical challenges that crop up in a design of this magnitude and complexity. Risk accrued as a result.

The large acquisitions for design and construction of the major components of the program were planned, sized, and budgeted early in the program, as was neccessitated to meet schedule

objectives. The prime contractors' costs typically ramped up in accordance with plan. These costs were comprised of both "fixed-base" elements (work force, test facilities, etc.), and variable elements. As the program dealt with subsequent budget cuts, the fixed-base elements were extremely difficult to reduce; cuts tended to be absorbed within the variable elements (e.g., deferred hardware buys). This led to a number of problems: it increased schedule risk as more activities crept onto the critical path; it deferred activities planned to reduce risk, delaying risk mitigation strategies and increasing overall risk; and it also became an exercise in diminished returns — fewer and fewer items remained in the variable elements of the budget to defer in the next round of reductions.

With the retirement of the Space Shuttle Program looming, great pressure was exerted to assimilate as much of the shuttle-heritage "fixed base" (e.g., work force, infrastructure, and industrial base) from that program as possible, per direction NASA received in two Authorization Acts (2005, 2008). While the operational requirements and sustaining budget planned for Constellation were smaller than that of the Space Shuttle Program, nearly every component, building, fleet, process, and cadre of workers had its advocacy group to sustain it. Because of the phasing of the Constellation Program, much of the infrastructure was not needed for the IC but would be needed for the LC. This created an Agency-wide phasing challenge for these assets: retire/mothball the asset, or sustain it for many years unused?

The tight coupling of the space shuttle retirement to the buildup of the Constellation IC, along with the necessity to plan the IC and LC with a large degree of commonality, made sense strategically when the plan was developed, but only if all of the schedule and funding assumptions held. The rationale did not withstand subsequent budget pressure and consequential schedule slips.

While the Constellation Program hardware development budget was also large in an absolute sense at the Agency level, it was not yet operational (as space shuttle and ISS), so it was often perceived as the only source for unexpected expenses that cropped up in the Agency. Indeed, expenses were charged to the program that had no benefit to the program. This is not atypical for flagship programs in governmental developments.

Cash flow disruptions, resulting from Congressional continuing resolutions (CRs), had been an occasional source of funding problems for the Agency in the past. During Constellation's lifetime, these became annual events that many times lasted well into the new fiscal year. While these are experienced government wide, they are particularly onerous on developmental programs in early stages when funding levels are increasing toward their peak. A typical program "ramp-up" is nearly impossible during a CR. These funding shortfalls sent annual "square waves" of additional re-planning through the program, projects, and contractor communities. These were never fully attenuated through the remainder of the fiscal year.

The Constellation Program content, constituted by the elements of the program architecture along with their associated performance requirements, was held as a higher priority than schedule performance by the Agency leadership; therefore, in the budget environment framed

above, schedules slipped, risk accrued, and reserves were depleted before serious consideration was given to de-scope program content.

2.2.3 The Mosaic of NASA Participation

As Constellation was the flagship program for the Agency, project and program work was distributed across the Agency to support the concept of maintaining “10 Healthy Centers” (Fig. 3). This distribution was planned at the Agency level. The concept was not sufficiently defined to satisfy either centers or the program in light of the space shuttle retirement. Details of the implementation were left to the program to sort out in consultation with center management. This resulted in a persistent tension between what was most efficient for the program vs. what was best for a particular NASA center to sustain or grow its current role. The nationwide team was probably larger than necessary, but it also covered “unused capacity” at some centers. The large teams at multiple locations led to instances of overlapping or unclear roles and responsibilities. Decisions to perform tasks “in-house” using on-site work force at a center vs. contracting the task out were often made at the center or project level, and were not optimized for overall program benefit.

The involvement of all 10 NASA centers exposed cultural differences that had to be managed by a management team that was geographically removed. Each center had different requirements, procedures, and processes, which were documented at various levels of detail and constraint. While these were useful to each center, the Agency had not completed an effort to assure that they were consistent, non-duplicative, and noncontradictory. This was a particular burden on the contractor community since it was charged with identification and compliance with duplicative and sometimes contradictory requirements. The mismatch of design and construction standards among centers, along with demands from the “insight” work force at each center, was a worrisome burden for the contractors, constantly threatening their ability to meet schedule milestones and cost thresholds. NASA’s use of an independent technical authority provided yet another source of direction and, thus, confusion to the contractor community. Contractors had difficulty distinguishing final decisions coming from the Agency, since direction could come from the program or the technical authority.

The industrial base used by the Space Shuttle Program and, to a lesser extent, the ISS Program was managed by a separate mission directorate at NASA HQ. Overlapping strategic interests among the three programs (e.g., facility usage, floor space, test stands) had to be resolved at the highest levels in the Agency (i.e., between mission directorates).

The position of an Agency flagship program carried benefits as well. The program had access to the entire Agency knowledge base, along with skills and infrastructure. The program was viewed as high priority at all centers, since it represented a path to a sustainable and growing role in most areas of expertise. Engagement of nontraditional human space flight centers allowed the program to tap into unique skills, approaches, and facilities. The contractors benefited from NASA’s technical depth and expertise, along with access to unique facilities (e.g., engine test stands, large vacuum chambers). The early test flights, *Ares I*-X and *Orion* Pad Abort-1, demonstrated the benefits of multicenter teams. These projects were successful

early pathfinders in identifying and resolving the problems that could arise from a conflict of cultures in design, testing, and manufacturing.

Fig. 3: The Constellation distributed team

2.2.4 Phasing of Project/Program Start-up

Two of the primary projects, the *Orion* Crew Exploration Vehicle and the *Ares* Crew Launch Vehicle, were begun well in advance of the Constellation Program. This enabled rapid start-up and early results from each project. They functioned for some time without an integration function between them, which led to an eventual Program Integration (PI) function that was very lean by historical norms.[1] The rapid start-up enabled rapid contract competition. However, these contracts were not fully scoped for the physical and analytical integration that was necessary. They were instead focussed on the IC, since trade studies had not been performed that would optimize an integrated architecture. These factors led to costly contract changes when the appropriate level of integration for a complete architecture was better understood.

This approach also provided an additional integration challenge. The projects had formed requirements, budgets, design approaches, acquisition strategies, etc., that needed to be

[1] A typical large space flight program historically used approximately 10% to 15% of its budget for PI. The Constellation Program was relatively lean, spending 5% to 7.5% on these functions.

integrated retroactively. The late addition of the integrating functions had a long-term effect that was not fully resolved by the end of the program. Strategies that were in a collective self-interest for the program were extraordinarily difficult to implement due to the cost of contract changes. Examples of these include unit policy (SI vs. heritage units of design and construction), data architecture, and facilities management. Boards and panels formed prior to the program office had different structures and responsibilities. Integration of these into a program board and panel structure confounded decision making. Moreover, integrated analyses by the program uncovered technical issues that could have been caught earlier (and been resolved in a more efficient manner) if the start-up timing had been different.[2]

Incentives on contracts were developed primarily to benefit each project rather than the overall program. Missing were incentives for contractors to participate in technical solutions that benefit the integrated program. This drove results that were less than optimum, and sometimes not mutually compatible.

[2] An example of this is what became known as the “thrust oscillation” issue. Integrated analyses indicated that unacceptably large thrust oscillations from the *Ares I* first-stage burn could be transmitted through the stack to the flight crew in the *Orion* vehicle during launch. Design changes were implemented in the PDR time frame to mechanically dampen the oscillations and sufficiently isolate the crew. We can speculate that earlier identification could have resulted in simpler, lower cost changes.

3.0 KEY FINDINGS

Given the challenges described in Section 2.0, the following is a brief listing of the key findings distilled from the Constellation Program. Explanatory information can be found in Section 4.0, and further detail is contained in Volume II. This list is hot linked to explanatory information in the electronic version of this document.

The character of these lessons is worth noting. The reader will observe that very few technical issues arose that could not be solved in relatively short order; rather, the most difficult and most persistent challenges involved cost, schedule, and organization. The reader will no doubt recognize this pattern from previous large-program lessons learned. While the Agency is renowned for its technical prowess, senior managers in flagship programs can be faced with a multitude of nontechnical challenges for which they have far less training or preparation. In this respect, lessons learned can be an invaluable source of insight.

- **Robust vs. optimal planning—the only certainty is that funding will not match the plan**
- **Schedule creep and the fixed base—the law of diminishing returns**
- **Tailoring and the design and construction standards—drinking from a fire hose**
- **Tailoring process simplification—the law of unexpected consequences**
- **Risk-informed design—risk as a commodity**
- **In-house tasks—sustaining the NASA institutional base vs. affordably supporting the programs—getting from "or" to "and"**
- **Roles, responsibility, and authority (RRA)—a non-thermodynamic application of entropy**
- **Decision making—is only as efficient as RRAs are clear and understood**
- **Organization is organic—you will never get it right, but you can make it better**
- **Communication among a far-flung team—interpersonal networks and information technology (IT) applications can improve bandwidth**
- **Flight tests—learning by doing**

4.0 LESSONS LEARNED

4.1 Robust vs. Optimal Planning — The Only Certainty Is that the Funding Will Not Match the Plan

Driving Events

Section 2.1 describes the context and driving events for the funding and planning challenges faced by the Constellation Program. Constellation found itself in a grounds-up re-plan at least annually.

Lessons Learned

The reality is that Agency flagship programs like Constellation must be robustly planned (e.g., "elastic") vs. optimally planned ("inelastic"). Absent a national imperative akin to the race to the moon, funding will not arrive as planned. Flagship programs are highly visible and stand alone in the national-level budget debates. As they are not part of a budget portfolio, they cannot look elsewhere for funding.

A flagship program will never experience complete alignment of the budget with the plan, either in net or in phasing. Therefore, flagship programs should resist the urge to optimally plan each budget line item.

Recommendation

Plan for CRs for the first quarter of each fiscal year until and unless Congressional processes change substantially.

Decouple programs/projects as much as possible in strategic, programmatic, and technical aspects.

Proactively determine sensitivities and breakpoints in budgets, and communicate these to stakeholders *a priori*. Establish expectations for funding reductions in advance. This is the best hope to influence budget decisions.

Develop scenario(s) to accommodate 5% to 10% funding shortfalls in any given fiscal year. Understand the major drivers to cost and options available (i.e., "the knobs to turn") when unexpected challenges appear.

4.2 Schedule Creep and the Fixed Base — The Law of Diminishing Returns

Driving Events

As discussed in Section 2.2, the Constellation Program dealt with funding cuts primarily through schedule slips rather than content reductions (due to NASA Administrator direction). Variable costs are early targets, since they can be deferred (while adding program risk). The fixed-base

costs — both within the Agency and for the contractors — become proportionally larger, making schedule slips less and less effective in addressing cost cuts.

Lessons Learned

Each schedule slip resulted in longer periods for which Constellation was expected to maintain the Agency's human space flight "fixed base" along with the industrial fixed base from its suite of acquisitions. This had the effect of reducing the overall cost savings being sought from the initiating event — the funding cut. A vicious cycle was established that only grew more severe during the life of the program as more and more time supporting the fixed base was added to the program lifetime. Ultimately it could not be resolved without addressing content reductions.

Recommendation

Understand the inherent limitations of schedule slippage to resolve funding shortfalls, since accrual of the fixed-base portion of the budget erodes the buying power in out-year funding. Reduction of program content warrants consideration under these circumstances.

4.3 Tailoring and the Design and Construction Standards — Drinking from a Fire Hose

Driving Events

The involvement of the 10 NASA centers (described in Section 2.2.3, Mosaic of NASA Participation), along with the overabundance and over-prescriptive nature of design and construction standards led to an avalanche of "shall" requirements on the Constellation contractors. While Constellation was allowed broad latitude to tailor requirements, such tailoring required rationale and negotiation with the requirement "holder." The sheer number of direct and embedded requirements made the task of tailoring intractable.

The following illustrates the extent of the problem:

- The *Orion* prime contract alone levied design and construction (D&C) specifications from: 34 NASA standards, 10 Johnson (Space Center) Program Requirement (JPR) documents, 11 JSC technical standards, 3 NASA Program Directives (NPDs), 6 NASA Program Requirements (NPRs), and 11 KSC standards. These included:
    - NASA STD 8739.3, Soldered Electrical Connections – a 93-page document with 391 "shall" statements inclusive of room temperature/relative humidity and 1077 lumens of light per square meter or 100 foot candles on the work surface.
    - NASA STD 8739.4, Crimping/Cables/Harnesses/Wiring – a 66-page document containing 391 "shall" statements requiring a (a) Snell far-vision chart 20/50; (b) near-vision Jaeger1 @ 355.6 mm; and (c) reduced Snell 20/20 or equivalent. Requires color vision testing and specifies temperature/humidity and lighting.
    - NASA STD 8719.9, Standard for Lifting Devices – a 126-page document containing 996 "shall" statements covering use of overhead devices and powered and motorized devices; it also approves the use of manufacturer's procedures

and provides instruction on how to set the parking brakes on mobile and motorized units.

All of the major aerospace contractors, who build systems for multiple government customers (Department of Defense (DoD), National Security Agency (NSA), NASA, etc.), have certified internal processes and suppliers that meet both national and international standards. The set of NASA requirements is often redundant to this.

Lessons Learned

The massive quantity of D&C standards defies tailoring for even a large program such as Constellation. Major aerospace contractors have sufficient processes such that NASA's D&C standards are of questionable value. This is a major driver of program-fixed costs.

Recommendation

NASA should assume the burden of "meets or exceeds" evaluations on itself instead of making the contractor prove it meets NASA requirements. NASA should implement this by establishing an experienced team to audit contractor internal processes at the NASA document level. This process should not burden the contractor with defending the adequacy of each individual requirement. For the most part, the aerospace contractor community is well versed in the appropriate manufacturing and safety measures required to develop space hardware. NASA should build on that expertise.

Currently, this topic (Affordability/Innovation) is the subject of discussion among the Chief Engineer's Office, the Office of the Chief Health and Medical Officer, and Safety and Mission Assurance (S&MA) leadership. A team has been tasked with describing a process and timeline for transforming the Agency approach to Technical Authority requirements and standards. This initiative should establish clear criteria for mandatory ("shall") requirements. It should also revalidate the Agency's current requirements base with the goal of significantly reducing the total number. Most requirements should become guidelines or best practices.

4.4 Tailoring Process Simplification —The Law of Unexpected Consequences

Driving Events

One of the many findings of the CAIB was that NASA had institutionalized the waiver and deviation process for requirements such that permanent or semipermanent waivers and deviations to requirements were the accepted norm. The CAIB, and other committees and panels studying the NASA human space flight culture, questioned the quality and validity of requirements that need permanent waivers or deviations to remain extant. Consequently, the need to establish a waiver or deviation developed an understandable cultural taint in the work force. Training after the *Columbia* accident reenforced this aversion. Indeed, important NASA stakeholders (e.g., Congress, the Aerospace Safety Advisory Panel, members of the public) were keen to maintain visibility on NASA's use of waivers.

Meanwhile, the Agency did not grapple with the plethora of requirements that drove the practical need for waivers and deviations to requirements. While the Agency approach to requirements was redesigned with the introduction of the independent Technical Authority, the actual number and scope of requirements was not addressed.

This left the Constellation Program in a quandary. While the Constellation Program was allowed broad latitude in tailoring requirements to its needs, the Agency decided that the program would use deviations and waivers to document tailoring outcomes. Cultural consequences were not evaluated. Moreover, the process for permanent deviations and waivers was formalized by the Agency. Discussions of tailoring were driven down to the level at which they were most productive — to those most familiar with design and implementation. However, waivers and deviations required higher visibility within the Agency to agree on. This cultural inconsistency, coupled with the sheer number of requirements addressed in the previous lesson, made the tailoring process nearly insurmountable.

Lessons Learned

While the use of waivers and deviations was intended to simplify the tailoring process of requirements for the Constellation Program, the cultural consequences were not addressed. This had the unintended consequence of confounding the tailoring process rather than assisting it.

Recommendation

Tailoring of requirements is necessary and should not carry a cultural stigma. The process should be revised to remedy the negative implication.

4.5 Risk-informed Design — Risk as a Commodity

Driving Events

The broad scope of the Constellation Program permitted, to great effect, some experimentation in the design process. The traditional aerospace design process (i.e., the “rule-based” approach), wherein the vehicle is designed strictly to requirements (and, by implication, all requirements are equal or nearly so), was used on most elements. Two elements employed a risk-based approach that resulted in overall better designs.

The *Orion* vehicle was designed initially using the rule-based approach. In meeting all requirements, the vehicle was overly constrained, was too heavy, and had performance challenges. To “close the architecture,” the project implemented a revised design process that prioritized mission-critical, reliability, and safety requirements. A “zero-based” vehicle was designed that met only these requirements. All other design features required justification based on an ability to reduce risk, i.e., risk as a commodity, using standard risk assessment tools (e.g., probabilistic risk assessment, hazard analysis, and failure modes and effects analysis) along with the beneficial use of other design commodities (e.g., power, mass, budget). The ability of

the *Orion* vehicle to minimize LOC (loss of crew) probability, along with meeting of performance and mass constraints, was improved through application of this process.

The *Altair* vehicle pioneered a similar approach, which was uniquely applied *a priori*. The Risk Informed Design Process used an analysis-based approach to design the absolute minimum vehicle necessary to perform the mission and then added design features by proven value in increasing vehicle reliability and safety. This resulted in more robust design solutions that either eliminated or better-controlled hazards.

Lessons Learned

Risk Informed Design (i.e., treating risk as a commodity in design) was a breakthrough for both *Orion* and *Altair*, resulting in designs that "closed" and were safer and more reliable than a "rule-based" design approach could yield.

Recommendation

A rule-based design approach can remove accountability for understanding the implications of design choices. Employ risk-informed design methodology *a priori* to focus design on overall mission success rather than compliance with "design rules."

4.6 In-house Tasks — Sustaining the NASA Institutional Base vs. Affordably Supporting the Programs — Getting from "or" to "and"

Driving Events

The driving events for this lesson are described in Section 2.2.3 under "Mosaic of NASA Participation."

While the Constellation Program attempted to distribute work in logical packages, the competing needs of "10 Healthy Centers," the scope of the program, and phasing considerations (e.g., placement of work in the post-shuttle era) drove instances of incoherent distribution, resulting in muddling of roles, responsibility, and authority.

An example of the *Orion* Launch Abort System (LAS) development further illustrates the wide distribution of roles and responsibilities. This development was a subsystem of *Orion* and is not an extreme example, but it is typical of the rest of the program. Responsibilities were divided as follows:

- JSC: *Orion* project management, lead for crew module and vehicle integration, prime contractor oversight, and independent analysis
- MSFC: LAS prime contractor oversight and independent analysis
- Langley Research Center: Lead for LAS integration, prime contractor oversight, and independent analysis
- Glenn Research Center: Flight Test Article and pathfinder production for service module and spacecraft adapter

- Dryden Flight Research Center: Lead for Abort Flight Test integration and operations

When everybody is responsible for everything, nobody is responsible for any one thing.

Furthermore, the relatively low cost of most in-house tasks can be deceiving. While sometimes low in cost, the price of confused RR&A can lead to major headaches that flow into the contractor infrastructure. These roles are often coupled with the desire for modernization of associated host center facilities, which can drive larger costs.

Lessons Learned

Task assignments for in-house work are strategic drivers within the Agency; they are more than a series of make-buy or in-house vs. contractor decisions. Clear RR&As must be a priority. In spite of the relative low cost, the distribution and RR&A for in-house tasks are deserving of management focus to avoid confusion and overlapping roles down the line.

Recommendation

Target in-house tasks for items that mutually benefit programs (e.g., unique expertise) and centers (e.g., institutional sustainment). Due diligence will be needed to achieve this balance of benefit to the program *and* benefit to the NASA institution. A balance will bring value to the program as well as provide strategic support for the NASA institution, equipping the Agency to accomplish future programs and missions.

Affordability, institutional benefit, and coherence of RR&A should be three additional strategic considerations in these decisions. Simply said, make sure the gain is worth the pain.

4.7 Roles, Responsibility, and Authority — a Non-thermodynamic Application of Entropy

Driving Events

The clarity of RR&A for the Constellation Program was degraded by the combined effects of the wide distribution of program responsibilities via the “10 Healthy Centers” policy, multi-decadal phasing of the program development in IC and LC, and assumption of traditionally understood roles from the space shuttle heritage component development as described in Section 2.2.

The program undertook a number of steps to improve this, by conducting work force surveys and regular management retreats. Perhaps the most successful effort was the Program Excellence Team, a council of program deputies that frequently met face-to-face and via telecon to work through specific issues related to RR&A.

Lessons Learned

There is no formula or checklist for clear RR&A in an agency-wide flagship program. The specific approach on organizational structure taken by Constellation in this regard is addressed in Appendix A, in the paper on formulation of the program. Projects housed at centers in which

previous or similar work took or takes place will tend to assume these heritage roles in spite of contrary direction.

Two early test flights provide examples of how strong leadership and imminent schedule milestones can drive improvements in RR&A and decision-making.[3] The *Ares I*-X test flight and the *Orion* Pad Abort-1 test flight were both pathfinders in how to function and succeed within the broad scope of the far-flung Constellation organization. Both were developed using distributed teams and hardware developments as the program relationships were forming. While initially hampered by the same factors described in this section, these teams were able to focus on the most important elements and succeed in meeting all of their test flight objectives.

RR&A can be improved through functional examination or by either combining like tasks or separating functions by need. Implementation was hindered during the development of the Integrated Master Schedule (IMS) by the conflicting needs of the product/task providers and the schedule assessment team. When these functions were separated, IMS development quickly gained focus and results improved.

Risk management was challenged because it was separate functionally from cost threat management. When broader aspects of risk (e.g., cost threats, safety, etc.) were included, the results from the system improved.[4]

RR&A for the IC was relatively clear and in daily operation. Roles for the LC, while defined at a top level, were best developed for projects that had “follow-on” content from the IC.

The program was also contemplating the roles the International Partners might take. This formulation is described in Volume 2, for interested readers.

Recommendation

A good start is important to define RR&A; however, periodic examination is required for large-scope, distributed programs. Attention to the effects of heritage RR&A and phasing are particularly important. RR&A should also be planned to adapt to the program phase(s).

Creating a dedicated team of decision makers (e.g., the council of deputies) to critically review and address RR&A can be very effective.

Use of annual employee surveys provides a useful metric toward gauging the effectiveness of measures taken to address RR&A issues.

[3] See also the lesson learned in Section 4.11 for more benefits of test flights.

[4] NB: Risk management systems quickly degrade to “issues-tracking” unless adequate reserves are maintained to address and retire risks at the appropriate time. Lacking this, risks become accepted *de facto.*

4.8 Decision Making — Only as Efficient as Roles, Responsibilities, and Authorities are Clear and Understood

Driving Events

The clarity and effectiveness of the decision-making processes for the Constellation Program were driven by the same events as summarized in Section 4.7 and described in more detail in Section 2.2.

The start-up phasing (late start of the program relative to the projects) previously described also confounded decision making. Projects made unilateral changes without considering integrated effects. For example, *Ares* made changes to the "stack height" that impacted the *Orion* and Ground Operations designs; *Orion*, without understanding the integrated effects, deleted a test flight that was found unnecessary. Once the program integration function was operational, decisions were better coordinated, but opportunities for early-phase, lower-cost changes were lost.

The mature decision-making structure affecting Constellation Program decisions is partially illustrated in Fig. 4. Not shown are other organizations that have a significant influence on decisions: the center institutional processes (e.g., Engineering Review Boards, Program Management Councils, Facility boards), the Technical Authority (which provides the appeals route for technical decisions), and the internal decision processes for the prime contractors.

Lessons Learned

Despite constant attention from senior management, the decision-making process remained a persistent issue that only marginally improved over time. In a program of this scope, attempts to balance timely decision making at the appropriate levels, consider strategic and tactical viewpoints, and clearly delineate accountability for execution while keeping all stakeholders informed and included often left someone dissatisfied. The need to maintain the multi-decadal focus was sometimes misunderstood, particularly in projects with immediate, near-term needs.

The need to make decisions regarding NASA center infrastructure that would or would not support Constellation over time was particularly nettlesome, bringing in communities that seldom dealt with program management. These decisions typically necessitated involvement at the Agency level and required extra time and staffing. Major infrastructure changes drew interest and attention from Congress as well, so it was necessary for many entities outside the program to be well informed.

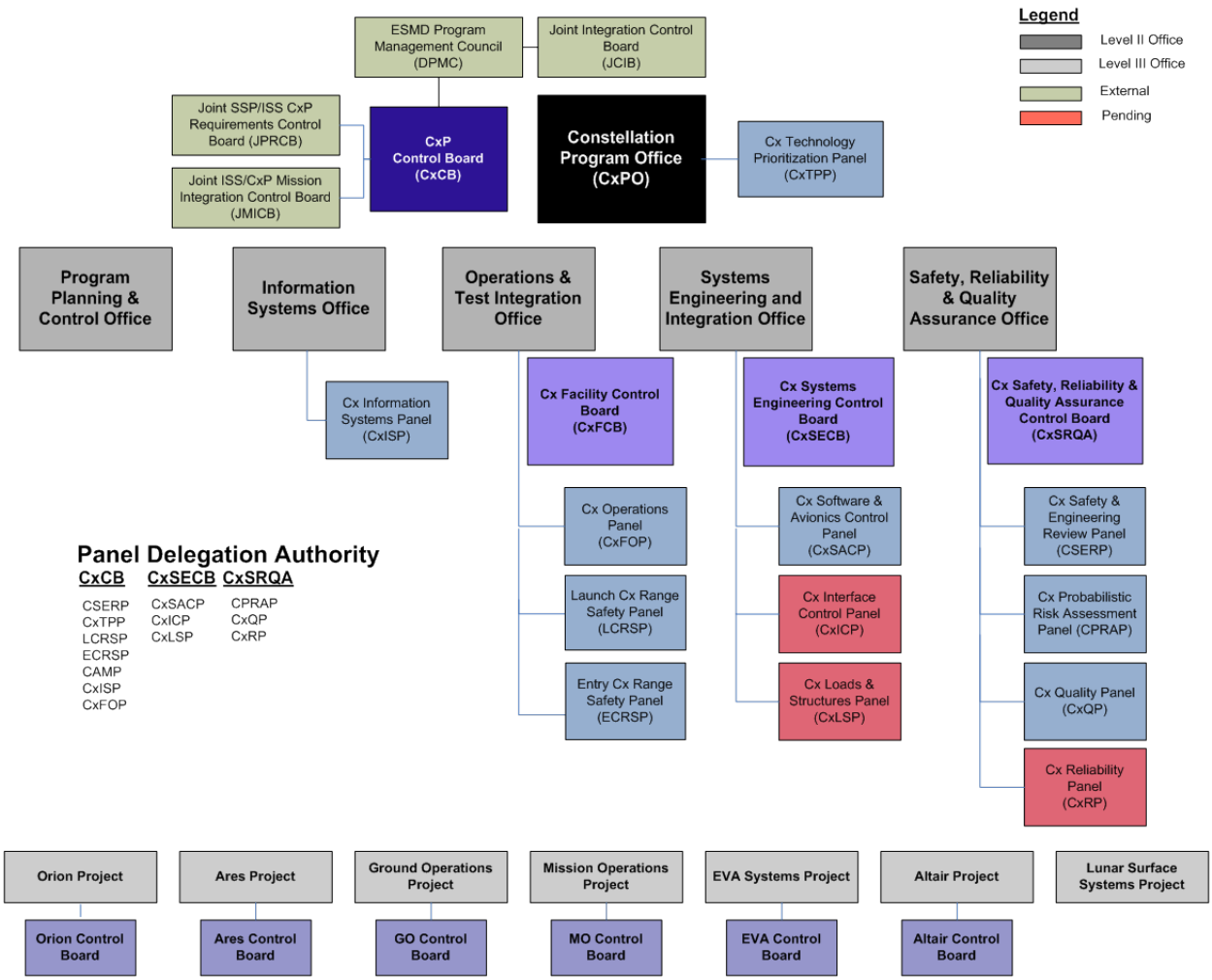


Fig. 4: Illustration of the Constellation Program decision-making board and panel structure. Note what is not shown: center institutional decision making bodies, Technical Authority (the appeals process), and the prime contractors internal processes. (SSP=Space Shuttle Program)

Recommendation

A good start is important to define the decision-making process; however, constant vigilance is required for large-scope, distributed programs. Invest the time and energy to define a comprehensive decision-making process that includes all affected parties (Technical Authority, center management, and contractors). Impediments will arise by not anticipating key stakeholder interests.

Attention to the effects of project phasing, particularly for decisions intended to last decades or affect center infrastructure, is very important.

4.9 Organization Is Organic — You'll Never Get It Right, But You Can Make It Better

Driving Events

The organizational structure for the Constellation Program evolved over time. Initially the organization was set up in a model derived from the Apollo Program — an integration function comprised of Systems Engineering and Integration (SE&I), Test and Evaluation (T&E), Operations, Program Planning and Control, and Safety, Reliability, and Quality Assurance (SR&QA),[5] along with the individual projects including *Ares, Orion*, Ground Operations, Mission Operations, and EVA. An Advanced Projects Office was also included to begin formulation of the lunar projects, including the lander and surface systems. Significant changes within the next year included the following:

- Establishment of mission managers for the *Ares I*-X and *I*-Y flight tests to enable the focus needed for integration
- Establishment of the Lunar Lander Project (*Altair*) and the Lunar Surface Systems Project, and dissolution of the Advanced Projects Office in response to the completion of early formulation activities for these projects, and no immediate need for succeeding early formulation activities beyond the lunar missions

In the following year, other organizational refinements were implemented:

- Combination of the Test & Evaluation Office with SE&I, since the T&E role had become entangled with that of SE&I and the *Ares I*-X and *I*-Y mission managers
- Establishment of the Program Architect to balance the maturation of the Constellation architecture (LC) with the near-term (IC) systems development.

In the subsequent year, further organizational refinements were implemented:

- SE&I was reorganized to transform its focus from requirements definition to design integration following completion of the program SDR.
- The Information Systems Office was formed in response to the focus needed in development and implementation of a program-wide data architecture.

The preceding listing is illustrative rather than comprehensive to communicate that the program adapted the organization over time to both emergent issues and task completion.

Lessons Learned

Organizations should be treated as organic entities, evolving and adapting to circumstances over time. Needed adaptation can be anticipated according to schedule milestones; the work force and organization should be focussed on achieving the next key milestone, not continuing to operate in the mode that achieved the last key milestone. Key milestones such as design

[5] See Appendix A for further discussion of the organizational structure based on the Apollo Program.

reviews mark natural breakpoints in organizational strategies and, indeed, the organizational scheme warrants assessment as part of a key milestone review. Consider that as the Constellation Program moved from requirements definition to development the needed changes were not uniformly recognized, so the organization was slow to adapt after the Systems Definition Review (SDR) to prepare for the PDR. Rather than preemptively assessing the organizational model, the program leadership reacted to issues associated with progressing to the PDR as they emerged. The post-PDR organizational adaptation to CDR objectives was accomplished more quickly since it was anticipated.

Recommendation

Revisit the organization at key milestone reviews to address the changing nature of the work ahead to achieve the next milestone. This should be documented in a revision of the Program Plan and be briefed to senior Agency management at the appropriate milestone briefing. Senior Agency management must be enlisted to mitigate social impacts across NASA centers due to the ebb and flow of assigned work.

4.10 Communication Among a Far-flung Team — Interpersonal Networks and Information Technology Applications Can Improve Bandwidth

Driving Events

As discussed in Section 2.2, Constellation's widespread 10-center team created a true communications challenge. While countless assessments and prevailing programmatic wisdom indicate that a small, centrally located team is the most efficient way to build a complex element, Constellation did not have that luxury. This posed many RR&A and decision-making issues, as described above (Sections 4.7, 4.8, and 4.9) as well as integration challenges. Well-understood RR&A and clear decision-making processes reduce the communication "overhead" for the program team. Beyond that, any and all efforts to improve communications are beneficial. Constellation used the following to enhance communication over and above holding regular face-to-face meetings:

- A council of project and program deputies, mentioned in Section 4.7, was formed to resolve issues related to roles, decision making, and communications. The council was formed in early 2007 to tackle issues already apparent in RR&A associated with the formation of the Program Office. This council became an informal communication network; members spent time with each other and gained trust by sharing perspectives and working through problems of mutual interest.
- "Communities of Practice" were formed to foster discussions in particular technical areas and aid information flow.
- IT tools and applications (telecon, WebEx [Cisco, San Jose, CA], LifeSize® [LifeSize® Communications, Inc., Austin, TX], ICE/Windchill, etc.) were all extensively used to enhance the flow of information.

Lessons Learned

This thorny issue was a classic case of “the devil is in the details.” RR&As were clear enough overall, as everyone understood the integrating responsibility of the Program Office with respect to the constituent projects; however, translation of this overall understanding into day-to-day practice was needed to address the real issues that cropped up daily.

As such, frequent meetings of the council of deputies were necessary, which gave the informal network an ideal opportunity to form. IT tools including telecon and WebEx allowed many virtual meetings to be interspersed with the face-to-face meetings, greatly increasing productivity of the group. Over time, as the relationships between group members grew stronger and the team’s norms of behavior became more ingrained in the team members, more and more of the group’s work could be accomplished via these virtual meetings, further increasing productivity.

The council of deputies is but one example; the integration groups for each of various engineering disciplines also benefitted from improved IT collaboration tools over the previous generation, allowing significant improvements in the utility of virtual team meetings.

Recommendation

Large-scope, geographically dispersed programs can benefit from interpersonal networks established across organizational boundaries.

Affordable, state-of-the-art IT tools can facilitate communications across time and space. They should be available as early and as broadly as feasible.

A large program should be diligent in anticipating the formal and informal networks that will emerge or intentionally be formed, and ensure that these networks have access to the IT tools that will enable them to work most productively.

4.11 Flight Tests — Learning by Doing

Driving Events

The value of flight tests in program development is undisputed; however, they are inherently resource intensive — that is to say, expensive. As such, they are typically reserved as risk mitigation for significant technical risks and demonstrations of critical capabilities. For the Constellation Program IC, flight tests were primarily focussed in two primary areas: *Ares* launch vehicle ascent performance and *Orion* LAS performance.

The *Ares I*-X was the first test flight in a planned series that would culminate in human rating of the vehicle. It was designed as a crewless development flight test to demonstrate the first-stage ascent performance. *Ares I*-X successfully flew in October 2009, achieving all test objectives. One of the primary purposes of *Ares I*-X was to acquire flight data early enough to influence and impact the design and development of the *Ares I*. The *Ares I*-X attributes were sufficiently similar to the *Ares I* to meet the test flight objectives. The test provided enough data for partial

validation of models and processes used in the *Ares I* design, and allowed the test data to improve *Ares* I design and development.

A series of flight tests was planned for the *Orion* LAS to certify safety and performance in the most challenging launch and flight regimes. The first flight test (Pad Abort-1) demonstrated LAS performance and crew module landing systems performance in a pad abort scenario. Pad Abort-1, which was launched in May 2010, was the second Constellation flight test and achieved all flight test objectives. A primary purpose of this launch, which was akin to that of *Ares I*-X, was to acquire flight data early enough to influence and impact the design and development of the *Orion* LAS and crew module landing and recovery systems. The test provided enough data for partial validation of models and processes used in the *Orion* design, improving *Orion* design and development.

The *Ares I*-X and Pad Abort-1 efforts were largely independent activities. As such, comparing the two flight test activities reveals fundamental similarities that may characterize successful flight tests and provide insight for future program success.

Lessons Learned

Both flight tests were very successful, achieving all flight test objectives and returning a wealth of technical data early enough in the development cycle to inform design; however, the key lessons learned involve the nontechnical returns from the flight tests. In both cases, these complex flight tests stressed the needed organizational constructs and drove clarity into RR&A and the decision-making structures. Had these issues been revealed later and addressed nearer to first full-system flight (e.g., the planned *Orion*-1 mission), significant delays and an increased risk posture would have resulted.

Furthermore, nontraditional approaches can be tried during a flight test, particularly a crewless flight test. For instance, *Ares I*-X used a “ping-test” approach to determine the structural characteristics of the stack rather than a much more expensive and time-consuming structural ground test. This approach worked very well and, after its successful demonstration on *Ares I*-X, the program was examining the cost savings vs. risk of adopting this approach for future flights.

Finally, it is noteworthy that when the program was cancelled, it was in the process of revising the development strategy for the IC to rely more heavily on flight tests, saving time and budget by reducing ground tests in response to the increased confidence in the analytical models and simulations that resulted from the *Ares I*-X and Pad Abort-1 flight tests.

Recommendation

Plan a series of flight tests to demonstrate key system capabilities and mitigate major technical risks. Ensure that some of the flight tests occur early enough in the development cycle (i.e., PDR time frame) to return data in time to inform the system design. Flight tests have the additional benefit of providing opportunities to test alternative approaches and discover efficiencies for overall organizational performance.

5.0 DEVELOPMENT PROCESS, KNOWLEDGE CAPTURE, AND CONTRIBUTORS

The entire Constellation Program team contributed to these lessons learned, in both the content of this Volume I Executive Summary and the content of Volume II. The knowledge capture process is described in Volume II.

An executive review committee assisted in synthesizing the lessons learned. This committee was comprised of: Bob Ess (*Ares I*-X Mission Manager), Jeff Hanley (Constellation Program Manager 2005-2010), Deb Neubek (Constellation Chief of Staff—Technical), Charlie Stegemoeller (Constellation Deputy Program Manager and former Program, Planning, and Control Director), Dale Thomas (Constellation Program Manager and former Deputy Constellation Program Manager), and Teresa Vanhooser (*Ares* Project Manager, *Ares* Projects). A full list of contributors to Volume II appears in that volume.

Dale Thomas, Deb Neubek, and Jennifer Rhatigan synthesized and structured these contributions into the Lessons Learned documents (Vol. I and Vol. II).

The program and its projects conducted knowledge-capture activities throughout its duration. These included many Lean Six Sigma events, a multitude of technical reports, conference papers, and final lessons learned activities. All formal program documents, reports, review materials, lessons learned reports, etc., will be both archived with the National Archives and Records Administration and made available in the ESMD ICE system.[6] Those lessons learned that are deemed as key risks are being fully documented, via text and video interviews, as knowledge-based risks. In addition, hundreds of lessons learned are being entered into the NASA Engineering Network's Lessons Learned Database. The ICE system will include a Constellation Program Knowledge Management wiki page that will link to the various topics to make finding all of these materials easier.

Current URLs [uniform resource locators] for these resources are below:

Exploration Systems Risk and Knowledge Management Portal:
https://ice.exploration.nasa.gov/ice/site/km
NASA Engineering Network (Click on the Lessons Learned Tab):
https://nen.nasa.gov/web/nen
Public NASA Engineering Network Lessons Learned:
http://llis.nasa.gov/llis/search/home.jsp

[6] In researching lessons learned from previous programs, primarily Apollo and space shuttle, a number of key documents were scanned into electronic form for wide distribution within the program and archived in the Constellation database. These documents are also available to interested readers.

APPENDIX A. PAPER ON PROGRAM FORMULATION

IAC-07-B3.1.06 *Formulation of NASA's Constellation Program*,
a paper presented at the International Astronautical Congress, September 2007

IAC-07-B3.1.06
FORMULATION OF NASA's CONSTELLATION PROGRAM

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ABSTRACT

NASA has recently formed the Constellation Program to achieve the objectives of maintaining American presence in low Earth orbit, returning to the Moon for purposes of establishing an outpost, and laying the foundation to explore Mars and beyond in the first half of the 21st century. The Constellation Program's heritage rests on the successes and lessons learned from NASA's previous human spaceflight programs: Mercury, Gemini, Apollo, Space Shuttle and International Space Station (ISS). This paper describes the rationale behind the formulation of the Constellation Program, including organizational structure, and workforce structure, as well as the approaches to requirements generation, budget formulation, operational philosophies, and procurement strategies.

INTRODUCTION

NASA's human spaceflight history of program formulation, development and operations was a primary resource in the formulation of the Constellation Program. We researched historical records from the Apollo Program, and its predecessors Gemini and Mercury, as well as the more recent Space Shuttle and ISS Programs. Most importantly, consultation not only with histories, but also with individual managers involved in key decision making in past programs, formed the basis of the structure of today's Constellation Program. Moreover, much of the Constellation hardware traces its history to previous programs and that corporate history and existing management structure have been leveraged to a great extent. This paper summarizes the rationale for the Program structure. We note that current technical descriptions of the program content may be found elsewhere.[1]

BACKGROUND

Following the loss of Columbia, NASA established the Columbia Accident Investigation Board (CAIB) to perform an in-depth review of the Space Shuttle Program. As a result of this review, the CAIB concluded that it was in the best interest of the U.S. to develop a replacement for the Space Shuttle. The CAIB concluded that it should be possible using past and future investments in technology to develop the basis for a system, "significantly improved over one designed 40 years earlier, for carrying humans to orbit and enabling their work in space"[2].

In January 2004, The White House issued a new exploration initiative[3] to return humans to the Moon by 2020 in preparation for human exploration of Mars and beyond. As part of this initiative, NASA will continue to use the Space Shuttle to fulfill its obligation to complete assembly of the International Space Station (ISS) and then retire the Space

Shuttle by 2010. NASA will also build and fly a new Crew Exploration Vehicle (since named Orion) by 2014. In 2005, Congress expressly endorsed the President's exploration initiative and provided additional direction[4], authorizing NASA to "…establish a program to develop a sustained human presence on the moon, including a robust precursor program to promote exploration, science, commerce and U.S. preeminence in space, and as a stepping stone to future exploration of Mars and other destinations."

In response to the Presidential direction, the Agency formed the Exploration Systems Mission Directorate (ESMD) at NASA Headquarters in 2004 to oversee development of exploration programs. The Constellation Systems Division was initiated to oversee the human exploration mission development.

In May 2005, NASA Administrator Michael Griffin commissioned the Exploration Systems Architecture Study (ESAS), a sixty-day study to perform the tasks of defining the top-level requirements and configurations for crew and cargo launch systems to support exploration objectives. The study concluded that the launch vehicles should be derived from existing technologies, leveraging the lessons learned from past programs. The ESAS recommended an architecture which included a Crew Launch Vehicle (since named Ares I) to ferry crew and cargo to the ISS and to carry crew to Earth orbit. A heavy-lift Cargo Launch Vehicle (since named Ares V), to support missions to the Moon and Mars was also defined.[5] The resulting architecture formed the basis of the Constellation Program.

In August that year, the NASA Administrator formed the ESAS Requirements Transition Team (ERTT) charging them to complete an architecture-level specification that defined the elements and their top level functionality; and to complete a draft of the Crew Exploration Vehicle System Requirements Document, validating its consistency with the architecture and providing the basis for subsequent prime contractor selection. It is also notable that the ERTT was asked to lead the first of many internal NASA cultural changes, including the adoption of a 'zero-based' requirements philosophy, in which only the minimum necessary and cost-effective requirements are included.

CONTEXTUAL DIRECTION

No modern program is created from whole cloth, and the Constellation Program is no exception. We note here the major themes, forces, situations, guidelines, constraints and environmental considerations underway at the time of the Constellation Program formulation. These are provided for contextual understanding of the Agency expectations of the Program.

Continue Human Spaceflight

The Agency's primary objectives are continued safe operations of the Space Shuttle and completion of the ISS. The human space flight work-force within the Agency is engaged in continuous operations in support of those objectives.

Transition the Space Shuttle

With the retirement of the Space Shuttle planned for 2010, the Constellation Program should plan to utilize the Space Shuttle workforce, hardware and infrastructure that support the Constellation mission, in a manner that enables a smooth transition from one to the next, but does not interfere with on-going operations.

Plan for Level Budgets

The Constellation Program should expect the Agency's allocation of the Federal budget to remain at levels consistent with the current environment. No increases other than modest cost-of-living increases should be expected, thus the Constellation Program development is constrained by completion of the Space Shuttle Program.

Lead an Agency-wide Team

The Constellation Program should leverage expertise across the Agency where possible,

in keeping with Agency objectives to maintain all 10 NASA Centers in healthy posture. Indeed, the Program should transform the 10 NASA Centers into a unified agency-wide team.

As the Crew Exploration Vehicle and the Crew Launch Vehicle organizations were previously formed in the Fall of 2005, the Constellation Program should establish a strong program to lead the integration of these established organizations.

Lead Culture Change

The Space Shuttle and ISS Programs were developed in the context of their times, facing challenges and unknowns that humble us in appreciation of the efforts it took to make them successful. There is an inherent legacy to efforts of that magnitude; some appropriate for direct adaptation by a new program, some not. The Agency leadership has given the Program license to explore new methods and approaches to developing and procuring future human space flight and ground systems. We've also been charged with using the Constellation Program to do nothing less than reconstitute systems engineering capacity within NASA's human spaceflight community, to smoothly transition the human spaceflight workforce to the next generation of capabilities and to lay the foundation of a program that will be cost-effective and sustainable into the far future. While remaining attentive to the lessons learned from current and prior programs, Constellation Program should lead the Agency in cultural changes—to re-invent how human spaceflight development is done.

Meet Commitments

The Constellation Program should meet its commitments; that is, do what we said we would do, when we said we would do it within the allocated budget, schedule, and technical requirements. If the budget is cut, let stakeholders know the impact to our schedule and/or technical commitments. The practice of maintaining unrealistic schedules in the face of budget cuts should not be continued.

Improve Spaceflight Risk

Achieve an order-of-magnitude improvement in risk to crew and mission over that of the Space Shuttle. Current probabilistic risk assessment puts the risk of loss of crew for the Space Shuttle on the order 10^{-2}. Constellation should improve this to the order of 10^{-3}.

Simplify Operations

The Constellation Program should plan and require simplified operations such that operational costs are minimized, particularly with respect to Space Shuttle heritage operations. New developments for lunar and Martian expeditions are only possible if budget is made available due to decreased operational costs. Thus Constellation will only be sustainable if the operational infrastructure and workforce are more efficient than today.

Recognizing the need to establish a program office co-located with the NASA program experience base, ESMD established the Constellation Program at the NASA Johnson Space Center in November of 2005. The following sections describe the decisions that were made in its formulation in the context of the guidelines discussed above.

ORGANIZATIONAL STRUCTURE

Constellation Program

The structural model that most closely resembles the current mission is the Apollo "5-box" management structure[6] and was selected because it worked effectively. These five organizational functions are comprised of program planning and control; test and verification; operations integration; systems engineering and integration; and safety, reliability and quality assurance. This was adapted and tailored to the Constellation Program's more evolutionary objectives. Constellation is envisioned to have developmental aspects throughout its life cycle in that new developments to support

the next mission will start in phases as current developments become operational. For instance, lunar outpost development will start after the low Earth orbit portions of the program are operational. The adapted organizational structure is shown in Figure 1. Note that an advanced development function (Advanced Projects Office) has been added to the Apollo "5-box" structure. This organization houses research and development activities for 'pre-projects' envisioned to support lunar missions and beyond. Organizations outside of NASA, such as international partners and commercial partners, could be involved in these later phases of the Program[7].

The program was staffed with recognized leadership within the Agency (e.g., from the ISS Program, Space Shuttle Program, and Mission Operations Flight Director Office) and the contractor/DoD space community between November 2005 and March 2006, seeking project managers with demonstrated experience in executing projects and discipline-area leaders able to assemble strong teams, articulate a clear vision of the task, and integrate horizontally and vertically.

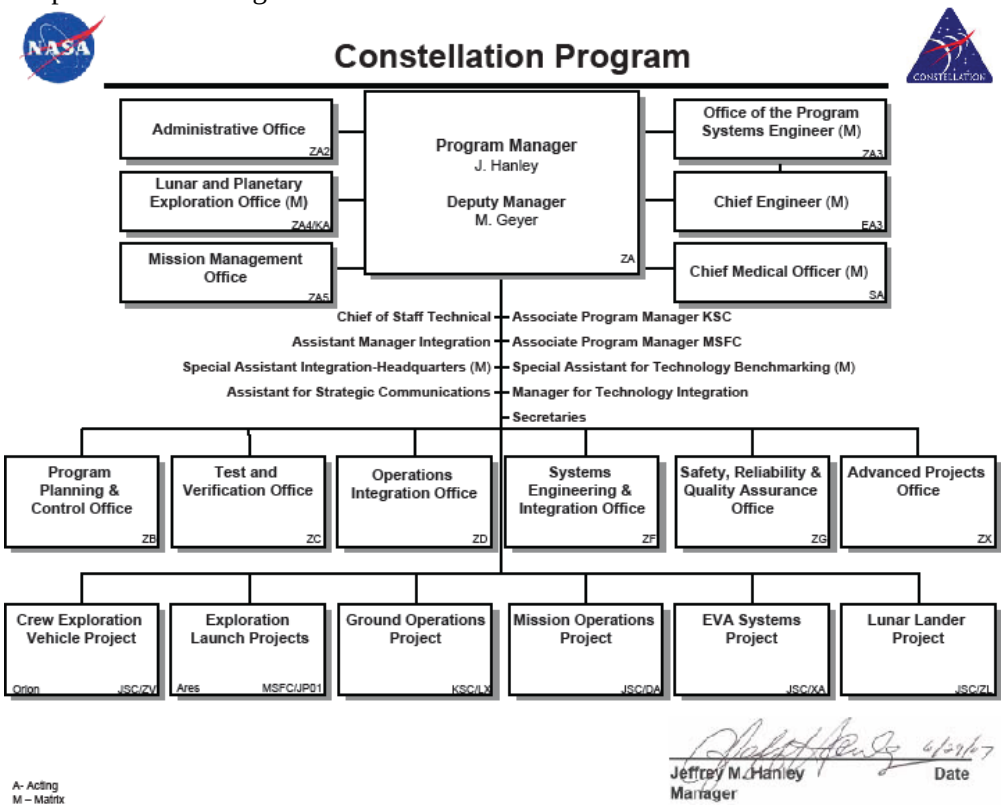

Figure 1: Constellation Organization Structure. Program Management (first row boxes); the Program Offices adapted from the Apollo 5-box structure (second row boxes); Project Offices (third row boxes).

Constellation Projects

The projects that comprise the Constellation Program are listed in the bottom row of Figure 1. Table 1 describes major responsibilities for each project in the development and operational phases of the Program.

Program/Project Integration

We know from Agency history that our success depends on a strong program

leading strong projects. As soon as the program office was staffed, we began a process of negotiating roles and responsibilities between the program and projects. All recognized the importance of having a program office integrate project interfaces, as well as the importance of allowing projects maximum flexibility in managing their assigned element. However, a detailed examination of integration processes was necessary to truly understand and assign responsibilities. The program and project deputies conducted integration process decomposition in order to understand and agree upon ownership for each step in the integration processes. This understanding is paramount for implementation of hardware and software interface agreements and is a key element leading into the design definition phase.

Constellation Project	Lead NASA Center	Function	
		Developmental Phase	Operational Phase
Project Orion	JSC	Develop and test the Orion (CEV) spacecraft to transport crew to and from space.	Provide Orion spacecraft.
Project Ares	MSFC	Develop and test the Ares I (CLV) and Ares V (CaLV) launch vehicles.	Provide Ares launch vehicles.
Ground Operations Project	KSC	Perform ground processing and integrated testing of launch vehicles. Plan, construct and/or reconfigure integration, launch, and recovery services for Orion Crew Module, Ares I and Ares V.	Provide logistics and launch services. Provide post-landing and recovery services for the crew, Orion Crew Module, and spent Ares Solid Rocket Boosters (SRBs).
Mission Operations Project	JSC	Configure, test, plan, and operate facilities, systems, and procedures. Plan missions and flight operations.	Train crew, flight controllers, and support staff. Coordinate crew operations during missions.
Lunar Lander Project	JSC	Develop and test the Lunar Lander to transport crew to and from the lunar surface and to provide a habitable volume for initial lunar missions.	Provide Lunar Lander.
Extravehicular Activities (EVA) Systems Project	JSC	Develop EVA systems (spacesuits, tools, and servicing and support equipment) to support crew survival during launch, atmospheric entries, landing, abort scenarios, and outside the space vehicle and on the lunar surface.	Provide spacesuits and tools.
Future Projects	To be deter-mined	Develop systems for future applications including Lunar Surface Systems (equipment and systems for crew operation on the lunar surface) and systems for future human exploration activities.	Provide future systems as needed.

Table 1: Constellation Project Descriptions

Agency Governance

The Constellation Program is the first new program within the Agency to implement the NASA Governance Model that resulted from the CAIB recommendations[2]. In brief, the Governance Model provides for checks and balances between the program and the independent technical authorities established within the Agency. For the Constellation Program, the Program Manager (and staff by

delegation) have authority over mission performance, programmatic, cost, and schedule requirements. The Office of the Chief Engineer (OCE), the Office of Safety and Mission Assurance (OSMA), and the Office of the Chief Health and Medical Officer (OCHMO) have authority over engineering; safety, reliability and quality assurance; and health and medical standards, respectively. They also have the responsibility to provide informed technical recommendations on programmatic issues throughout all stages of a program life cycle. In addition, they provide an appeal path for program office personnel or line organization personnel who disagree with a program decision. NASA and industry standards, ranging from human rating standards to conformance to the metric system, are owned by the technical authorities. However, not all requirements in these documents are applicable or appropriate for the Constellation Program. It is the Program's responsibility, with the assistance of the technical authorities, to develop and recommend a tailored set of these requirements. It is the technical authorities' responsibility to review and approve the tailored set of requirements. Risk acceptance is the Program Manager's responsibility, including the acceptance of residual safety risks that result from ground or flight anomalies, hazard analyses and FMEA/CILs[‡‡]. However, the technical authority may appeal if they determine that a risk is unacceptable for flight.

Decision Making Structure

The Constellation Program uses a board/panel structure for making decisions that affect the baseline, as well as for making technical implementation decisions at a program level. An example of the decisions that affect the baseline would be anything that requires a change to a Program approved document. An example of a technical implementation decision would be whether to approve a design modification requiring additional funding. The Constellation Control Board is chaired by the program manager; membership includes each project and program office appearing in Figure 1.

In order to implement the Governance Model, the technical authorities are also board members on the Constellation Control Board. This avoids the 'shadow organization' that has evolved in past programs. These representatives cannot be program office personnel, nor can they be funded by the program. In this board structure, program office personnel (SE&I, Program SR&Q, etc.) are responsible for providing a recommendation to the Program Manager for their functional area. It is the responsibility of every board member, whether within the program or part of the technical authority, to ensure that the board is aware of dissenting opinions, that they are discussed, and that the dissenter is advised of the disposition. If an individual or individuals disagree with a Program Manager or Technical Authority decision, and believe that the decision poses a risk to safety or mission success, there is an established appeal path.

WORKFORCE

As noted in the Background section, the Constellation Program has been formulated, and must execute, during continuous operations of the Space Shuttle (through 2010) and ISS. Moreover, we must be prepared to make best use of the expertise resident in the Space Shuttle workforce, when it becomes available as that program phases out. Constellation has developed a phased development program in anticipation of this workforce availability. This phased approach is described in more detail in the Schedule section of this paper.

‡‡ FEMA=failure modes and effects analysis; CIL=critical items list

The Program office workforce is comprised of engineers, scientists, and administrative personnel and was sized utilizing experience from past programs as well as guidance on availability of key personnel to support three human spaceflight programs at the Johnson Space Center. The initial size estimate was based on previous human spaceflight programs and was set at approximately 8% of the total program content. After the Program System Requirements Review there was sufficient experience in the office to attempt a reduction in the budget to only ~ 6.5% of the total program content. This was based on expected workload and products and a better understanding of the program integration responsibilities. The Program team continues to track risks incurred with this funding level and to reprioritize work as needed to meet the program milestones.

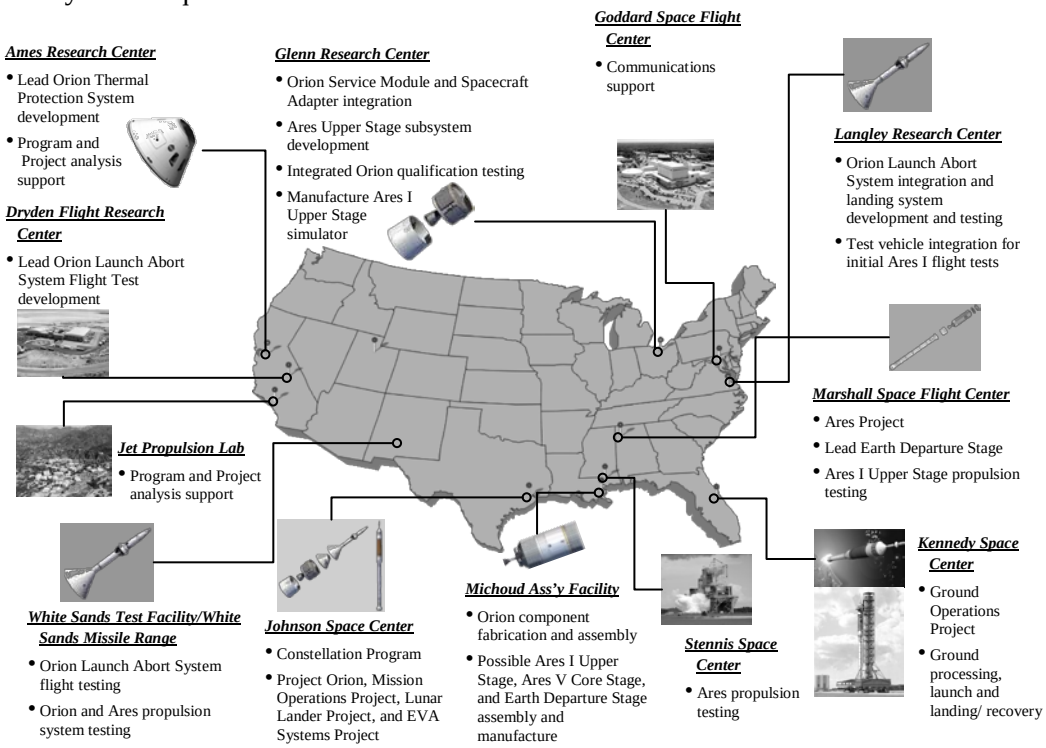

Figure 2: Constellation work assignments at NASA Centers

Distributed Teams

The projects are staffed by leveraging expertise across the Agency. Project work assignments at the 10 NASA Centers (and the White Sands Test Facility/White Sands Missile Range) are described in Figure 2.

We recognize that managing a team distributed to this extent is a daunting challenge; indeed it is only now possible with current communications technology that enables real-time electronic meetings, single-source record keeping, and maintenance of the requirements baseline in a single database accessible by all program elements. All members of the workforce must use the selected electronic tool suite in order to make this distributed team work.

Sage Advice

Though NASA has considerable talent in its workforce, programs intended to carry humans to and from space are characterized by design, development and testing challenges which differ greatly from those encountered by the orbiting International Space Station or operational Space Shuttle. To reach back and capture launch and return

vehicle experience, the Constellation Program created a ready resource - SAGES - Shuttle and Apollo Generation Expert Services. This contract provides a simple pathway to enlist the aid of retired experts from NASA's past (e.g., George Mueller, Chris Kraft, Glynn Lunney, etc).

Beyond review and advice, SAGES was created to transfer knowledge through mentoring. It is based on relationships between Apollo and Shuttle-era program managers and discipline experts, and the Constellation team. SAGES provides mentors on an as-needed, targeted basis in areas ranging from technical design and analysis disciplines, to ground and flight operations, to program management. Twenty four tasks have been initiated to date, including margins management; relationship between Level II program office and the Level III project office responsibilities; lunar lander requirements; test and verification planning; and launch abort design and operations.

REQUIREMENTS

The ESAS team had developed an Exploration Architecture specification and draft system requirements documents (SRDs) for both the CEV (Orion) and the Ares I (CLV). In lieu of an established Program office, the follow-on ERTT formulated, as its primary task, a requirement set consistent with the architecture defined by the ESAS team and a CEV SRD sufficient to support a down-select of CEV contractors in 2006 as part of the Call for Improvement (CFI) process. Thus initial requirements for the basic architecture, Orion, and Ares I were established at the time the Constellation Program office began work. The Program team had to quickly establish processes, roles, responsibilities, and team organizational structure to align an integrated set of requirements that would unite the elements together into a strong program that could integrate and execute missions.

Zero-Based Requirements Approach

Requirements development was the linchpin for concurrent maturation of program cost and schedule. A zero-based requirements philosophy has been adopted in which only the necessary and cost-effective requirements are included. Projects are directed to "drive-out" unnecessary requirements, write requirements in terms of outcomes and not solutions or "how-to" and drive out non-value-added steps in achieving outcomes. This approach is requisite for all contracts and 'in-house' work. The need for data deliverables, reviews and applicable/reference documents is carefully scrutinized in order to be sure that these requirements are necessary, value-added and cost-effective and are required to achieve the desired outcome of a project. This will be a continual process not only in the pre-award phase, but also in the post-award administration of contracts.

Evolving the Architecture

With an integrated program team under development, several significant improvements to the architecture outlined by the 60-day ESAS team became apparent through trade-study and risk analyses. The Program base-lined the Apollo-heritage J2-X engine as the primary upper stage engine for both the Ares I and Ares V configurations. A cluster of five RS-68 engines (common with the Delta IV) was selected as the baseline first stage engine configuration for the Ares V. And the first stage solid rocket booster configuration was lengthened to include 5 segments (rather than 4) for both the Ares I and Ares V configurations. Architecture requirements were also established for the EVA suit systems, ground operations and mission operations[8].

Program Requirements Reviews

The Program embarked on a season of System Requirements Reviews (SRRs), commencing with a Program SRR in the Fall of 2006, progressing through project SRRs, and culminating in Program baseline synchronization in May 2007. The SRR is

conducted to ensure that the program requirements are properly formulated and correlated with the Agency and ESMD strategic objectives. Specifically, the SRR assures that: the high-level program requirements are complete and approved, the interfaces with other programs are approved, the program requirements are cost-effective, the program requirements are decomposed and adequately levied on projects, the plan for controlling changes to program requirements is approved, the approach for verification of requirements is approved, and mitigation strategies for addressing major risks are approved. After project SRRs, the program baseline synchronization was conducted to resolve discontinuities identified among project requirements and between project and program requirements.

In January of 2007, Constellation gathered Apollo and Shuttle veterans (via the SAGES contract mentioned earlier) in a "greybeard" review of the program baseline to seek advice and management guidance through the early phase of the program. This advice is currently being integrated into the program, particularly in our approach towards risk management. We intend to continue involvement of our spaceflight veterans as we move forward towards program implementation.

Projects are beginning System Definition Reviews (SDRs) at this writing, to ensure the readiness of the program for making a program commitment agreement (PCA) to approve project formulation startups and move into the program implementation phase.

Safety, Reliability and Quality Assurance (SR&QA) Requirements

It is the goal of the Constellation Program to achieve an order-of-magnitude improvement in risk to crew and mission over that of the Space Shuttle. Some of this improvement can be achieved through design improvements. The Ares I/Orion system is estimated to be much more reliable for the crew than the Space Shuttle, primarily due to its in-line design and incorporation of the Launch Abort System for crew escape.

Other improvements must focus upon changing the way we 'do' SR&QA. This centers around: the early identification of requirements driving safety and mission success, the performance of safety and mission success analyses throughout the life cycle, but early enough to influence design and operations, and an assurance framework that verifies that the system is designed, built and operated in accordance with requirements.

SCHEDULE

The primary schedule requirements for the Constellation Program are to develop the CEV (Orion) to transport humans to and from ISS by 2014[§§], and to return humans to the Moon by 2020. These two goals lead to a phased schedule approach, illustrated in Figure 3 (through 2011). Figure 3 shows two primary elements of schedule execution: Initial Capability (IC) development and Lunar Capability (LC) development. The IC includes the elements necessary to deploy the CEV/CLV (Orion/Ares I) configuration that will support ISS, including the ground and mission operations capabilities and the spacesuits (EVA systems) needed for the crew. The LC includes the Cargo Launch Vehicle (Ares V), the Lunar Lander and the Lunar Surface Systems (e.g. rovers, habitats, scientific equipment). The current focus of the Program is development of lunar capable elements that support the ISS. Many of the elements of the IC now under development are accelerating the LC. For example, the J2-X engine is the primary engine on the upper stage of both the Ares I and Ares V vehicles. This aggressive development for the Ares I will provide higher confidence during the Ares V vehicle development. The five-segment solid rocket motor first stage

§§ Reference discussion of confidence level in following section resulting in current commitment to field Orion and Ares I by 2015.

of the Ares I is common with the twin solid rocket motors on the first stage of the Ares V. In addition, the crew's EVA and pressure suits for the IC are being developed as a modular single-suit system with capability to add/exchange elements necessary for the LC.

While the continued operations of the Space Shuttle constrain the budget and workforce available to develop Constellation through 2010, we also must prepare to make best use of the experienced workforce as it becomes available though the phased retirement of the Space Shuttle. Responding to that need, targeted activities in the LC development have begun. Requirements must be developed to a level to enable contract acquisitions in the 2010 timeframe in order to deploy and utilize the resident expertise in the Space Shuttle Program's civil servant and contractor workforce to the extent possible. Initial concept development of the Lunar Lander and Ares V are underway to mature the requirements set to the necessary level.

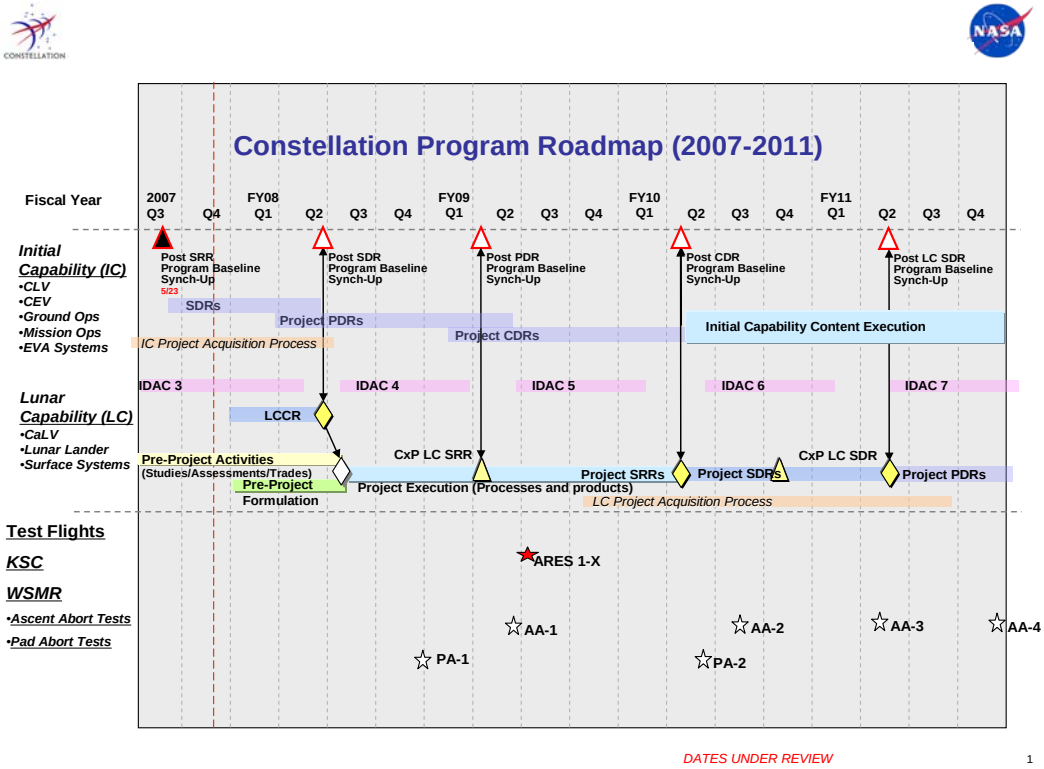

Figure 3: Constellation Program Roadmap through Fiscal Year (FY) 2011

The lower portion of Figure 3 illustrates the flight test program planned for the remainder of this decade. The Orion design incorporates a Launch Abort System (LAS) that would pull the Crew Module to a safe landing if necessary in the event of an abort during launch and early phases of ascent to orbit. While this system is based on Apollo heritage, it must be thoroughly tested prior to utilization with a crew on board. A series of flight tests of the LAS is planned for the White Sands Missile Range (WSMR) that will include both pad abort and ascent abort tests. In 2009, Ares I-X--the first developmental flight test of the 'integrated stack'--will be launched from the Kennedy Space Center (KSC). Ares I-X will test the integration and performance of a simulated Ares/Orion 'stack' prior to Critical Design Review (CDR) so that resulting design changes could be incorporated before production of flight articles. Further flight testing at KSC is planned into the next decade.

BUDGET AND ACQUISITION

Budget Development

The ESAS team had assembled a preliminary budget estimate for execution of the recommended architecture. In the spring of 2006, the Constellation Program developed an unconstrained "bottoms-up" budget estimate for the purposes of establishing a "first cut" understanding of the drivers for costs and schedule from present to the lunar landing phase of the Program. This analysis provided the element break-down and the raw data for building a subsequent budget that was realistically constrained by Agency priorities and needs. By the summer 2006, the Program was able to establish the first budget baseline meeting Agency schedule commitments of deploying the CEV (Orion) by 2014, and landing on the Moon by 2020.

These were updated in the Fall of 2006 as program requirements matured. Completion of the Program's System Requirements Review (SRR—see Requirements section), provided a further level of requirements development that allowed for more refined estimates in the Agency's FY07 budget development cycle.

Confidence Level

The history of human spaceflight is replete with examples of cost overruns due to confluence of under-funding, insufficient or poorly phased reserves, misunderstood risks and complexities, overly aggressive schedules, and difficulties meeting ambitious technical requirements. We have no illusions that we will not encounter these challenges; therefore the Constellation Program is pioneering within NASA the implementation of probabilistic techniques to assess the confidence level expected that the program can achieve given schedule milestones within the budget allocated[9]. Our guidance within the Agency is to maintain a confidence level of 65% that we can meet our schedule commitments within the allocated budget and technical base-line. Program confidence level is calculated incorporating project-level confidence levels, project-level risks, and program-level risks, along with assumptions on dependencies among the risks. The Program conducted confidence level assessments during the budget development process, and plans to refine these during annual budget cycles. This analysis is key to assuring that we maintain our commitments to our stakeholders and have underpinning rationale for dialogue when requirements changes to the baseline are under consideration.

During 2007, the Program was allocated less funding than planned in the Federal appropriation bill. Since the Constellation Program proceeds as a 'go as you can afford to pay' program, this resulted in a 6-month delay in our commitment to fielding the first Orion crew vehicle and Ares I launch vehicle for Initial Operating Capability (IOC). This date is now March 2015, rather than 2014[10].

Acquisition Strategy

As plans are made for the retirement of the Space Shuttle, NASA is assessing possible synergies to be gained between the contracts and acquisition strategies already in place. The Integrated Acquisition Roadmap Team (IART) has been chartered to map all existing and planned Space Shuttle, ISS and Constellation contracts and to identify opportunities to save costs, including life cycle costs, to utilize lessons learned and best practices, to address transitions across program phases, to maximize the

effective use of both the existing civil service and contractor workforce, and to facilitate strategic competitive opportunities.

Where appropriate, the Constellation Program is utilizing current, proven technology in order to achieve safer, more reliable and affordable solutions. For example, the Ares I and the Ares V are based on proven systems from the Space Shuttle and Apollo Saturn V programs, enabling NASA to reduce development costs compared to designing and building an entirely new launch vehicle. This approach maximizes the value of existing facilities, certified parts, production tools and expertise. Common propulsion elements help reduce operation costs for a more sustainable exploration program. The Constellation Program has entered into sole source production contracts for heritage- based elements; ATK-Thiokol for the Ares I first stage and Pratt & Whitney Rocketdyne for the J2-X engine.

Lockheed-Martin was selected as the prime contractor for the Orion development through full and open competition. The production contract for the Ares I upper stage was recently awarded to Boeing through full and open competition. Further prime contract awards are expected over the coming year.

The Constellation Program acquisition strategy places an emphasis on the criticality of reducing and controlling life cycle cost in each acquisition phase because NASA plans to produce and fly these vehicles for decades to come. Understanding and managing life cycle cost is pivotal to the overall long-term success and viability of the program.

OPERATIONAL PHILOSOPHY

As noted in the contextual discussion in the Background section, the cost burden of Space Shuttle operations cannot be inherited by this Program if the Lunar Capability and the eventual Mars Capability is to be developed concurrently with Initial Capability operations. It is interesting to note that minimization of life-cycle costs, particularly operational costs, was an important objective of the Space Shuttle Program during its development[11]. This is not to point out folly, but indeed to illustrate how difficult this objective can be even under proactive management. We believe that we have the advantage of a much simpler system to operate, but are also cognizant that we inherit operational processes ingrained over a 30-year history. To that end, the Program has undertaken a number of efforts aimed at life cycle cost reductions. Examples are discussed below:

Stretch Requirements

The architecture requirements include 'stretch requirements' defined as those that enable ground and flight system supportability and reductions in operational life cycle costs. Modeled after the Boeing 777 development, stretch requirements specify a desired outcome believed to simplify operations. For instance, a 'clean pad' concept has been specified to challenge designers to minimize services and interfaces required at the launch pad as well as location/access on the vehicle. Each service or umbilical (e.g. cooling) attached to the launch vehicle is thus challenged for relevance or 'must have' capability. The Ground Operations Project and Mission Operations Project are focal to manage the stretch requirements; these are incorporated into flight design via negotiation of Interface Requirements Documents (IRDs) with each of the flight projects (Orion, Ares, EVA, and Lander).

'Con Ops' Development

Constellation has developed a Concept of Operations (Con Ops) for operation of the program through its mission phases, in order to drive out operational features that influence hardware, software and interface requirements. This is a typical best practice in NASA program development. Design reference missions have been developed for ISS missions, lunar sortie missions, lunar outpost missions, and a Mars mission so that operational design drivers are identified early.

Moreover, we've also initiated similar but perhaps unique con ops efforts for targeted processes that can influence life cycle costs. For example, the current practice of quality assurance in the Space Shuttle program is being bench-marked for efficiency improvements. By developing a con ops for how quality assurance

is conducted through the life of the program, a more efficient path to quality assurance may be determined a priori.

Life Cycle Cost Evaluations

Change evaluations to the program baseline must include an assessment of the life cycle cost impact of each change to the baseline. Constellation procurements--both 'end-item' and 'award fee' types--include incentives to reduce life-cycle cost.

Lean Efforts

Lean six-sigma and Kaizen studies were conducted on some early developments, such as the Ares 1-X test flight. This has proven successful and the Program is seeking further opportunities to gain process time reduction and simplification.

The 'handoff' between designers and the sustaining engineering and operational communities is being studied for efficiency improvements. Current practice includes overlapping responsibilities and designer involvement in post-design processes. Efforts are underway to identify and minimize this to ultimately reduce costs.

Industry Advice

The Ground Operations Project conducted feasibility studies under the Broad Area Announcement capability; requesting novel ideas from industry on how to streamline processing, launch and recovery operations. The concepts are intended to produce 'cleaner' techniques and processes in the belief that fewer anomalies are possible with simpler processes. Examples of concepts include new approaches to emergency egress system for the crew, isolation of the launch pad lightening protection system, and alternatives to hypergolic fuel loading to reduce processing time.

If we are truly successful in driving down operations costs such that the cost per flight is as low or lower than we project, and we've designed the supremely operable system that can be processed, flown, recovered and refurbished with a minimum of effort, then we've opened the door to other acquisition strategies in the production phase that would not be open to us with a more labor intensive system. Specifically, the option to buy services as a commodity would be available so that we can then devote our expertise to designing the next Constellation element in the plan.

SUMMARY

As the long-term objectives of U.S. space exploration evolve, the near-term goals remain the same: to develop the flight systems and ground infrastructure required to enable continued access to space and to enable future crewed mission to the ISS, the Moon, Mars and beyond.

The initial formulation of the program requirements baseline was completed in November 2006 at the Cx program SRR. The program is evolving within this structure of organization, requirements and funding as its foundation. A major challenge is to stand up an organization that draws on the best expertise in the Agency while maintaining primary focus on the currently operational Space Shuttle and ISS programs.

The formulation of the Constellation Program is a robust system, based on the best of NASA's heritage, and designed to evolve as technical and programmatic needs demand.

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APPENDIX B. ACRONYMS

APA	allowance for program adjustment
CAIB	*Columbia* Accident Investigation Board
CDR	Critical Design Review
CR	continuing resolution
Cx	Constellation
CxP	Constellation Program
D&C	design and construction
DoD	Department of Defense
ESAS	Exploration Systems Architecture Study
ESMD	Exploration Systems Mission Directorate
EVA	extravehicular activity
FY	fiscal year
HLR	human lunar return
IC	Initial Capability
IMS	Integrated Master Schedule
IOC	Initial Operational Capability
ISS	International Space Station
IT	information technology
JPR	Johnson (Space Center) Program Requirement
JSC	Johnson Space Center
KSC	Kennedy Space Center
LAS	Launch Abort System
LC	Lunar Capability
LEO	low-Earth orbit
LOC	loss of crew
MPCV	multipurpose crewed vehicle
NPD	NASA Program Directive

NPR	NASA Program Requirement
NSA	National Security Agency
PBS	President's Budget Submittal
PDR	Preliminary Design Review
PI	Program Integration
PMR	Program Manager's Recommendation
RRA	roles, responsibility, and authority
S&MA	Safety and Mission Assurance
SDR	Systems Definition Review
SE&I	Systems Engineering and Integration
SLS	Space Launch System
SR&QA	Safety, Reliability, and Quality Assurance
SSP	Space Shuttle Program
T&E	Test and Evaluation
URL	uniform resource locator

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13. ABSTRACT *(Maximum 200 words)*

This document (Volume I) provides an executive summary of lessons learned from the Constellation Program. A companion document (Volume II) provides more detailed analyses for those seeking further insight and information. In this volume, Section 1.0 introduces the approach in preparing and organizing the content to enable rapid assimilation of the lessons. Section 2.0 describes the contextual framework in which the Constellation Program was formulated and functioned, which is necessary to understand most of the lessons. While context of a former program may seem irrelevant in the heady days of new program formulation, some time should be taken to understand context. Many of the lessons would be different in a different context, so the reader should reflect on similarities and differences in his or her current circumstances. Section 3.0 summarizes key findings, at the program level, developed from the significant lessons learned that appear in Section 4.0. Readers can use the key findings in Section 3.0 to peruse for particular topics, and will find more supporting detail and analyses in a topical format in Section 4.0. Appendix A contains a white paper describing the Constellation Program formulation that may be of use to readers wanting more context or background information

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