NASA Exploration Systems Mission Directorate
Ares I-X Knowledge Capture

Volume I: Main Report

Ares I-X Project Management and Integrated Product Teams

ESMD Risk & Knowledge Management Office

May 20, 2010

FOREWORD / APPROVAL: Exploration Systems Mission Directorate (ESMD)

The Exploration System Mission Directorate (ESMD) Integrated Risk & Knowledge Management (IRKM) Office developed this report with the ultimate goal of synthesizing and documenting key experiences to assist future flight-test programs and projects.

David Lengyel, the Lead for IRKM in ESMD, led the Knowledge Capture Team with contractor support provided by Dr. J. Steven Newman and Mr. Don Vecellio from ARES Corporation and Mr. Tom McInnis from Jacobs Engineering. Additional support was provided by the Marshall Space Flight Center (MSFC) Ares I Project Risk Management Office and the Ares I-X Project Integration Office.

The Knowledge Capture Team endeavored to recognize the accomplishments of Ares I-X while providing a balanced summary of opportunities for improving management approaches and processes for future fast-track demonstration efforts. This report draws on the views and opinions of hundreds of participants, including:

- Integrated product team (IPT) leads and members
- Mission Management Office
- System Engineering and Integration (SE&I)
- Engineering and Safety & Mission Assurance (S&MA) technical authorities

Participants were located at the Glenn Research Center (GRC), Johnson Space Center (JSC), Kennedy Space Center (KSC), Langley Research Center (LaRC), and MSFC.

This knowledge capture effort considered the Ares I-X effort from two specific perspectives, each with its own set of assumptions, expectations, and experiences. One perspective was provided by the fast track, flight-test project management team that often operated in the context of dynamic risk management, making tough choices to achieve schedule goals. The second perspective consisted of the traditional systems engineering and engineering management processes defined by the Agency. This traditional perspective was represented by most of the "people in the process," individual engineers and managers within the IPTs and management organizations.

If you ask people what they think, they will tell you, although individual perspectives may not always agree and sincere differences of opinion may exist. Some may view Ares I-X as the template for how to do the next fast track flight-test. Others may view it as an experiment that demonstrates how careful one needs to be when tailoring traditional aerospace engineering processes. Indeed, there is validity in both viewpoints.

In any event, everybody is proud of the Ares I-X team and recognize when all is said and done that their combined efforts and dedication led to a successful flight test on October 28, 2009. No matter what lens you may choose to reflect upon the Ares I-X experience, we are confident that these lessons will assist in the formulation of future successful flight test projects and programs.

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The success of the Ares I-X flight test is a tribute to the dedicated people that made it happen. The benefits of mission transcend the flight test objectives in that Ares I-X helped inspire the next generation of inventors, researchers, and pioneers. This lessons learned captured in this document reflect the candid responses of the people that worked Ares I-X. Comments range from the negative to the positive and when put in the context of the Ares I-X plan and the results achieved, lessons learned can be derived to inform new projects and programs on what worked well and what could have been done better. Ares I-X was a true team effort where the team worked towards a common vision and succeeded.

From the early concept days in 2005 through the launch on October 28, 2009, to the post flight processing of test data in 2010, the team believed that NASA could succeed and they did. This was no easy endeavor because this test was undertaken during the early days of the Constellation Program when most processes were new or under development. In January 2006, flight test objectives were crafted and a feasible concept was formulated. By late spring and early summer of that year the organization was staffing-up and by the end of the year we had completed a systems requirements review. We learned during start-up that it would have been nice to have a fully staffed team, but we achieved great results with the team we had. Throughout the entire life cycle of Ares I-X, we found ways to work around obstacles and rely on our strengths through the ingenuity of the team. As the mission marched on we inspired many young people. One such young new fan started a home grown rocket club.

Every day from authority-to-proceed until launch was challenging, and some days extremely difficult, but the overall experience was rewarding. The hardware took longer to build than originally planned, but we generated lessons learned on how to be more efficient in machining large structures, developing new parachutes, testing complex avionics, designing separation systems, understanding the affects of outer mold line shape on loads, and how to improve the process for environments development. We clearly learned many other lessons from this experience and most of all we learned that we could balance risk and succeed with our modern processes and systems.

The comments you will read are both passionate and well thought-out. We ask the reader to put these comments in context. The mission was complex and full of risks, all of which were analyzed and none of which were taken lightly. For example, the ground operations team at KSC was asked to evaluate its capabilities, assess the associated risks, and accelerate its schedule, and they did. The loads team had to re-validate their models late in the mission's life cycle, and they did. The launch team was requested to optimize their training schedule, and they did. This was the case throughout the Ares I-X mission where team members from different centers, companies, and cultures banded together to make it happen, and they did. On behalf of all the Mission Managers and the entire Ares I-X team, I hope our lessons will help your next program or project.

EXECUTIVE SUMMARY

The Ares I-X Flight Test Vehicle (FTV) was successfully launched from Launch Complex 39B at the Kennedy Space Center, Florida, on October 28, 2009. The Ares I-X mission overcame many unique engineering, management, and process-level challenges and ultimately met all of its primary objectives. The Ares I-X accomplishments included:

- demonstrating control of a vehicle dynamically similar to the Ares I launch vehicle with an Orion spacecraft using Ares I relevant flight control algorithms
- performing a nominal in-flight separation/staging event between an Ares I-similar first stage and a representative upper stage
- demonstrating first stage separation sequencing (i.e., tumble motors, parachute deployment, and other first stage recovery control subsystems)
- demonstrating assembly and recovery of a new Ares I-like first stage element at KSC
- quantifying first stage atmospheric entry dynamics, and parachute performance
- characterizing the magnitude of integrated vehicle roll torque throughout first stage flight
- demonstrating effective and efficient use of ground systems and ground operations processes to integrate, launch, and recover a new vehicle

In accomplishing these objectives, the Ares I-X team developed and evolved cooperation and teamwork across traditional space centers and research centers. The team also evaluated processes and software tools intended to be employed in subsequent Ares project and Constellation program activities.

Ares I-X was faced with an aggressive schedule to meet the data needs of the Ares I design teams. The need to save time dictated the use of heritage hardware, software, and integration processes whenever possible. In addition, the teams implemented other measures to accelerate the pace, including tailoring a number of important systems engineering processes. Ares I-X team members ultimately learned that these early life cycle schedule savings were costly (in terms of time and effort) and that mission success was achieved only because of good risk management and exceptional effort and sacrifices by team members.

Two Systems Engineering Perspectives

No single summary statement captures the essence of this story. Rather there are at least two interesting, and valid, perspectives.

Many of the individuals in the Ares I-X project who participated in the knowledge capture activity had – by education, training, and experience – a traditional systems engineering perspective, similar to the one described in NPD 7120.5D and NPR 7123.1.

Interestingly, the Ares I-X management team, which also participated in the knowledge capture activity, had a different mind-set based on a “fast-track flight-test” systems engineering perspective that in many cases ran counter to 7120.5 and 7123.1 but may be just as valid given the circumstance.

Both groups labored together over a 42-month period to accomplish the mission, and this report strives to capture both points of view.

Lessons Learned From a Traditional Systems Engineering Perspective

The Ares I-X flight test demonstrates the need for caution when tailoring critical systems engineering processes. Although tailoring can save time in the early life cycle steps, it might result in more work and added cost, as well as unintended consequences, later in the life cycle. At the outset of a project, the management and team need to:

- Establish, effectively communicate, and gain acceptance of the concept of operations, articulating:
  - Roles, responsibilities, accountability, and authority
  - Requirements management processes and flow-down
  - Common processes and tools (especially IT support applications – e.g., requirements management, scheduling)
  - Control processes (boards, panels, technical authority)
- Develop critical planning documents, effectively communicate their intent, and gain acceptance of the key management tools:
  - Systems Engineering Management Plan (SEMP)
  - Program Communication Plan (or equivalent protocol ensuring effective communication) – discussed in detail in section 4.6.4
- Develop mature requirements, including Safety Reliability & Quality Assurance (SR&QA), Development Flight Instrumentation (DFI), post-flight data processing, acceptance, and disposal, prior to issuing contracts

- Develop and implement program/project specific, mandatory "101" training, orientation, and team-building events addressing key areas of interaction (e.g., KSC-101, Requirements Management-101, SE&I-101, IPT-101).

Lessons Learned From a Fast-Track Flight-Test Systems Engineering Perspective

Ares I-X might become a template for future fast track flight-tests and provide a primer on balancing risk in a severely schedule constrained environment. The following lessons were derived from interviews, dialogues, and comments on early drafts of this knowledge capture effort from Ares I-X mission managers.

- Recognize and communicate that schedule is the driver (independent variable) and other factors (with the exception of safety) must bend to accommodate
- Effectively communicate the concept of operations to include a risk-balanced approach wherein program phases may overlap in order to meet schedule
- Build the right team
- Appoint strong, aggressive interface managers
- Gain acceptance from all participants to work together to evolve a flight test approach that unifies typically disparate Center and contractor procedures, processes, and practices
- Use Agency policy as advisory and incorporate and/or tailor as appropriate (where value is evident)
  - Get approval, at a high level, of senior management for the tailoring or deviations
  - Ensure that everybody understands the tailoring or deviation and acknowledges their roles within the revised policies
- Ensure that all flight test participants have a common understanding of roles, responsibilities, and terminology
  - Verify this understanding through "deep-dive" (multiple levels of detail) simulation activities
- Gain recognition from all participants that iteration in requirements (e.g. environmental loads) will be inevitable and to plan accordingly with respect to design margin whenever possible
- Get started right away under a unified command and control paradigm while developing formal flight test project policies, plans, and process

- Since a fast-track project will likely not have time to change the infrastructure, define how the project will work within the available infrastructure

- Dynamically balance the risks of waiting for project maturity verses the risks of schedule delays

- Accept and foster a “good enough” philosophy that acknowledges the importance of a one-off flight test but acknowledges that it can, in fact, fail

    - This needs to include actively managing expectations at all levels within the agency, program, and project, including the leadership, management, workers, as well as public and legislative affairs

- Employ pathfinder hardware to prove or verify processes involving multiple organizations as a means to uncover process shortcomings and/or misunderstandings regarding roles, responsibilities, and authority

Conclusion

This knowledge-capture effort was undertaken so that future projects can benefit from the successes and failures encountered by the Ares I-X team. In preparing for future flight test projects, either fast track or traditional, readers are encouraged to consider all viewpoints, and to critically read and discuss the information contained in all three volumes of this report.

Finally, congratulations again to the Ares I-X team for their successful flight-test.

Table of Contents

Volume I: Main Report

NASA Exploration Systems Mission Directorate
Ares I-X Knowledge Capture

1 INTRODUCTION

The Ares I-X Flight Test Vehicle (FTV, Figure 1) was successfully launched on October 28, 2009. The test flight met all primary mission objectives and provided important data for future NASA space-systems development. To better understand the processes used during this fast-track program, the Associate Administrator for the Exploration Systems Mission Directorate (ESMD) called for a more dynamic and interactive lessons learned acquisition and dissemination process. This recognizes the need to move away from the "collect, store, and ignore" paradigm of the database-centric lessons learning approach used in the past. This report summarizes the management and process-level lessons learned during the flight-test project, and hopefully provides insights for NASA and commercial developers of future space systems.

Figure 1. The Ares I-X Flight Test Vehicle (FTV) was was successfully launched from Launch Complex 39B at 11:30 a.m. EDT on October 28, 2009. The 327-foot-tall vehicle produced 2.96 million pounds of thrust at liftoff. (NASA)

1.1 Report Layout and Elements

This report consists of three volumes. This volume, Volume I, summarizes the results of a storytelling-based knowledge capture activity. The knowledge capture activity has included over 100 individuals from 12 separate teams, each contributing narrative vignettes – contextual stories (tacitly recognizing constraints and challenges) that describe what worked and what did not during the Ares I-X flight test effort. Sections 2 and 3 provide an overview of the knowledge capture and transfer processes used by the Knowledge Capture Team. Section 4 discusses and synthesizes consensus issues identified by multiple individuals from multiple participating IPTs. Section 5 provides summaries of individual IPT (or participating organization) perspectives, issues, and success stories. The knowledge capture effort began in May 2009, before the launch of Ares I-X, and continued through a workshop held in late January 2010.

The opinions and vignettes (data) acquired (and provided in Volume II) represent individual Ares I-X experiences judged from the context of each individual's formal training and previous experiences on aerospace project teams. For the most part, this training and experience corresponds to the traditional systems engineering concepts embodied in the various NASA policy documents.

In addition, Sections 4 and 5 include opinions from a "Fast-Track Flight Test" systems-engineering management perspective and commentary from that frame-of-reference on the IPT observations. This discussion, provided in part by Ares I-X managers, provides additional context concerning risk balancing, "eyes-open" accepted risk, and the sort of compromises necessary to meet the schedule constraints.

Volume I also contains seven appendices: Appendix A describes the knowledge capture methodology, Appendix B summarizes knowledge transfer and communication processes, Appendix C describes specific Ares I-X knowledge transfer activities in-work, Appendix D identifies key knowledge capture events, Appendix E provides background on the Ares I-X organization, Appendix F provides an overview of the Ares I-X flight test mission, and finally, Appendix G provides a list of acronyms.

Volume II contains over 200 pages of IPT narrative documenting the experiences of the Ares I-X IPT and Technical Authority participants. This volume also includes a matrix of IPT-Lead issues and observations captured during the telephone interview process from May to October 2009**.**

Volume III contains slides from a three-day Ares I-X Lessons Learned Workshop held in Huntsville on January 25-27, 2010, as well as other lessons-learned documents developed by the IPTs and other stakeholders in the Ares I-X flight test.

1.2 Ares I-X Success and Accomplishments

The Ares I-X test flight was successful in collecting data to enhance the development of Ares I and Orion. The effort demonstrated that both the flight and ground system performed nominally. Perhaps most importantly from a management perspective, the mission successfully integrated the efforts of multiple NASA Centers into a cohesive flight test activity. It was successful example of senior leadership providing a fast track, *lean* project with the technical and managerial leeway to accomplish its goals.

> **… The data collected from Ares I-X represents a treasure trove to be mined for years …**
>
> *"Status Report of Ares I-X Flight Test Results" February 17, 2010*
>
> *– Butrill Smith*

During 2009, the Ares I vehicle had been embroiled in several major controversies based on analysis and modeling at various NASA Centers and several contractors. Providing data to validate, or not, these worst-case model predictions became a major goal of the Ares I_X test flight. The successful launch of Ares I-X:

- Demonstrated the viability of the guidance, navigation, and control systems on the 327-foot-tall vehicle and all algorithms worked as predicted.

- Experienced less lift-off vibration than worst-case modeling had predicted. Vibration had been a major concern based on early analysis.

- Experienced lower thrust oscillation than worst-case modeling had predicted. There was a major concern that thrust oscillation on production Ares I launch vehicles could present a possible danger to the Orion crew.

- Experienced less roll torque than worst-case modeling had predicted.

- Provided data that will be used to adjust and validate models used during the final design of the Ares I and Ares V launch vehicles. These validated models may also assist in designing or refining future launch systems.

Ares I-X was successful in meeting its primary objective:

- Demonstrate control of a vehicle dynamically similar to the Ares I/Orion vehicle using Ares-I-relevant flight control algorithms.

- Perform a nominal in-flight separation/staging event between an Ares-I-similar first stage and a representative upper stage.

- Demonstrate the assembly and recovery of an Ares I-like first stage at KSC.

- Demonstrate first stage separation sequencing

- Quantify first-stage atmospheric entry dynamics and evaluate first-stage recovery parachute performance.

    - During first-stage recovery, one parachute failed and a second was damaged. Performance of remaining chute was characterized. One of the mechanisms in the parachute deployment system did not operate as expected because of an unexpected condition that was revealed during the flight test.

- Characterize the magnitude of integrated vehicle roll torque throughout first stage flight.

Ares I-X was also successful in meeting key secondary objectives:

- Quantify the effectiveness of the first stage separation motors.

- Demonstrate a procedure to determine the vehicle’s pre-launch geodetic orientation vector for initialization of the flight control system.

- Characterize induced loads on the launch vehicle on the launch pad.

Another secondary objective that remains in work was to characterize induced environments and loads on the vehicle during ascent. It should be noted that data reduction and analysis continued throughout March and April 2010, with additional activities extending into autumn 2010. Ares I-X management will provide Agency management with updates throughout the coming months.

The mission also provided information on ground processing and allowed KSC to gain valuable experience using new technology and processes during many phases of readying the vehicle for flight.

1.3 Ares I-X Challenges and Constraints

The primary challenge, and constraint, posed by the Ares I-X flight-test was schedule. As already mentioned, Ares I-X was a fast-track flight test implemented in a three and one-half year period (see Figure 2) after a preliminary authority-to-proceed (ATP) in April 2006. This schedule, dictated by senior management, was relatively inflexible since the overarching goal of the mission was to provide flight test data to influence design (and validate models) of the production Ares-I launch vehicle. The design team needed this data at least six months prior to the Ares-I critical design review (CDR).

To support the fast-track schedule and to minimize costs where possible, Ares I-X was also designed to use as much heritage hardware and software as possible.

At the same time, another goal of the flight-test effort was to transition from the Space Shuttle model of operations to the Constellation Program (CxP) paradigm. This involved a significant shift in process (and in some cases, technology), particularly at the Kennedy Space Center.

The flight test team also strived to develop and evolve critical skills across a broad range of NASA Centers while achieving higher levels of workforce utilization. Thus, the mission was structured to bring together the traditional spaceflight Centers – Johnson Space Center (JSC), Kennedy Space Center (KSC), and the Marshall Space Flight Center (MSFC) – with two traditional aeronautics-research Centers – Glenn Research Center (GRC) and Langley Research Center (LaRC).

Recognizing the many challenges, in particular schedule goals, senior leadership gave Ares I-X management significant latitude (notwithstanding public and personnel safety requirements) to tailor CxP management and systems engineering requirements, CxP processes and requirements, and Ares I Project processes and requirements.

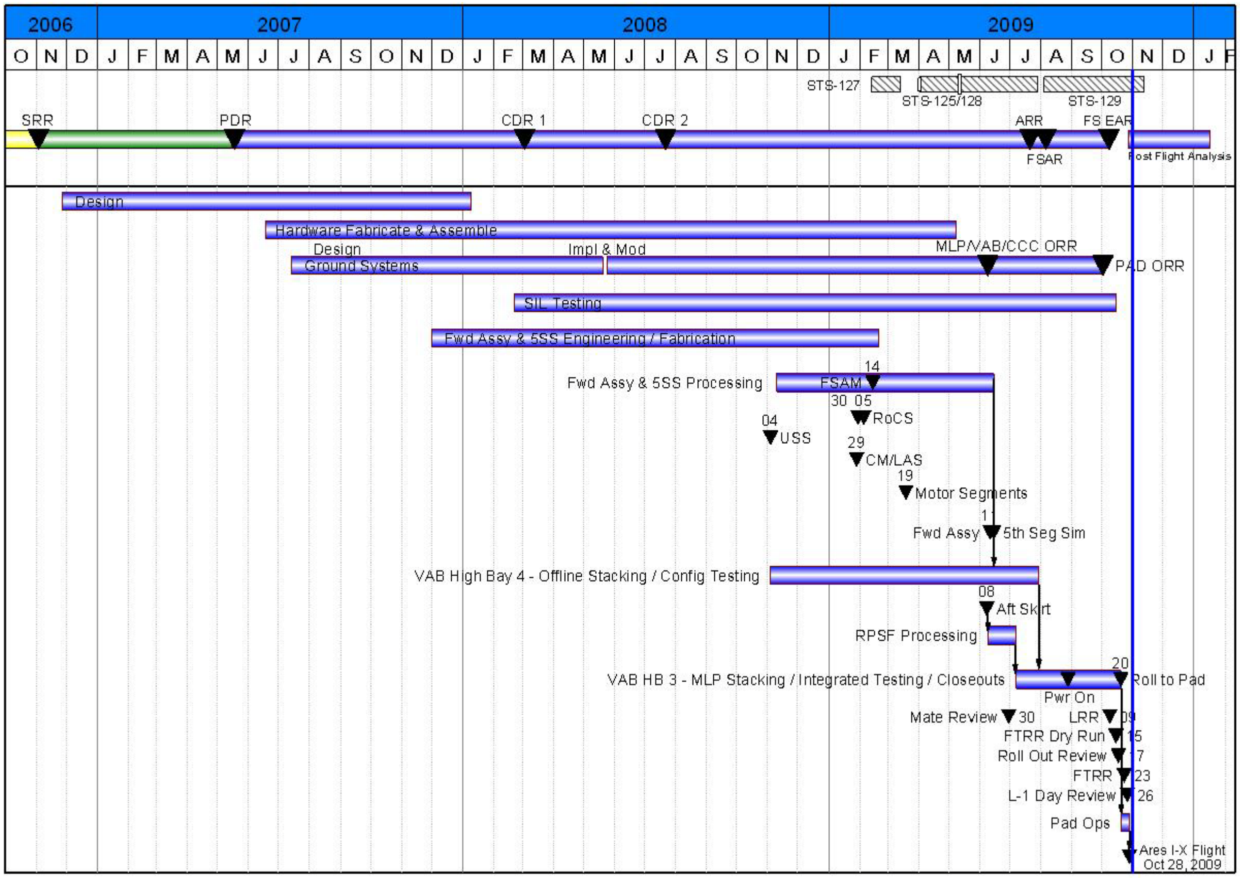


Figure 2. Ares I-X Summary Schedule

1.4 Lessons Learning

As an agency, NASA continues to struggle with institutionalizing lessons learning across programs and projects. The unwillingness to reflect on one's planning and processes is usually articulated as, "I am too busy," "that doesn't apply to my activity," or "I am already doing that." This phenomenon is particularly acute once a program has started and the participants are "on the clock" driving to meet schedules and milestones and lessons learning quickly becomes relegated to looking for solutions to specific technical problems or risks. Therefore, for programs underway, it becomes a management and leadership challenge to find a way to conduct a self-audit or to crosscheck "the moving train." Nevertheless, if the program is going to move forward in an efficient manner, it is critical that management support knowledge-capture and lessons-learned as a best engineering (and management) practice.

2 KNOWLEDGE CAPTURE PROCESS OVERVIEW

The Exploration Systems Mission Directorate (ESMD) Risk & Knowledge Management Office conducted a "knowledge capture" activity across the Ares I-X Project. These efforts began during the summer of 2009 and continued until March 2010.

The thematic framework (originally derived from Ares I-X risk records) used in the knowledge capture process included:

- Engineering Management
- Technical Authority (S&MA and Engineering)
- Systems Engineering
- Schedule
- Requirements Management
- Design
- Organization
- Manufacturing
- Test and Verification
- Communication
- Resources

The knowledge capture process focused on eliciting mini-stories or vignettes from integrated product team (IPT) members relevant to each of the thematic areas. To initiate the thought process, each participant was asked to consider three questions:

1. Up-front, early on we should have ______.

   (Note: this phrase emerged from early interview sessions as a ubiquitous response to "what worked well – what didn't work so well)

2. Our team really did well with ______ because of _____.

3. If I were "King/Queen," the top three things I would change are ______.

From June through August 2009, telephone interviews were conducted with the IPT leads. After the successful Ares I-X launch, three-hour face-to-face knowledge capture sessions were conducted with IPTs at GRC, JSC, KSC, LaRC, and MSFC. Each session combined structured group brainstorming with ThinkTank group-collaboration tool technology. Additional details of the process are provided in Appendix A and in Volume II of this report.

3 KNOWLEDGE TRANSFER COMMUNICATION PROCESSES

The story-telling modality is key to the knowledge capture delivery process. In addition to this knowledge-capture report, other output products will emphasize briefings, seminars, and small group discussions. Technology-based knowledge transfer will include a wiki space and blogs to enable a broad discussion of findings. Additional details of the process are provided in Appendix B.

4 INTEGRATED OBSERVATIONS

The Ares I-X project was a fast-track, schedule-driven effort to design, manufacture, test, and launch flight-test vehicle within a 42 month time span after the preliminary authority to proceed was issued in April 2006. Ares I-X was also a "first flight" mission that represented an enormous challenge in coordinating many organizational "moving parts" for the first time. In addition, the first flight of any space vehicle type also historically experiences "start-up transients" and technical issues as latent defects in design, manufacture, and operations are exposed.

4.1 Self Assessment: Things Done Well

Before examining issues and opportunities for improvement, it is important to acknowledge those areas that worked well for Ares I-X and might serve as guideposts for future efforts. The following bullets summarize the opinions of the individuals and IPTs that participated in this knowledge capture effort. Things done well included:

- Leveraging personnel, hardware, software, processes, and the testing approach from the Lockheed Martin Atlas V program

  To reduce cost and schedule risk, the Ares I-X team used heritage hardware and software to the greatest extent possible. Items used from the Atlas V program included the Fault Tolerant Inertial Navigation Unit, Redundant Rate Gyro Unit, and Flight Software (with modifications).

- Leveraging other government assets such as LGM-118 Peacekeeper hardware

  The team used components from decommissioned Peacekeeper intercontinental ballistic missiles to develop a Roll Control System (RoCS) for Ares I-X, reducing cost and schedule.

- Use of conservative structural design considerations

  The RoCS IPT took advantage of the robust performance margins of the heritage components, and by not being mass/volume constrained for the support structure, employed conservative design margins. Maintaining conservative design margins was also important during the design of the Upper Stage Simulator (USS) and other elements since it helped mitigate uncertainty in the flight environment loads.

- Leveraging Space Shuttle hardware, processes, and infrastructure

  Ares I-X used significant amounts of Space Shuttle hardware and infrastructure. This included a modified Space Shuttle four-segment solid rocket booster for the first stage, the Mobile Launch Platform (MLP), the transporter-crawler, Launch Complex 39B, and selected assembly and integration work processes. NOTE: While seeking efficiencies by reusing existing Space Shuttle processes, some of these experienced implementation issues Such as the iPRACA to CxPRACA interface that is further discussed in Section 5.9, S&MA.

- Utilization of the avionics Software Integration Laboratory (SIL)

  The (Lockheed Martin) SIL played a key role in resolving countless problems prior to vehicle integration. SIL testing of the integrated avionics and Ground Command, Control, and Communications (GC3) unit directly minimized vehicle integration issues. The link between the SIL and KSC also enabled launch procedure simulation and training.

- Expanding Agency space launch support and management capabilities

  Great strides were made in developing space launch program/project support and management capabilities at GRC and LaRC, and in developing broad inter-Center cooperation and teamwork. There are now over 400 civil servants and contractors experienced in navigating inter-Center and multi-contractor cultural differences. The challenge was not strictly one of geography and history. The cultural "mixing bowl" included:

  - JSC program/project management culture
  - KSC Space Shuttle operations culture
  - Lockheed Martin Atlas V evolved expendable launch vehicle (EELV) culture (avionics)
  - MSFC SRB/First Stage culture
  - USAF systems engineering management culture (Peacekeeper)
  - ATK SRB/First Stage culture
  - GRC manufacturing culture (USS)
  - LaRC research culture for systems engineering and integration (SE&I) and the crew module launch abort system (CM/LAS)

- Process excellence in system safety hazards analyses

  The Ground Operations (GO) IPT cited process excellence in their implementation of system safety hazards analysis in vehicle integration at KSC. Specifically GO noted excellence in addressing integrated hazards, implementing controls, mitigation in processes and procedures.

- Accomplishing process excellence in ground, sea, and air transportation to KSC

The USS, First Stage, and CM/LAS teams demonstrated excellent logistics planning and coordination in transporting hardware to KSC.

- Developing flyaway maneuver

  The Ares I-X groups, Ground Systems (GS) and Flight Systems (FS), successfully collaborated to develop the initial flyaway maneuver designed to minimize damage to pad infrastructure. The challenge was using an infrastructure designed for one vehicle (Space Shuttle) for a new vehicle (Ares I-X) with a significantly different drift profile during the first few seconds of ascent. Ultimately, the damage to the MLP zero-deck and 95-foot hinge column was minor in comparison to early predictions. It was a perfect example of two IPTs from different Centers working together.

4.2 Innovations and Initiatives

Three other areas with ultimately positive outcomes were recognized by some observers as positive but described by others as problematic in execution.

- Management initiatives: flat organization / minimal boards / panels

  Most contributors felt that the flat Ares I-X organization enabled horizontal communication and contributed greatly to the resolution of issues and inter-IPT visibility. At the same time, many participants felt that the structure required too many decisions to roll-up to the top decision board (XCB) that appeared to create a bottleneck at certain times. Many felt that delegation of decision authority to lower level boards might have been a more effective approach. This was eventually accomplished by the XCB creating the Technical Review Board (TXRB) and the DFI Control Board (DXCB) late in the mission.

- Transition from Space Shuttle to CxP concept of ground operations

  While Ares I-X was leveraging legacy Space Shuttle hardware and processes, it was simultaneously trying to develop a CxP "way of doing business." This dual charter led to an inevitable "learning curve" in which all participants worked together in forging a new paradigm for integrating and processing flight hardware.

- Effective use of independent reviews

  Implementation of independent reviews within the Ares I-X mission was hailed as an important contribution in a variety of areas (e.g., verification) while other independent assessment activity was cited as overwhelming, with up to four separate independent assessment teams simultaneously evaluating the same issue. Ultimately, all parties involved in independent assessment found ways to work together effectively and to streamline review activities (e.g., combining S&MA and engineering technical review activity).

4.3 Integrated Analysis of Opportunities for Improvement and Issues

Figure 4.1 shows the three-tiered method of rolling-up, analyzing, integrating, and communicating the enormous amount of lessons learned information acquired during the knowledge capture activity. The top level contains the "Top 3" overarching, most important lessons learned characterized as Mission Success Factors (MSF).

The term Mission Success Factor is used to describe things that are important to achieving mission success, and as such, might be applicable to future fast-track development efforts. Mission Success Factors can be described as actions (or inactions) that contributed to or impeded progress.

The key Mission Success Factors are presented in Section 4.4 using a "Policies & Procedures, Planning Preparation, and Processes," paradigm to communicate the wisdom and insights of the Ares I-X knowledge capture participants. Figure 4.2 shows the key Mission Success Factors that are wholly from the knowledge capture data set and represent the factors that would mitigate the greatest number of risks and concerns.

The top tier also includes other critical Mission Success Factors as a broader and more detailed set of key lessons.

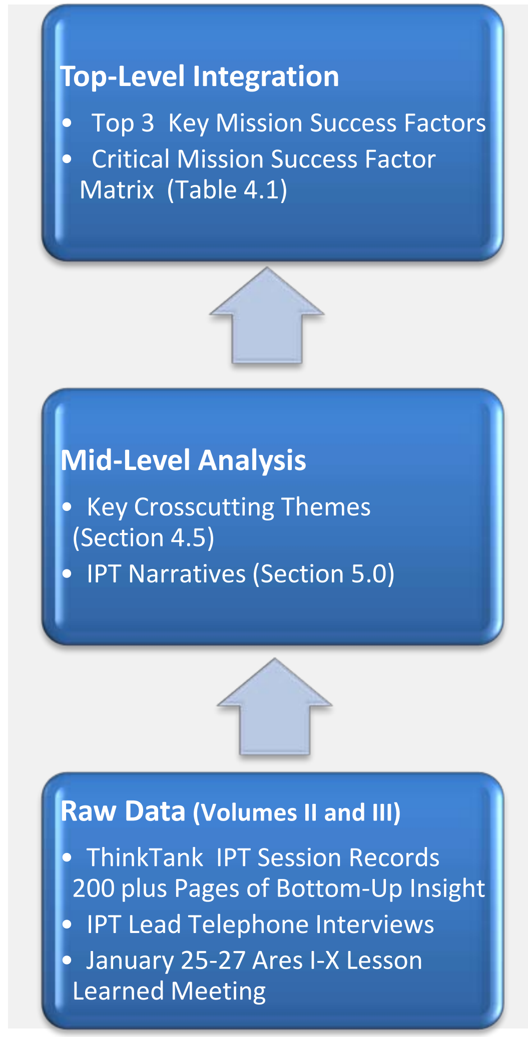


Figure 4.1. Hierarchy of Analysis

The second tier contains Crosscutting Narratives (Section 4.6 of this document) addressing each of the thematic areas used in the knowledge capture process. Section 5.0 provides summaries of individual IPT key concerns and lessons. Finally, the third tier, Volume II of this report, contains the "raw data," over 200 pages of IPT ThinkTank narrative discussion of issues, concerns, and lessons.

4.4 Key Mission Success Factors

The knowledge capture team sought to identify overarching issues identified in commentary that would address the greatest number of subordinate issues (e.g., parent-child in a risk context or root cause factors in a mishap investigation).

Figure 4.2 contains the Top 3 Mission Success Factors to consider in future development and test activities based on the lessons from Ares I-X. The Top 3 Mission Success Factors are derived from Table 4.1 (on the following pages) which includes a broader set of critically important Mission Success Factors. These are based on identifying consensus issues discussed in the aggregate knowledge capture data set.

The Ares I-X deputy project manager assisted in the analysis by indexing each item using the familiar "stop light" paradigm:

- Things Done Well
- Things Not Done Well (not communicated effectively, not accepted, or not implemented in a timely manner)
- Things Not Done

.

Key Mission Success Factors

Establish, Effectively Communicate, and Gain Acceptance of Program/Project Concept of Operations, Articulating:

- Roles, responsibilities, accountability, and authority
- Requirements management processes and flow-down
- Requirements and verification ownership and waiver authority
- Common processes and tools (especially IT support applications)
- Control processes (boards, panels, technical authority)

Conduct Necessary Planning Up Front and "Early On," Especially:

- Develop Systems Engineering Master Plan
- Develop program communication plan / rules / norms (see section. 4.5.4)

Conduct Necessary Preparation and Orientation

- Develop mature requirements (including S&MA) prior to issuing contracts
- Implement mandatory "101" training, orientation, and teambuilding events

Figure 4.2. Key Mission Success Factors

Table 4.1 Ares I-X Knowledge Capture: Future Efforts – "Must Do" Success Factors

Legend: Done Well   Not Done Well Not Done

	Policies & Procedures	Planning	Preparation	Processes
Program / Project Management	■ Define and Document Mission Success Criteria ■ Define Clear Roles and Responsibilities for S&EI, MMO, IPTs, and Interface Management ■ Develop and baseline all necessary policies, procedures, and work instructions (command media) ■ Baseline Program/ Project - Level Technology Tool-set (Requirements Management, Scheduling, Document Management) ■ Do-not Beta-Test hardware/software in a severely constrained project ■ Define (baseline) "constraint requirements" (mandatory overarching requirements set including S&MA requirements, human rating requirements, engineering standards, workmanship standards) – tailor as allowable but document and establish the baseline ■ Define formal Milestone Reviews to be implemented (e.g. 7120.5D, 7123.1A) –	■ Develop and Maintain Master Schedule ■ Develop Integrated Communication Plan (see Section 4.5.4) ■ Develop Co-location Approach for each phase of the project to the extent possible ■ Develop and implement Information Architecture (common structure relevant and intuitive) ■ Plan to enable intuitive access to all critical project resources ■ Develop Integrated Budget & Resource Management Plan ■ Develop an Integrated Acquisition Strategy (Plan) with Clearly Defined relationships between IPT Management, Project Management, and contractors ■ Develop Human Capital – Staffing/skill mix Analysis and Plan ■ Define Information Sharing Ground Rules – "what is proprietary and	■ Develop and Implement Mandatory Training, Teambuilding & Orientation Seminars (with attendance as appropriate) ■ Requirement Writing-101 ■ S&EI-101 ■ KSC-101 (Old SSP GO class was done) ■ IPT-101 ■ Boards & Panels-101 ■ IT Tools-101	■ Implement Project-Level Board Structure ■ Implement rigorous schedule management process up-front

Table 4.1 Ares I-X Knowledge Capture: Future Efforts – "Must Do" Success Factors

Legend: Done Well Not Done Well Not Done

	Policies & Procedures	Planning	Preparation	Processes
Program / Project Management	Enforce Event (Gate) Driven Mgmt. Approach ▪ Define Program/Project-Level Board Structure and Authority ▪ Define Mandatory Elements for all Acceptance Data Packages (ADPs) ▪ Ensure mutual understanding of ADP requirements ▪ Develop and define waiver process and especially Authority to approve a waiver or tailoring of baseline constraint requirements ▪ Define Acceptable Verification Approach For Heritage Hardware ▪ Implement WBS structure and resource loaded schedule at program/project and IPT levels to enable EVM implementation	what is not" ▪ Develop Role for NESC		
Systems Engineering	▪ Define Clear Roles, Responsibilities for System-Level Requirement Ownership (especially at interfaces) ▪ Define Clear Roles & Responsibilities for System-Level Verification (especially at interfaces) ▪ Ensure inclusion of launch-site support requirements, facility	▪ Develop System Engineering Master Plan ▪ Develop Configuration Management Plan ▪ Develop Requirements Master Plan ▪ Develop Verification Master Plan ▪ Develop System-Level Requirements	▪ Attend Mandatory Training, Teambuilding & Orientation Seminars ▪ S&EI-101 ▪ KSC-101 ▪ IPT-101 ▪ Boards & Panels-101 ▪ IT Tools-101	▪ Implement SE Board Structure ▪ Implement Requirement Change Process ▪ ▪ Implement waiver process

Table 4.1 Ares I-X Knowledge Capture: Future Efforts – “Must Do” Success Factors

Legend: Done Well Not Done Well Not Done

	Policies & Procedures	Planning	Preparation	Processes
Systems Engineering	requirements, and, range safety requirements ■ Define CoFTR Requirements and Launch Commit Criteria (LCC) ■ Establish Waiver Process ■ Establish Change Control Process	■ Develop System-level Verification Plan		
IPTs	■ Develop IPT process documentation (command media) as necessary ■ Develop IPT Boards as appropriate ■ Consider Establishing Lead Design Engineer Role	■ Develop Design Requirements ■ Develop corresponding verification requirements ■ Develop hardware transfer documentation (DD-250 and 1149) and Acceptance Data Pkgs ■ Develop assembly drawings ■ Develop Assembly-Integration test procedures ■ Develop Work Authorization Documents (WADS) as required	■ Attend Mandatory Training, Teambuilding & Orientation Seminars ■ S&EI-101 ■ KSC-101 ■ IPT-101 ■ Boards & Panels-101 ■ IT Tools-101	■ Implement IPT Board Structure as appropriate
	■ Work with management early-on to baseline S&MA requirements and engineering standards, including common workmanship standards	■ Develop S&MA Plan and flow-down through contracts ■ Present TA assessments and recommendations	■ Attend Mandatory Training, Teambuilding & Orientation Seminars	■ Implement S&MA Boards as appropriate ■ CESRP

Table 4.1 Ares I-X Knowledge Capture: Future Efforts – "Must Do" Success Factors

Legend: Done Well Not Done Well Not Done

	Policies & Procedures	Planning	Preparation	Processes
S&MA / CE	(Not Done Well) OCE must clarify and better document ERB process requirements and implementation approach (Not Done) Define single and consistent PRACA process to be followed by all IPTs (Not Done Well) Define MRB Process (Not Done Well) Ensure consistency of S&MA requirements across all IPTs and Centers	periodically to team, external customers, and stakeholders.	(Not Done) S&EI-101 (Not Done Well) KSC-101 (Not Done) IPT-101 (Not Done) Boards & Panels-101 • IT Tools-101	(Done Well) Implement System Safety Process (Done Well) Provide avenues for dissenting opinions to appeal to higher authorities
Contracts Management		(Not Done) Develop an acquisition strategy that clarifies relationships between elements and ensures incorporation of mature project requirements (including S&MA)	(Not Done) Attend Mandatory Training, Teambuilding & Orientation Seminars (Not Done) Boards & Panels-101 (e.g., Change Request Boards)	(Not Done) Do not issue contracts with immature requirements (whenever possible – always a consequence)
Agency CIO / Center CIOs / ICE Team	(Not Done Well) Implement Project-defined IT tools (requirements management, scheduling, PRACA, MRB, CAD) in a consistent and interoperable manner (Not Done Well) Streamline and improve IT access processes	(Not Done Well) Carefully consider the consequences of Beta or pilot testing software or IT technology in schedule constrained flight-test projects	(Not Done) Attend Mandatory Training, Teambuilding & Orientation Seminars (Not Done) IT Tools-101	

4.5 Selected, Key Lessons by Thematic Area

Remember that Individual commenter's are expressing their opinions concerning what they would change if they had the power to change it (…in a perfect world…) and what they would have done up-front to make thing work more smoothly and/or more effectively.

This section provides a brief narrative of the key issues within each of the thematic framework areas used in the knowledge capture activity. The framework provided a necessary (and effective) structure for the capture activity, but at the same time is imperfect. Almost every issue or "story" is cross-linked with one or more themes. For example, a given issue such as "… problems with Solumina signal reception at the launch pad …" could be booked as a resource issue, a communication issue, or a test and verification issue. The knowledge capture integration team developed each section from carefully considering thematic content contained in Volume II (bottoms-up Ares I-X IPTs), identifying shared (multiple commenter's, multiple IPTs) issues and concerns, and abstracting overarching lessons.

In addition, many of the sections include a "Fast-Track Flight Test" systems engineering management perspective and commentary on the IPT observations. This discussion, provided in part by Ares I-X managers, provides additional context concerning balancing risk, "eyes-open" risk acceptance, and the types of compromise necessary to meet schedule constraints.

4.5.1 Engineering Management – Program/Project/Mission Management

Implement strong management / leadership up front: A fast-paced and geographically dispersed organization demands a strong, command and control, directive management / leadership approach early on. With many personnel "growing up" in a Space Shuttle (i.e. human-rating) culture, it will be important for management to more clearly articulate expectations for future flight-test projects. Specifically, management should articulate the work processes, design margin, factors of safety, S&MA requirements, verification philosophy, and test and verification requirements.

Concept of Operations – Roles and Responsibilities: Clarify roles and responsibilities early and articulate "the rules" To everybody involved in the project. Examples of clearly defining the roles and responsibilities that would have assisted Ares I-X include:

- Early development of management plans such as the Systems Engineering Management Plan (SEMP), configuration management/data management (CM/DM), requirements management (RM), etc.

- Clearly delineate SE&I functions – "SE&I is in-charge of X,Y,Z, and verification shall be conducted in the following manner …"

- Define roles and responsibilities for the IPTs, SE&I, MMO, and Center functional entities

- Follow a traditional systems engineering framework (complete analysis before design / complete design before fabrication)

- Define the requirements change control process and change-board hierarchy

- Complete element verification prior to shipping hardware to the use site (e.g., KSC)

- Conduct end-to-end process "table tops" of requirements / design / product verification to ensure continuity of the SE&I domain (top-to-bottom process)

Standard Tools and Processes: A major, overarching lesson/challenge was the decision to allow participating IPTs to continue employing different tools, processes, and procedures after accepting fundamental differences. These differences ultimately resulted in a myriad of problems, each consuming time and money, and some even preventing implementation of critical controls. Recommendations from the participants include:

- Use common, standard project schedule software and allow no exceptions. Since Ares I-X was a fast-track project on a limited budget, in most cases individual groups were compelled to use existing application software (whatever was standard at their Center or company).

- Use NASA standards (not Center standards), and if this is not possible/practical, at a minimum use common standards.

- Use a common computer-aided design (CAD) format to facilitate transfer of configuration data for modeling, analysis, and configuration management. CAD data provided by government design organizations, contractors, and subcontractors must be convertible to the program-defined format.

- Use common, standard workmanship procedures (or demonstrate equivalency). During Ares I-X, it was determined that Centers implemented NASA Standard 8739.4 differently. Because of this, a project should detail the implementation of Agency standards for key requirements.

- Use a common, standard project-defined information architecture within a single, consistent, requirements management system (e.g. Windchill)

  While the Ares I-X "lived" the experience of non-standard, poorly integrated information technology (IT), CxP has yet to experience the full life-cycle impact of these issues. The issues experienced by Ares I-X should be a wakeup call. CxP Information Systems supporting the Ares and Orion projects is making excellent progress in this area. However, seemingly minor problems, if not addressed now, will result in multiple programmatic, engineering, S&MA, and operations risks. The CxP will again become a "victim" of poor IT if the program/project, Centers and Office of Chief Information

Officer (OCIO) fail to bring the senior management emphasis necessary to ensure coordinated, interoperable, secure, user-friendly IT applications.

Fast-Track Flight Test Systems Engineering Perspective: The traditional systems engineering perspective makes many good points, but Ares I-X knowingly employed an aggressive concurrent engineering process with inherent and accepted risks. The real question is how can one make concurrent engineering work better? Based on the Ares I-X experience, recommendations to enable a quick start with managed risk include:

- Recognize and communicate that schedule is in fact the driver (independent variable) and other factors (with the exception of safety) must bend to accommodate
- Effectively communicate the concept of operations to include a risk balanced approach wherein program phases may overlap in order to meet schedule
- Co-locate main design leaders and managers (LSE, Designer) for short period (at least 3 months)
- Establish contract flexibility
- Implement IPTs under SE&I direction and control until identified plans/documents (an agreed to set of core documents) are in place
- Identify the minimum requirements that must be verified at vendor (or manufacturing location) prior to shipping to the use site (i.e., KSC) – do this at time of requirement document baseline

4.5.2 Systems Engineering (SE&I) & Requirements Management

Early Implementation of a Robust SE&I Function: The number one challenge was the late implementation of the SE&I function and associated systems engineering control processes. The project succeeded because of heroic efforts of many team members during the last six to twelve weeks before launch with unsustainable (17-hour workdays) individual efforts from many key players. Identifying the breakdown of the SE&I control processes earlier in the 42-month Ares I-X effort would have provided much needed relief during the final push to launch.

As it was, however, issues were raised concerning the management of requirements – a core SE&I responsibility. Specific suggestions for improvement include:

- Requirements management needs to be carefully implemented with due attention to interfaces, including drawings
- A common language for requirements management must be discussed and agreed to up front

- Time must be expended to train requirements owners (at various levels of decomposition) how to write a complete, verifiable, requirements statement that includes verification methods, (as appropriate) and quantitative measure of effectiveness

- Time must be allocated to develop relationships through face-to-face teambuilding events early in the formulation process

- Roles and responsibilities must be clearly articulated, defining ownership of requirements, responsibility for defining verification methods, and responsibility for conducting the verification

- Interfaces should be under the authority and control of strong, aggressive "Interface Managers," not book managers who were perceived by many to lack authority and who operated in a passive role

- Requirements management discipline needs to be enforced to ensure timely development and transfer of requirements between elements (e.g., cables and wiring)

Late definition of loads and environments was the most vexing problem for SE&I and the element IPTs, which continuously worked loads compliance issues through the launch timeframe. Key lessons extracted in this area include:

- Ensure adequate and early analytical resource availability, including a fallback plan to add resources

- Ensure adequate resources for verification and validation of analyses

- Ensure open and accurate communication of design margins and factors of safety for all hardware and software (in-house designed and built, vendor provided, and heritage)

Fast-Track Flight Test Systems Engineering Perspective: It is important to recognize that the loads and environment issue was an artifact of a fast moving process and late startup of SE&I. In particular, aero tests, the foundation of the loads and environment analysis were late in arriving. Future fast-track flight tests should:

- SE&I should be stood-up and completely functional at the beginning of a project to exercise authoritative control over the entire requirements development process

- Plan and communicate design analysis cycles (DAC) in coordination with concurrent engineering activities and built-in tests

- Identify what is expected from each IPT, Center, and contractor in the DAC plan.

4.5.3 Organization and Culture

> **… we went up to Marshall Space Flight Center to talk to all the IPTs on how we were going to do business at KSC and we mentioned "WADs" ... everybody looked at me like I had two heads ...**
>
> **[thus the need for a true KSC-101]**

A “discovered challenge” in Ares I-X was the strength of “center-centric gravity.” This included the need for negotiation and resolution of conflicts with Center functional managers who preferred Agency policies and/or Center standards and procedures to those adapted by Ares I-X and/or CxP. There existed a general lack of willingness to adopt the practices and procedures used by the integration Center (KSC).

Conversely, this can be viewed also as KSC’s hesitance to embrace the policies, practices, and traditions of the other design Centers. Every IPT interviewed expressed concern over the friction and costs associated with working through these kinds of issues. Each Center and each IPT would have appreciated being treated “as a customer” – a relationship of mutual respect in which every IPT provided requirements to others and was willing to accept requirements from others.

Senior leadership should make it clear to the program/project/mission management, and the leadership and management at each of the Centers and contractors, that an acceptable compromise will be reached quickly, and then adhered to throughout the effort. Strong, involved leadership and management are essential.

The overwhelming message or lesson learned is the need for program/project/mission management to implement mandatory teambuilding and orientation seminars, or their equivalent, for all program/project participants up-front and early on. These orientation events (two hours – maybe half a day) should include presentations but especially discussions among participants – developing the “human interfaces” within the program/project/mission. These orientation sessions should focus on specific areas important to the program/project. For Ares I-X, the types of seminars/classes that would have been useful include:

- SE&I-101 would cover the roles, responsibilities, expectations, and describe the authority of the SE&I organization
- IPT-101 would cover the roles, responsibilities, expectations, and communications expected of each IPT
- KSC-101 would describe how to work effectively at/with KSC, including the culture, security, access, scheduling, policies, processes, range, ground service equipment [GSE], and facilities
- Boards and Panels-101 would define the authority and frequency for each board, and the bottleneck-mitigation policies to be used
- IT Tools-101 would cover all of the common tools, including document management, requirements management, scheduling, verification, and CAD
- Meetings & Teleconferences-101 would define the rules, tools, and techniques to conduct effective meetings and teleconferences

In addition, more mutual planning up-front would have helped each Center better appreciate the skill set, specialties, culture, traditions, and capabilities of the other Centers. Finally, the Ares I-X experience positively demonstrated the importance of, and need for, strong directive leadership to build teamwork by clearly defining roles, responsibilities, and authorities, and enforcing discipline in a multi-cultural team environment.

Fast-Track Flight Test Systems Engineering Perspective: The management team recognized that KSC (vehicle integrator) had one way of doing business while other Centers building flight hardware had different approaches. The management team strove to find a way to get each organization what they needed to do their job and it was a different solution for different elements/hardware. The lessons learned is to get a piece of hardware (even a pathfinder) through the system as early as possible to find those areas that have clashing paradigms. One is unlikely to find these until a real piece of hardware making its way through the process.

4.5.4 Communication Processes and Information Technology

Effective communication is difficult under the best of circumstance, and a multi-Center/contractor effort that is geographically dispersed complicates matter further. The Ares I-X IPTs raised issues with every imaginable communication modality used during the project.

A universal concern related to meetings and teleconferences. The majority of commenter's felt that there were too many meetings and that many meetings suffered from inadequate time management – allowing endless discussion and often extending into the evening. Issues that were resolved in one meeting were then re-examined at the next meeting with the same lengthy discussion. The meetings might have been necessary, but the perception was that meeting leads could have been more efficient.

The meeting concern is linked also to the program/project board structure. Many observers noted the need to revisit the Ares I-X Control Board (XCB) approach and consider delegating some responsibilities to lower-level boards with more authority earlier in the mission.

However, the greatest ire was reserved for Windchill. Key concerns involved "lumbering slowness," ponderous access approval processes, impossibly unintuitive information architecture, and ineffective search capability. These criticisms are not unique to the Ares I-X project, and are commonly expressed across the Constellation Program. The need for a common collaboration environment is undisputed, and obviously, no commercial product will satisfy all users, but the CxP implementation of Windchill is far from ideal. Future projects may wish to consider:

- development of a user defined flight test project information architecture
- evaluation of other application software

Given that Windchill is the CxP standard, and the Program is heavily invested in it, perhaps a better recommendation is for a mutli-Center, multi-disciplined group to be chartered to reengineer the CxP implementation of Windchill to address its perceived (and actual) shortcomings and to make it more user friendly and intuitive. The tool itself is sufficiently flexible and tweaks to its current configuration might be able to address at least the major issues identified by the Ares I-X project.

Other communication concerns involved multiple tools used for management of problem/non-conformance reports (iPRACA and CxPRACA) – in particular the Solumina tool used in the field to support verification activity. One notable quote stated, “Do not beta-test IT solutions in critical roles on schedule-driven programs/projects.”

Another issue involved the construction and use (or not) of the integrated project master schedule. In particular, problems emerged when it became apparent that everyone had a different scheduling application.

Perhaps the most important – and overarching – recommendation from IPT interviews was to develop an integrated communication plan that addresses the full range of issues up-front and early on in program/project planning. The plan should include, at a minimum:

- Board and Panel processes
- Inter-IPT forums
- Teleconference Management
- Meeting Management
- IT Tool Implementation and Project Standards
- Access
- Permissioning / Passwords / Support / Non Disclosure Agreements
- Document Management Systems
- Requirement Management System(s)
- Non-conformance Management System(s)
- Calendar and Scheduling System(s)

On a positive note, the Ares I-X Mission Manager’s (MM) “open door” policy, weekly IPT Lead meetings, open communication, and significant leadership qualities were in many ways responsible for the success of Ares I-X and should be modeled by future Project Managers or Mission Managers.

Fast-Track Flight Test Systems Engineering Perspective: The imperatives of schedule constraints (fast track) mean that one must work with the infrastructure available. Unfortunately, participating Center IT applications were not necessarily in-step with each other or with the CxP baselines. The same is true when pulling together multiple contractors, each with its own IT applications and processes. Planning is important, and can help, but a degree of inefficiency (and risk) must be accepted in a fast-track project.

4.5.5 Resources

In the Human Resource area, concerns were raised related to available staffing and experience at GRC and LaRC, where the workforce traditionally has supported aeronautical research activities. This transitional challenge was not unexpected. At the same time, it was essential that critical functions such as "integration" have the appropriate staffing levels and skill mix.

As the CxP moves forward, it will be important to carefully plan and match roles and assignments with staffing capability. This planning should also recognize the importance of carefully selecting individuals with the right experience and "the right personality" (aggressive, extraverted, relentless, determined) to serve in the role of interface managers, a job requiring proactive leadership on both sides of critical interfaces.

In the budget management area, concerns were raised by the GO and GS organizations that funding authority was disconnected from project management authority, creating issues and slowing down approval and implementation of requirement changes. Concern was also voiced that IPTs needed to be more proactive in defining facility and ground support equipment needs at KSC.

4.5.6 Technical Authorities

The roles and responsibilities of the various technical authorities (S&MA, engineering, etc.) were often blurred, and were further complicated by multi-Center, multi-contractor environment that existed on the Ares I-X project.

4.5.6.1 Safety and Mission Assurance (S&MA)

Many positive observations were offered concerning S&MA support, in particular in the area of system safety hazards analysis. Nevertheless, the late definition of SR&QA requirements was a huge issue for Ares I-X. Observers noted that this resulted from a combination of issues including mission schedule demands and early mission team role and responsibility issues. In addition, difficulties and delay arose in negotiation of SR&QA requirements between Agency SMA organizations and the Constellation Program, Ares Project, and Ares I-X management.

In the future, Agency S&MA functional managers (beginning with Headquarters Office of Safety & Mission Assurance) need to be engaged early in the process to ensure that the Constellation Program S&MA organization at JSC coordinates rapidly with the various Projects and Centers. At the same time, the Project and Center management must ensure coordination with the Agency and Program S&MA organizations and aggressively work together to tailoring Agency S&MA requirements and standards, as appropriate, to ensure that common standards are adopted and implemented across each effort.

On Ares I-X, the S&MA Plan was signed in January 2008, over a year into the project. IPTs were designing and building hardware and contracts had been issued prior to the definition of

SR&QA requirements. In the future, this requirement set needs to be articulated in an S&MA Plan that serves as the governing document for S&MA implementation. The S&MA Plan will also mitigate Center-to-Center S&MA disconnects with regard to applicable requirements, in particular manufacturing quality-assurance and workmanship standards.

Finally, the S&MA staffing levels were not adequate to support the workload (simultaneous teleconferences, meetings, and hundreds of emails), limiting the effectiveness of the independent oversight role. A key benefit was the appointment of an Ares I-X Deputy Chief Safety Officer (CSO) at KSC. He represented the CSO and was able to provide a hands-on perspective for issues arising during processing. This greatly streamlined the process.

4.5.6.2 Engineering

The Engineering Technical Authority (TA) function made important contributions to Ares I-X mission success. The TA function enabled open and broad discussion of technical issues leading to risk identification and implementation of mitigations. The TA was respected and listened to on Ares I-X.

Inputs were formally solicited (required) at all Ares I-X and CxP boards, including the Ares I-X Control Board (XCB), Constellation Control Board (CxCB), Integrated Center Management Council (ICMC), Mate Review, Launch Authority Team (LAT), etc.

The Engineering Technical Authority supported all mission efforts including lean events, tiger teams, review boards, schedule meetings. The combined Engineering and S&MA Readiness Review (ESMARR) was a good forum for the TA communities to have a clear understanding of the status of work and risk level prior to entering the Flight Test Readiness Review (FTRR) and Safety and Mission Success Review (SMSR). Ultimately, the TA played an important role in accomplishing system level verification activities during the last weeks leading up to launch.

At the same time, there were also issues associated with the implementation. For instance, TA roles and responsibilities were a matter of broad debate. Some of the IPTs questioned the role of the TA as independent reviewers, suggesting that they needed to be more engaged as problem solvers, addressing technical issues and using their independent reporting path only if necessary.

TA resource implementation was also an issue, with some Centers unable to provide the necessary staffing. Other Ares I-X personnel discussed confusion associated with multiple chief engineers participating in decision forums or supporting individual IPTs.

Many participants cited the problems inherent in establishing an Engineering Review Board (ERB) without providing the authority to disposition technical issues. Various IPTs cited frustration at having to present the same issue to multiple System Engineering Review Forums (SERF), then to the ERB for several sessions, before finally being elevated to the XCB where decision authority resided. Related concerns included the duration of SERF, ERB, and XCB meetings, the tendency to rehash issues repeatedly, and the perception of “too much view graph engineering.”

4.5.7 Schedule

One participant noted, “We burned out three schedulers.” Scheduling was a major challenge for the Ares I-X mission and a major lesson-learned was the importance of developing a single, shared, realistic schedule. Many issues (e.g., requirements, requirements changes, verification) were related to schedule. Many of the IPTs voiced concern that the top-level schedule was not taken seriously and the official schedule was considered by many to represent an idealized, stretch goal. The *de facto* schedule was “get it done as soon as you can.” Meanwhile, some IPTs were actually trying to work to the published schedule and voiced frustration with those seemingly ignoring it. The consequences stemming from schedule issues included:

- Frustration on the part of those working to the schedule
- Unnecessary conflict among IPTs (anti-teambuilding effect)
- Transfer of hardware before engineering and acceptance data packages (ADP) were ready
- Late engineering impacting the KSC processing and launch site schedule

The lack of a credible, top-level, integrated master schedule was in part a result of communication issues. Almost every IPT used a different, not interoperable, version of Primavera or a home-built scheduling application, or some combination of the two.

Out-of-sync schedule management problems were further exacerbated when IPTs were directed by the Mission Management Office (MMO), to begin shipping hardware to KSC with significant open work and incomplete assembly. The MMO understood, and accepted, this as a risk, but as a result, hardware arrived without drawings, test instructions, and transfer paperwork. Another concern involved lack of visibility into GO implementation schedules once hardware arrived at KSC.

Consider this observation, “Even after hardware arrived at KSC there was zero schedule accountability. I understand there are many factors involved, but as far as I can remember we in Ares I-X did not meet a single planned milestone prior to March 2009.”

However, another participated counters, “Schedule was king, what people didn’t like was that that the day-to-day estimates for tasks were not accurate. This was because it was the first time doing these tasks on new hardware. This was not a common occurrence with people used to working with mature Shuttle and station hardware.”

Many individuals commented on the “Lean Event” held in April 2007. Some of the IPTs found the activity to be an effective intervention in helping improve delivery of hardware. Other IPTs saw little value in the events conducted in the summer of 2007 due to inadequate follow-up, and considered the activities as “band-aid” attempts to make up for inadequate schedule planning and management up front.

Fast-Track Flight Test Systems Engineering Perspective: Recognizing the schedule issues discussed above, it is imperative that fast track projects ensure that subordinate organizations (i.e., the IPTs) adhere to a mast schedule managed from the top. In addition, all participants need to recognize that interface products must have milestones on both sides of the interface, and everybody needs to assist in finding ways to implement integrated schedules across multiple IPTs, Centers, and contractors.

4.5.8 Design

Ares I-X presented several quandaries to management and workers alike. First was the issue of design philosophy, which drove design requirements – should Ares I-X be treated as a test flight or a human-rated space system? The lack of clarity and mixed signals on this issue resulted in delay and misplaced effort in a number of cases (e.g., RoCS, USS, and avionics).

The second major issue was also related to requirements – the expected environmental and induced environments – in particular coupled loads. A third, and late arriving “discovered challenge” was the range-safety triboelectrification design requirements.

Yet another design requirement dilemma was the question of verification requirements for designs based on heritage hardware. Did the program want to accept certification based on testing conducted 30 years ago or re-test Using modern procedures and test equipment? All of these requirements issues related, in part, to the need to demonstrate compliance with margins and factors of safety. In some cases, the uncertainty, or changes in philosophy, resulted in hardware being manufactured and discarded. One member of the Upper Stage Simulator IPT summed it up this way: “Place more emphasis on requirements analysis before proceeding to design – much less fabrication.”

Ares I-X employed a heritage first stage (a four-segment SRB from Space Shuttle), roll control system (made from Peacekeeper ICBM components), and avionics system (from the Atlas V EELV). An early expectation of “easy integration” proved very much an illusion. One notable observation was that “heritage hardware/software is no bargain” and a great deal of effort was involved in adapting heritage systems, in particular avionics. On a positive note, the Lockheed Martin Atlas V Systems Integration Laboratory (SIL) facility provided outstanding support to the design and testing of avionics.

A final, but most vexing, issue was associated with interface design, including ownership, coordination, and verification. Almost all IPTs emphasized the need for a strong, independent integration function across the various elements. One participant noted that the IPTs had to become “self-integrating” – an *ad hoc* approach to interface management that although ultimately successful, was less than ideal.

Configuration and Data Management (CDM) was a challenge for Ares I-X for the same root causes that drove many other lesson areas: the need to establish the CDM plan early, decisions on product/milestones under CDM control, firmly delineated lines of communication and accountability, IT challenges, and diversity of processes that required integration.

Fast-Track Flight Test Systems Engineering Perspective: The delayed implementation of SE&I led to the late authorization of interface managers. Notwithstanding this delay, the interfaces came together successfully. The fact that the IPTs were asked to work out the interface and integration details was not necessarily wrong. IPT’s writing interfaces, with oversight and issue resolution from SE&I, was successful in Ares I-X and may be appropriate for future fast-track projects.

4.5.9 Manufacturing

Manufacturing requirements were an issue on Ares I-X, in particular workmanship standards. Many observers noted that these standards must be clearly articulated up front by mission management and the S&MA quality assurance organization. Different Centers and contractors employed different standards (bolted versus welded plate junction, shielded versus metallic tape wrap, etc.). In addition, the flow-down of manufacturing requirements to the avionics suppliers appeared largely absent, and those suppliers tended to use processes based on their respective business models and past customer influences.

Manufacturing staffing and skill mix issues were identified by multiple IPTs including the certification of the contractor workforce to perform specialized assembly and manufacturing operations. SE&I suggested that Ares I-X should have used more Evolved Expendable Launch Vehicle (EELV, in particular Atlas V) personnel to support integration and verification efforts at KSC.

There was not an overall quality surveillance plan, and each IPT was left to determine its own needs and methods. One IPT recommended the development of an integrated surveillance plan that extended to all areas including the launch site. SE&I cited concerns that manufacturing quality assurance artifacts provided by subcontractors were not always made available for SE&I review. Verification processes had to be changed for one of the IPTs (RoCS) so that verifications did not have to be approved by SE&I for acceptance because test data and results were not available (the Peacekeeper hardware was certified thirty years ago).

Nevertheless, the use of MSFC S&MA Resident Offices at manufacturing sites, such as ATK-Utah and the KSC Assembly and Refurbishment Facility (ARF), greatly enhanced the ability of S&MA to implement quality assurance programs with highly experienced personnel who were intimately with the hardware and contractor processes.

Several IPTs emphasized the need to do as much manufacturing, assembling, and integration at the home Centers, prior to delivery to KSC to preclude increased schedule processing time and increased cost. At least one IPT cited the lack of configuration management between IPTs, which forced significant rework at KSC with respect to connectors, harnesses, and the routing of harnesses.

Several IPTs cited the importance of having a full-time IPT representative at KSC during build-up to address Field Engineering Changes and provide continuity in TxRB, RAC, and other local boards. These representatives could also provide a clear point of contact among the IPTs. Avionics IPT commenters suggested that they should have been more involved in the installation of avionics hardware, “where practical, Avionics IPT should install the avionics hardware.”

While developing the MRB and non-conformance reporting requirements, KSC pushed to limit design IPTs to one signature that represented the IPT manager, the Lead Engineer, and S&MA. Although this single signature may have saved time, the design IPTs perceived it as limiting their concurrence role and diminishing the independent assessment role.

Several IPTs discussed the benefits of implementing an engineering pathfinder or engineering/manufacturing test article as an enabler for overall manufacturing success, stating, “the learning benefits are too numerous to mention.” IPTs also discussed the benefit of conducting a dry-run (or trial operation) whenever possible as an effective way to find and resolve processing issues.

Technical lessons learned were identified in areas related to welding, tube bending, flow restrictors, and fasteners. A recurrent issue in the manufacturing area was the issue of fasteners. Knowledge capture participants commented on issues associated with procurement lead-time, availability, pedigree, and the sheer number of different types, with over 200 fastener types on the Upper Stage Simulator (USS) alone. The use of conductive aluminized tape for First Stage harnesses caused significant effort to be expended late in the project to understand fully the risk associated with this practice.

A number of comments related to the use of IT applications in manufacturing and manufacturing verification. Some IPTs considered Solumina a bottleneck for timely execution of installation and vehicle hardware integration, in particular because of limited (or no) access for individuals that had concurrence responsibilities. Others praised Solumina for providing access (for those at KSC) to all work orders and their status. One IPT commented, “There were too many ‘news’ at one time.” Solumina should have been incorporated at some other time. Connectivity to the server was very difficult, especially from other Centers.” Another commenter stated, “Beta testing of new tools such as schedule or design software needs to be accompanied with implementation time. If schedule is most important, beta tests should not be done.”

One USS IPT member noted that manufacturing technicians had trouble visualizing the segment design based on 2D drawings. She suggested converting Pro E solid models into the PTC Product View format that would allow the techs to view the solid model without having a seat of Pro E. Techs could zoom into the solid model to view fine detail. PTC Product View is part of the Windchill suite of applications.

Numerous comments and observations were made concerning the lack of adequate documentation, drawings, and procedures (e.g. “Manufacturing should have their specialty operations ‘how to’ documentation plans such as welding activities, inspection, and contract requirements.”)

SE&I noted that Acceptance Data Packages were spread out and not easily available for review for some of the IPTs, and, in fact, SE&I had difficulty getting data from these packages. Other IPTs commented that SE&I tracking of documentation for delivered components were not consistent. Serial numbers and calibration sheets for sensors were not available for delivery for some components.

S&MA noted that Quality Engineering was not adequately involved in developing work authorization documents (WAD), commenting, “This is highly unusual as the QE organization should be making sure that appropriate inspection points are incorporated into the WADs and that the WADs are clearly written and include appropriate pass-fail criteria.”

4.5.10 Test & Verification

The test and verification theme generated some of the most passionate discussion during the knowledge capture process. All participants agreed that the roles, responsibilities, and authorities of SE&I and the IPTs must be thoroughly defined and clarified, if possible through tabletop simulation of a complete and full verification scenario that exercises every participant (e.g., IPTs, SE&I, GS, MMO, S&MA, CE, and contractors).

A second topic involved verification requirement ownership at a system level, at an element level, and at interfaces. A third area of concern was communication and decision authority throughout the verification process. As previously discussed, in some cases it took months to closeout a verification. One suggestion from the KSC-based GS IPT was, "Co-locate verification decision authority. Find ways to co-locate project element representatives with decision authority at the integration site (KSC) to facilitate more efficient verification."

A fourth area of discord was the universally disliked Windchill application that slowed all aspects of performing the work of verification. To make matters even more difficult, the Solumina wireless PDA-based "experiment" had many issues (signal dropouts, no way to print a procedure) and further frustrated verification teams at KSC.

A fifth topic of contention was the issue of test adequacy (e.g., numbers of tests, test levels, duration) to demonstrate compliance with requirements or to provide the rationale for reduction in factors of safety.

In summary, issues within test and verification existed with:

- Roles and responsibilities
- Verification ownership
- Decision authority
- Verification support technology (Windchill and Solumina)
- Verification method adequacy – especially verification test rigor and adequacy
- Timing – when to do the verification.
- Terminology regarding design verification vs. product verification

5 INTEGRATED PRODUCT TEAM (IPT) KNOWLEDGE CAPTURE NARRATIVES

In this section, the Knowledge Capture Team has summarized key broadly applicable issues challenging each individual Integrated Product Team (IPT) in a (nominal) 300-word narrative. The narratives are derived from ThinkTank sessions typically reflecting a traditional systems engineering perspective. Some sections also include a fast track flight-test systems engineering management perspective and commentary on the IPT observations. Each IPT has provided careful review, editing, and/or co-authoring of paragraphs within each section. A brief summary of organizational responsibilities and relevant background or context is also provided in each section.

Again – note that each section summarizes vignettes from individual commenter's expressing their opinions concerning what they would change if they had the power to change it ("… in a perfect world …") and what they would have done up-front to make thing work more smoothly and/or more effectively.

Lessons summarized as part of one IPT narrative is often related to one or more other IPTs. Context is critically important, as are interrelationships. Nearly all of the experiences and lessons that can be derived from the Ares I-X experience are broadly applicable to aerospace programs in general.

5.1 Ground Operations (GO) IPT

The Ground Operations (GO) IPT, comprising civil servants and contractors assembled from the Space Shuttle Program at KSC, was in the unique position of not only integrating the hardware, but also hosting the final assembly of flight elements. GO assisted design IPTs in completing unfinished flight element design verification and further assisted IPTs and the Mission Management Office (MMO) in implementing system-level verification activities, developing assembly drawings, and operational testing requirements.

… Communication of transferred work was not clean. A crime scene investigation was needed every time hardware arrived …

The GO organization expressed a broad range of comments related to Ares I-X implementation. GO confronted the challenge of flight element teams arriving with differing philosophies of work processes, workmanship standards, and often late drawings, OTRs, and transfer documentation. The perceived lack of work process discipline and adherence to documented processes was at odds with the KSC culture, which prides itself in work process rigor and excellence. Another issue was the premature shipment of flight hardware to KSC, stressing the Center's ability to provide facilities and services for final assembly.

In a "cultural collision," the GO IPT expected to assume ownership and control once a payload arrived at KSC. GO also intended to streamline the integration process and was not expecting design teams to be involved through the entire process. On the other hand, given the "first flight" of a new launch vehicle, design teams expected to be fully involved in integration, testing, and launch as with the first Space Shuttle – obviously a key disconnect with regard to roles and responsibilities.

Another major issue for GO was the need to clarify project roles, responsibilities, authority, and accountability for system-level verification, in particular the role of SE&I. Late-arriving loads environment data was a further problem, extending verification closure activity to days (even hours) before launch. Finally, the late recognition of range-safety triboelectrification requirements created constraints that resulted in launch delays.

On a positive note, the GO IPT recognized the outstanding support of the S&MA organization in developing the system safety hazards analysis.

One key to the success of Ares I-X was when they reorganized the project into IPTs with budget and schedule authority. Bringing KSC on board to lead the efforts for developing the operational test requirement (OTR) plan, the launch commit criteria (LCC), and the integrated vehicle drawings for SE&I was very positive. CxP may wish to consider doing this for the main line program. It was different from just having a Launch Integration Office (MK) type organization. MK represents the design side and does not always understand the GO side. Having key GO people lead these activities would facilitate communication between GO, SE&I, and the IPTs in a way that an MK-type group could not.

Using a single lead for all DD250 and DD1149 (property transfer documents) reviews was outstanding, ensuring all hardware was treated in a similar manner with respect to receiving inspections. Having the design center representatives in the prime firing room during testing was critical. One IPT member commented, “There were several times when we had a hardware or procedural problem that needed to be discussed. Having them present allowed us to quickly disposition problems and/or change the procedure. This should be considered mandatory for the next test flight.”

5.2 Ground Systems (GS) IPT

The Ground Systems (GS) IPT, located at KSC, had responsibility for critical ground support equipment and systems including the Mobile Launch Platform (MLP), launch pad, and lightning arrest tower system. The GS IPT was also responsible for conducting or supporting Ares I-X verification activities conducted at KSC.

… Verification of a requirement should take days, maybe weeks – but not months …

This IPT identified many areas for improvement in the verification management process. The IPT cited verification process complexity (in comparison with Space Shuttle processes) as an issue, driven by the need to coordinate and communicate with IPTs and SE&I remotely. Related requirements management and verification issues involved:

- clarification of roles and responsibilities for element- and system-level verification – especially SE&I

- slow, cumbersome, and unreliable IT tools, specifically the Windchill and Solumina applications

- inadequate/cumbersome change control processes

… Having a streamlined team does not always pay off when you have other constraints like time and risk …

- inadequate definition of CoFTR and Flight Test Readiness Review success factors (mandatory requirements).

The GS IPT also voiced concern that system-level verification methods and "artifacts" needed to be more clearly defined and communicated more effectively. Other key GS issues included difficulties in the closeout of paperwork, noting that the waiver process should not be used to correct documentation and late arriving Environmental Data Book and Vertical Stabilization System (VSS) requirements. However, a key success factor identified by the GS IPT was the need to have on-site presence of key individuals with decision and sign-off authority to witness testing.

The GS IPT shared the GO IPT concerns that other IPTs arriving at KSC needed to take the time to understand KSC tools, work processes and procedures, and culture. Not doing so resulted in confusion and delay. Further, the GS IPT stressed that more team building needed to take place up front to develop trust and a sense of mutual respect, especially when so much remote or virtual communication is involved.

The GS IPT identified the need to re-examine core communication processes, most notably teleconferences and decision boards. Other issues of concern included the confusion associated with multiple problem reporting and corrective action processes (i.e., CxPRACA, iPRACA). This issue is discussed further in section 5.9 (S&MA).

Schedule performance was improved by providing a pre-agreed amount (typically 15 percent) in each design/build tasks for Field Change Notices. This allowed contractors to accomplish the job with maximum flexibility and gave them the ability to react much more quickly to unexpected issues. Having good subcontractors led to good products and on-time deliveries and involving GO during initial design concepts provides a superior product and reduced actual design and implementation costs.

… Management needs to "provide equal consideration between flight systems and ground systems"…

Ground Systems input to flight system designs is important in reducing program operational costs. An example for Ares I-X would be the RoCS. The lean event that allowed GS and GO perspectives into that system design provided significant cost savings and schedule reductions in both design and processing for Ares I-X. These types of costs could become significant when flying five missions a year over the course of a 30-year program. The cost impact to the flight system was minimal with regards the RoCS redesign.

5.3 First Stage (FS) IPT

The First Stage (FS) IPT, located at MSFC, was responsible for working with ATK to create a fully function Ares I First Stage including specific Ares I designs (frustum, forward skirt extension, forward skirt) and a 5-segment (4 active, one simulator) Reusable Solid Rocket Motor (RSRM) and aft skirt which were transferred from the Space Shuttle Program. What might have appeared to be a low risk design task had an enormous built-in challenge: all of the RSRM segments and numerous other components were either out-of-shelf life or excessed Space Shuttle hardware. The FS IPT addressed a range of topics including communication, decision processes (e.g., boards), roles and responsibilities, and basic management processes.

… You have not explained something to NASA until you explained it to everyone at NASA …

In the case of communication, FS IPT members cited too many meetings, and meetings that seemed to never end. Specifically, recurring working group meetings tended to re-hash the same issues repeatedly week after week. Also linked to the communication (and management) theme was the topic of decision boards. The XCB, early in the life cycle, was considered a bottleneck inhibiting efficient decision-making, especially related to change control. The FS IPT joined the chorus calling for development of a thorough communications plan during the up-front formulation process. It is worth noting that a flat organization enables efficiency in one sense but also creates huge pressure at single decision points like XCB (versus an alternative hierarchal board structure with distributed authority).

The FS IPT voiced concerns regarding roles and responsibilities of SE&I and the Mission Management Office (MMO). Part of their concerns related to the direction of contractors. While there has been much discussion on the management approach of IPT contractors, the FS IPT believes its more traditional approach was effective and responsive to Program and MMO needs. Given the ATK First Stage contract was awarded and technically managed by the FS Project, additional direction provided by a third party such as SE&I would have created an unmanageable situation due to specific contractual funding and performance limitations. The FS IPT believed that is was simply not acceptable for another IPT such as SE&I to "direct" or have control over another IPT's contractors, and MSFC Procurement would not allow it. The FS IPT strongly disagreed with the input provided in Section 5.8 as being a "no brainer."

Other suggestions included clarifying and better communicating roles, responsibilities, and authority. Discussions extended to clarifying the interacting roles of SE&I, IPTs, S&MA, contractors, and the KSC Engineering Directorate. The SE&I discussion also extended to the "integration vacuum" and the need for a strong, aggressive, empowered integration function.

Also in the management arena, the FS IPT discussed the need to conduct adequate up front planning in the areas of requirements, verification, and schedule management. FS as well as other IPTs voiced the need for an integrated master schedule and the adverse effects of schedule pressure, and the FS IPT believed, "Schedule should never be traded for technical rigor."

The FS IPT questioned the effectiveness of "celebrated" Lean Events. While a significant number of mitigation activities identified in the Lean Events did not materialize, the overall communication of the IPT status and issues was an efficient method to bring the management team to a common consensus on programmatic direction. An interesting FS IPT discussion examined the issue of "aggregate risk" – the combined effect of multiple risks that individually may not raise an alert or concern with management. The individual risks cited included: shortage of skills, rejected parts, schedule pressure, limited staffing, a single set of hardware, and a tight budget.

… Lean Events were a band-aid for poor planning up front …

Flexibility in the use of alternative facilities and personnel to support the schedule was important in supporting some key delivery milestones. An example of this was the use of the Astrotech facility for fifth segment processing and the availability of USA and ATK technicians to support KSC operations.

Fast-Track Flight Test Systems Engineering Perspective: The flat organization made Ares I-X work! The risks associated with potential bottlenecks were well worth taking given the benefits of fewer decision nodes and greater cross-IPT integration that came with a flat organization.

5.4 Roll Control System (RoCS) IPT

The Roll-Control System (RoCS) IPT, located at MSFC, used decommissioned LGM-118 Peacekeeper intercontinental ballistic missile (ICBM) components (axial engines, propellant storage assembly and pressurization system) to provide directional roll control for the Ares I-X flight test vehicle. Using these heritage components required a Memorandum of Understanding with the U.S. Air Force at Hill Air Force Base where the hardware was stored. Although the Peacekeeper ICBM was an extremely high-reliability weapon system, the RoCS IPT was required to spend an extensive amount of time working design verification and analysis since it was a new system made from these components.

The RoCS IPT used Teledyne Brown Engineering (TBE), which has a long history with space hardware, as a contractor. TBE drafted the mission implementation plan and acceptance data package, and built the support structure to meet the structural and vibro-acoustic environment. TBE built two flight units plus one spare. A fourth unit was used for engineering development, handling, and assembly verification. Recognizing that delays would occur in developing environmental data books, the RoCS IPT purposely structurally overdesigned the system.

Test requirements creep was a constant challenge for the RoCS IPT. Qualification and acceptance testing became a requirement late in the project. The environmental loads were a moving target. For example, a new fairing designed to go over the engines was determined to be under-designed. It could not handle updated predicted aero-buffet loads and had to be stiffened.

Multiple participants from the RoCS IPT cited unclear and overlapping roles and responsibilities between engineering, S&MA, and the NASA Engineering & Safety Center (NESC) as an issue. The Ares I-X project had too many personnel involved in decisions. The roles and responsibilities for such projects need to be stated clearly in great detail so that there is quick and final decision-making occurring at the appropriate level.

> ***"… It has been an exercise in 'just as hard to qualify this heritage hardware as it would be to build it new' – but in many ways, we made it that way …"***

With a three-year project, the RoCS IPT had to make many assumptions on concurrency and analysis, and they proceeded at risk. The ultimate design of the final RoCS configuration depended on the highly proven and reliable Peacekeeper configuration. MSFC Engineering had to come full circle regarding in-house design philosophies (redundancies, dual regulators, parallel check valves, etc.) to show that the Peacekeeper configuration provided the best reliability in the context of the Ares I-X mission.

Based on Ares I-X implementation experiences, IPT participants suggested (perhaps obvious but nonetheless important) that detailed verifications should be defined as much as possible when the requirements are established, and the schedule should be front end-loaded as other unplanned problems would certainly come up later.

Participants also cited the importance of getting the easier requirements verifications accomplished as early as possible to minimize the bow wave of closing the more difficult ones later. It was noted that the IPT Lead and Lead Systems Engineer (LSE) maintained a good graphical and quantitative verification-tracking tool to show progress of closures.

5.5 Avionics IPT

The Avionics IPT, located at MSFC, was responsible for supplying three major systems: flight command and control, including hardware and software (this encompassed flight control as well as the implementation of the NASA-supplied guidance algorithm); ground command, control, and communication (GC3); and developmental flight instrumentation (DFI). Development risk was greatly reduced by basing Ares I-X avionics on the existing Atlas V systems. The Avionics IPT was also responsible for delivering post-flight data within 30 days after launch.

The Avionics IPT observed that there should have been a stronger SE&I function at the beginning of the project. In particular, SE&I should have exercised the authority and accountability for interface management (requirements and requirements verification) from the top-down, not the bottom-up. Several participants noted that the IPTs had to be self-integrators.

The Avionics IPT also shared a litany of requirement management concerns with other IPTs, including the need for:

- system-level requirements early in the project with a broader involvement of design IPTs
- better flow-down of Interface Control Document (ICD) requirements to Ground Operations
- a "solid" Systems Requirement Review
- top management to better control requirement changes and attendant costs

Corollary problems were identified in the design phase, where contracts were issued based on assumptions rather than well defined requirements.

One area of difficulty for the Avionics IPT was the changing emphasis on DFI. While some DFI was essential to accomplish mission objectives, the majority were not (the DFI requirements began with 1,200 sensors; there were over 700 at launch). The DFI requirements were defined just prior to the Avionics Preliminary Design Review (PDR), driving a DFI system redesign. DFI continued to consume excessive resources as issues with sensor delivery, installation, and testing progressed. Resources continued to be drained as the DFI system hardware was delivered and integrated at KSC. The project addressed the "DFI issue" in several steps beginning with assigning a priority to each sensor (mandatory, secondary, or low-priority). The Assembly, Integration, and Test (AIT) Plan further defined testing requirements. During vehicle integration at KSC, the Mission Manager established a DFI Control Board (DXCB) with authority to delete non-mandatory sensors without presentation to the XCB. This control board, consisting of representation from each IPT as well as the Ares I project, was able to effectively manage decisions to replace, use as-is, repair, or abandon sensors that did not perform as expected. Overall, less than 3-percent of sensors failed to perform as expected during flight.

> ***"… Avionics IPT had its own control board with representation from each IPT and SE&I that worked well …"***

Participants from the Avionics IPT indicated the need to better define the review board hierarchy and responsibilities to minimize repetition (e.g., MRB vs. SERF vs. ERB vs. TXRB vs. DXCB). In fact, the Avionics IPT established its own Avionics Control Board, with representation from each IPT, to resolve issues at the lower level and bring a solution to the proper upper-level board.

The Avionics IPT cited significant organizational and cultural challenges. The group strongly recommended that future programs develop a communication document at the beginning of the project to anticipate and mitigate potential cultural differences. The Avionics IPT also felt that future flight tests should plan to leverage expertise from the NASA Launch
Services Program Office at KSC.

> ***"… Through the entire project, Shuttle vs. Atlas [cultural] differences caused strife, miscommunications, and added risk to integration activities …."***

The Avionics IPT also suggested that avionics should be viewed as a vehicle-level system instead of a "stage subsystem." The participants felt this would allow:

- vehicle-level system optimization
- commonality to be employed (e.g., Atlas URCU / BRCU, ORCA)
- elimination of separate management organizations
- elimination of inter-organizational interface coordination

- reduced layers of coordination, approval, and authorization during the design and development process.

The System Integration Laboratory (SIL) was responsible for the resolution of countless problems prior to vehicle integration. Having a test-like-you-fly (TLYF) SIL enabled the avionics system testing to operate almost flawlessly. The integrated testing on the vehicle was smooth and virtually anomaly free. This is a direct result of the SIL facility and TLYF philosophy.

Finally, integration of avionics onto the vehicle was complicated by multiple methods for the recording and disposition of non-conformances including: 1) avionics contractor system; 2) the First Stage contractor system at the Assembly and Refurbishment Facility (ARF); 3) the Ground Operations contractor iPRACA system; and 4) the Constellation CxPRACA system. These multiple systems were confusing, and in some cases not value-added.

The Avionics IPT considered Lockheed Martin's processes and requirements adequate for the project. This saved many hours that would have been needed for the contractor to understand the NASA requirements and then demonstrate that they "met the intent" of the NASA documents. The IPT solved many problems quickly that would have otherwise taken longer by viewing contractors as team members instead of merely product providers. This demonstrates that open communication successfully reduces communication inertia. Government and contractors were able to operate with an "integrated team" effort (note that scope changes still required program approval / contractual direction). The face-to-face TIMs and meetings helped reduce tensions between the various cultures. The use of Table Top Reviews for drawings and procedures reduced release cycle time. A weekly one-on-one was held with the mission manager and each IPT lead. This was a strong management tool.

Fast-Track Flight Test Systems Engineering Perspective: Given the fast-track nature of the flight test, IPT self-integration was appropriate. In the end, there was a strong SE&I function, that used the good work started in the IPT self-integration phase. A fast track project must be willing to accept the risk of getting started rapidly while evolving management processes. In the case of avionics, a SIL-like facility and process is considered a best practice. A similar concept should be employed on all space flight programs, especially fast-track projects.

5.6 Upper Stage Simulator (USS) IPT

The Upper Stage Simulator (USS) IPT was responsible for developing, manufacturing, and testing of the 110-foot-tall, 430,000-pound USS at the Glenn Research Center (GRC). The USS simulated the shape, mass, and center of gravity characteristics the interstage to the top of the service module of the Orion vehicle.

The USS IPT had a noted success story in transporting USS segments from GRC to KSC. Through careful planning and development of relationships between participating organizations, the USS IPT trucked the USS from GRC to the Ohio River, then shipped it by barge (*Delta*

Mariner) via the Ohio and Mississippi river system to the Gulf of Mexico and around the tip of Florida and back up the coast to Port Canaveral in a flawless operation.

As with many Ares I-X IPTs, flow-down of requirements from SE&I (particularly loads and interfaces) needed to occur earlier in the design and analysis cycles. (Note: These comments concerning requirements may seem like "motherhood" but they represent real problems that impeded progress in implementing Ares I-X.) The full scope of SE&I functions in Ares I-X was not fully appreciated during the formulation phase. This was manifested in issues such as the need for a consistent vibro-acoustic methodology plan across all IPTs, problems with grounding and bonding requirements, the late realization of range-safety triboelectrification requirements (which became a problematic launch commit criteria), misinterpretation of the safety factors as applied to flight and ground hardware, and the very late loads data book releases.

The USS ended up being "over-toleranced" because design requirements defaulted to tight tolerances that were only backed off when the team had to resolve an issue or sought waiver because the requirements could not be met. In hindsight, SE&I should have taken more of an integration role and done more than just provide oversight to the IPTs. In the future, SE&I needs to do more of the integrated analysis, assessments, and take a stronger role in managing the integration of the IPT products.

> ***"… For a development flight test, the default should be loose tolerances that only tighten with technical justification, traceability to requirements, or other well-substantiated need …"***

Internally, support to the USS IPT structural dynamic analysis should have been better planned. The USS IPT found that the thermal and fluids design engineering effort was significantly underestimated for USS, and that an experienced lead engineer should have been identified from the start of the project. The USS IPT learned that too many IPT products were controlled at the XCB level, which resulted in additional effort to get documents approved and revised. In addition, all of the requirements contained therein had to be verified at the XCB level.

The development of engineering and manufacturing test article "pathfinder" segments produced substantial learning benefits for the USS IPT. The dry run process for the stacking and processing of the USS segments was equally useful.

Fabrication consumed the most resources during manufacturing. The USS IPT discovered that fasteners require the full-time attention of one knowledgeable individual on the project. Conducting manufacturing operations and procedures training sessions with the technicians and QA staff before starting each procedure would have benefited the IPT. Workmanship standards (particularly for electrical) were not well understood by the design and manufacturing teams and were not well defined until the majority of the work was complete.

In a related lesson, the lack of a comprehensive inspection program hurt the verification process, resulting in items that were not properly received or inspected (forcing re-inspection). Acceptance Data Package format requirements were defined late in the program, resulting in some costly and time-consuming "busywork." The huge bow wave of verifications due to Engineering Change Notices (ECN) in the last month of Ares I-X almost delayed the flight, suggesting the need for improved engineering ideas and plans (*"measure twice, cut once …"*). Finally, cost growth in a fast-paced, high-risk flight demonstration project like Ares I-X is to be expected and should be considered the norm, not the exception. This lesson learned implies that each project element needs access to program reserves, with a well-defined process for applying for those reserves.

A concurrent engineering process was put in place at the start of the processing phase to allow the integrated drawings to be developed in parallel with the processing due to the compressed schedule. This process was extremely successful because of the team's willingness to learn and adapt to each other's way of doing business. This was important because Ares I-X crossed many Centers and contractors and reflected that makeup. Through the concurrent engineering process, everyone stepped out of their comfort zones, took the best parts of the different ways of doing business, and combined them into an efficient Ares I-X way of doing business. Ares I-X brought the team members close together, creating good, open relationships that were part of what allowed this team to succeed. Cultural differences between the Centers and contractors can be large, and overcoming and appreciating these differences is a difficult and time-consuming process, but rewarding if accomplished. If at the highest level of the project, the management accounts for this and tries to bring the team together early in the process, the team will be more efficient.

Participants from the USS IPT suggested that Ares I-X be considered a "shining star" that demonstrates it is possible to pull together organizations from multiple Centers and contractors to design and build a launch vehicle in a relatively short time span.

5.7 Crew Module / Launch Abort System (CM/LAS) IPT

The Crew Module / Launch Abort System (CM/LAS) IPT, located at LaRC, were responsible for designing, manufacturing, and testing the CM/LAS simulator for Ares I-X. The CM/LAS was 53 feet tall, 16 feet in diameter, and weighed 16,000 pounds. The simulator included approximately 150 Developmental Flight Instrument (DFI) sensors.

IPT participants noted the need to clearly establish roles and responsibilities, including clear lines of authority for boards, panels, and interfaces between IPTs. The CM/LAS IPT also noted the need to set clear lines of authority where appropriate to prevent situations where individuals with valid and necessary input are not given adequate voice; and conversely, prevent someone without apparent and useful input from impeding progress.

"… This was not a human-rated vehicle yet was treated as such once at KSC – calling in much overhead probably not required …"

SE&I lessons from the CM/LAS IPT included the need to be very clear about ownership and verification of interface requirements. These requirements should have been verified at the interface and not on both sides of the interface. More emphasis should have been put on interface management details (technical, ownership, verification, cultural, and operational). This is often the most overlooked aspect of integrated team dynamics.

The CM/LAS IPT found that SE&I's Interface Requirements Document (IRD) were not empowered to enforce the agreements between IPTs. It was noted that interface management would have gone smoother if individuals working on interfaces would have had the opportunity to meet to develop the "human interfaces." The IPT would have benefited from the selection and use of a single configuration / data management tool upfront; the lack of such a tool made tracing requirements complicated and inefficient.

Participants from the CM/LAS IPT also believed that resource priorities, as well as standards and requirements, should be more consistent across and within the Agency, Centers, Project, and mission. A pressure point for the CM/LAS IPT was the crush of redundant meetings, across both Ares I-X and at the Center level, which may have been an artifact of the unclear roles and responsibilities issue. More effective meetings for virtual teams that minimize multi-tasking of participants and control meeting overlap and duration may require some prior planning on part of organizers, but will save time and frustration for all participants.

Locking down the Outer Mold Line (OML) took some time since the CM/LAS IPT could not follow Orion changes in lockstep and had to pick one design and proceed at some nominal risk. Changing requirements, as well as changing SE&I-provided load cases, also drove design. The LAS had to be largely redesigned to meet higher loads, which fortunately occurred prior to main fabrication. Fasteners were the largest issue for CM/LAS fabrication, including long lead times, late delivery dates, and changing availability that drove changes in design.

Differences in Center cultures and processes across the IPTs that delivered hardware to KSC resulted in what the CM/LAS IPT termed a "rude awakening once at KSC." This should be alleviated by earlier and more effective liaison, communication and training before IPT personnel and hardware arrive for ground processing.

"… Do as much manufacturing, assembling, and integration at the home Center prior to delivery to KSC to preclude increased schedule processing time and increased cost …"

Openness of management was beneficial. The general feeling was that one could call, write, or walk into an office to discuss problems with much of the management. The regular updates from the Mission Manager through email (et. al.) to the team were appreciated.

5.8 Systems Engineering & Integration (SE&I)

The SE&I organization was the lightning rod for a great deal of comment and dissatisfaction regarding roles and responsibilities across Ares I-X. Interestingly, the SE&I organization shared those concerns.

One IPT member noted that SE&I effectiveness was hampered from a late start and never really caught up. Not surprisingly, the number one recommendation from SE&I was to, "Stand up SE&I activities prior to establishing contracts, implementing product organizations, etc. Requirements must be established first [to allow] more time for up-front planning." SE&I also highly recommended giving "… SE&I the authority over IPTs commensurate with the SE&I responsibilities." It is reasonable to assert that if SE&I are to be held responsible for integration and requirements, then they should have clear authority, including definition of contract requirements and communication and control over contractors. [Editors Note: While reasonable, this may not be a realistic approach in practice due to contractual and legal constraints.]

> ***"… Give SE&I the authority over IPTs commensurate with the SE&I responsibilities …"***

SE&I also noted the need for a "real" Phase A formulation process as set out in NPD 7120.5D or NPR 7123.1 during which thorough planning can be conducted to develop, document, and staff critical systems engineering control processes (e.g., requirements, verification, configuration management, data management, risk management). SE&I joined other IPTs in criticizing the award of contracts prior to having systems-level requirements in place – whatever time was saved was surely lost several times over in terms of unsnarling a requirements mess and implementing costly contract changes. Further, on the matter of requirements, SE&I were trapped in the middle of a philosophical debate: is this a flight test or something more? This type of boundary condition must be defined by program/project management at the beginning.

SE&I joined others in citing the ineffectiveness (slow, difficult to access, difficult to use) of Windchill – a concern voiced by every IPT. In addition to others, SE&I's comments further caution against underestimating the importance of IT tools. Center ownership (or "IT turf") of a tool should not be a factor in deciding which tools should be used. Only tools proven effective should be implemented, and IT security should be balanced against the ability of project personnel to access data. IT Tools should not be allowed to be the "tail that wags the dog" – good IT tools should be almost transparent, not a topic of constant discussion and continuous training events to "fix the users."

The intuitive documentation naming conventions was a huge help. This was defined early in the Ares I-X SEMP and implemented at the system level and by several IPTs. Co-location to LaRC and KSC by the Mission Manager was very successful and speeded up decision-making processes and transfer of information and communication since the Mission Manager ran an open-door policy. Co-locating with the rest of the GN&C team was tremendously effective in getting the group to work together well and interact as a team instead of individual Centers. Removing the Center tags was very effective in getting over cultural bias.

The addition of a project coordinator was incredibly helpful for logistics of regular meetings, reviews, and TIMs. Creating teams that spanned NASA Centers and external partners developed a sense of team and ownership. Each member had to learn cooperation, and logjams were identified early. In addition, the SIL was very instrumental in validating the telemetry system. It was an invaluable asset.

5.9 Safety and Mission Assurance (S&MA)

Each IPT, SE&I, and the Mission Management Office (MMO) received Safety & Mission Assurance (S&MA) support with personnel located at GRC, KSC, LaRC, and MSFC. The S&MA Lead, located at MSFC, had deputies at GRC, LaRC, and MSFC. In addition, the use of resident S&MA personnel at manufacturing sites enhanced the ability of S&MA to implement quality assurance programs. Valuable experience and knowledge was gained about the hardware and contractor processes and practices. While broadly distributed, S&MA staffing levels were often thin. It is important to ensure that adequate S&MA resources are provided in order to support the multiple meetings and technical reviews that occur at lower levels, to assure that there is appropriate S&MA technical review and risk acceptance, and to prevent overworked, and over-stressful conditions among the team members.

> ***"… The working pace was too fast and not enough stand-down periods during the project. Information came in like water from a fire hose. 100 e-mails a day was extreme. Very difficult to take a sanity check …"***

A major issue was that S&MA roles were not clearly defined at the beginning of the project. This was later resolved with a flattening of the Level II/ III structure, but this cost time. There was no flow-down of SR&QA requirements to Ares I-X until approximately a year after project startup, following the reorganization into the Mission Management Office. S&MA did not become involved at the proper level until after PDR and, therefore, until after contracts were let. It is unclear why the original S&MA Lead, under the old organization, did not get the S&MA requirements in place earlier. Ares I-X S&MA requirements were not baselined until after PDR, hindering the influence that the hazard analysis process should have had on the design. The delay also increased the desire to reach compromises on items such as workmanship standards and nonconformance systems, which proved challenging later on. Consequently, a great deal of time and energy was spent debating and justifying S&MA requirements while the design matured. S&MA was playing catch-up for much the test flight activity.

With the fast pace of the Ares I-X project, it was vital to have a strong S&MA presence to ensure a successful mission. S&MA leadership often asked the hard questions in decision forums and was a good balance to the Mission Manager. The S&MA Technical Authority was respected and heard. The Chief Safety Officer (CSO) was embraced as a key part of Ares I-X leadership team. Inputs from S&MA were formally solicited (required) at all Ares I-X and CxP boards (XCB, ERB, etc), and the S&MA perspective was routinely presented at forums such as monthly ICMCs, CxCBs, briefing to NASA Administrator at SSC, and at major milestone reviews such as CDRs, Mate Review, Mission-level FTRR, CxP FTRR, and the Agency FTRR.

However, an opportunity exists for the Agency to better define how program, project, and element boards should be conducted. Boards are typically chaired by the "Programmatic Authority" chain, not the "Technical Authority" chain. This adds confusion when a TA-owned standard, requirement, or waiver is being discussed. If indeed the Technical Authority is paramount, then the chair should shift. In addition, NASA OSMA and OCE standards should be written to make it clear that compliance is required unless a deviation or waiver is approved by the applicable Technical Authority.

Knowledge was shared through weekly S&MA meetings, creating synergy within the S&MA community. The weekly S&MA tag-up charts were extremely useful in maintaining awareness of all Ares I-X S&MA activities, and this documentation made it possible to stay up to date on current issues during the times when direct participation in the meetings was not possible. WebEx was a very effective tool for this project, and it helped make Ares I-X successful by having a way to organize people quickly and effectively to communicate unresolved issues, design and requirement changes.

Problem and non-conformance reporting and tracking is an important element in the S&MA assurance role. The project needed to have a single system (e.g., CxPRACA) within which everyone could communicate, but the Centers and contractors wanted to use their own systems. Although it allowed for flexibility, the use of different nonconformance systems also created confusion. In hindsight, it would have been better to go to a single nonconformance system, especially as hardware custody was passed from a design IPT to downstream processing IPTs. A key example is the case of avionics. The Avionics IPT shipped hardware (sensors, harnesses, etc.) to other IPTs for installation and testing with open problem reports that had to be manually tracked, or even worse, tracked in multiple systems with duplicate PRs. The iPRACA-Solumina "super-system" made work difficult, hindering the inclusion of design IPT members, and forcing a cumbersome interface to CxPRACA. The systems required MRB participants to be behind the KSC firewall for access. This tool should not be considered as the "official record" of nonconformance, and a clear decision needs to be made and communicated regarding tools to be utilized on the CxP/Ares Projects. Further, while the CxPRACA tool for this project was made available for all the IPTs, due to unfamiliarity with the tool, everyone waited until they got to KSC to learn the system, where it was a requirement.

The Integrated Hazard Fault Tree TIM was instrumental in laying a foundation for the overall integrated fault tree and ensured IPT buy-in. It also helped to ensure all possible faults would be covered. The independent review panel identified this as a good practice.

Ares I-X's use of the 5x5 risk-management matrix on waivers helped boards characterize, sort, and identify the more significant waivers. S&MA would recommend that CxP have a standard waiver form that includes a required 5x5 risk-matrix field. However, several concerns existed regarding the risk management process, particularly confusion over trade-offs within the risk space (i.e., technical/safety vs. schedule vs. cost). There was resistance to applying "safety" scores to risks that clearly had potential technical/safety consequences as schedule/cost risks were mitigated. There was also confusion associated with moving back and forth between the 5x5 matrix for program risks and the 3x5 matrix for safety risks as well as the meaning of "red" versus "yellow" in each of the matrices.

Combining tailored requirements from the Air Force Range Safety Requirements (Space Command Manual 91-710) with NPR 8715.5 to provide "one-stop shopping" for all Range Safety Requirements worked extremely well. This approach should be the standard for future projects. Numerous working group meetings with the Air Force, NASA Range Safety, project engineering, and S&MA were key to this effort and were guided by the Launch Constellation Range Safety Panel (LCRSP).

It was noted by several IPTs that Range Safety and other outside organizations can drive design requirements. The most prominent example was the "triboelectrification" launch constraint imposed by the Air Force. The implications of this requirement were not understood until very late in life cycle. If an earlier understanding had existed, Ares I-X would have selected different outer skin materials or launched an earlier pursuit of an LCC exception (provided sufficient technical rationale could have been generated).

The Ares I-X use of heritage Space Shuttle systems (First Stage) and non-NASA heritage systems (Atlas Avionics) revealed a significant disagreement on the value of post-installation testing of electrical harnesses via DWV (hi-pot) testing. While verification is required by NASA-STD-8739.4, the Atlas V program does not perform this testing and considers it low value, costly, and presenting some risk to its avionics. In light of this disagreement, it is recommended that CxP and NASA HQ revisit the current NASA standards required post-installation testing requirements to determine whether they are cost-beneficial.

The launch countdown teams were composed of members of multiple IPTs and Centers. Despite initial conflicts, the roles of the teams, and of individuals on each team, unofficially evolved into the right roles. Nevertheless, the Primary Firing Team (PFT) needed to better understand and use the capabilities of the Launch Support Team (LST) (primary technical knowledge base) residing in Hangar AE.

The Ares I-X Launch Commit Criteria (LCC) contained the basic LCC requirements but did not have technical depth when it came to items such a technical basis for the LCC and/or preplanned contingencies. Fortunately, Ares I-X did not have many LCC violations to work during the actual countdown, but the simulations proved very challenging without this type of ready information

[*This summary incorporates key issues identified by the Ares I-X Chief Safety Officer and other input from the November 9, 2009, ThinkTank knowledge capture session.*]

5.10 Engineering Technical Authority / Chief Engineers (CE)

In accordance with NPD 1000.0 and NPR 7120.5D, the engineering technical authority was delegated from the Ares I-X Chief Engineer to lead engineers (LE, also known as lead discipline engineers in NPR 7120.5D) at the SE&I and IPT levels. However, there was confusion regarding the difference between the roles and responsibilities of the LEs and LSE who reported to the mission manager and IPTs. The roles seemed to overlap, which caused confusion in the institutional engineering community. Lead engineers ensured applicable policies and standards were appropriately implemented. Additional confusion was observed by having two Ares I-X Chief Engineers (vehicle and ground) at the Mission level, although the Chief Engineer for the vehicle was given the authority as the Chief Engineer for Ares I-X.

As with any project, communication was critical to the success of Ares I-X. Weekly and monthly meetings and quarterly face-to-face sessions among the chief engineers and lead engineers were very beneficial for keeping up with issues and progress.

The Engineering, Safety, and Mission Assurance Readiness Review (ESMARR) was a new review implemented by the Ares I-X technical authorities and its content was defined in the Mission Implementation Plan (MIP). The ESMARR served as a technical preparatory review for the Certificate of Test Flight Readiness Review (CoFTR) process and ensured the technical community, including institutional/Center engineering and S&MA directors, lead engineers, S&MA leads, and Constellation- and Agency-level technical authorities, were equally informed. The engineering and S&MA technical authorities had a good working relationship, which led to effective and timely resolution of issues and acceptance of risks. There was healthy tension and open discussion between mission management and the technical authorities. Technical issues were appropriately discussed and researched to allow sufficient resolutions. The mission management and technical authorities provided their assessments and recommendations at team meetings, milestone reviews, Constellation Board meetings, and Integrated Center Management Council (ICMC) sessions. However, the mission manager did not delegate project-type authority to boards (such as the Engineering Review Board for waiver approval) until late in the mission. This resulted in long, late night and weekend Ares I-X Control Boards (XCB).

The mission did not know what it was “buying” when heritage processes and hardware were employed for Ares I-X. There were conflicts among the heritage processes and requirements that caused problems late in the mission flow. There was a lack of adequate, up-front definition of what was heritage, modified heritage, and non-heritage hardware, leading lead to confusion on standards and requirements (e.g. dielectric withstanding voltage testing and metallic tape use).

In addition, taking time initially to ensure individual Center tools (e.g. design, modeling, analysis, configuration management, manufacturing, etc.) could communicate within the dispersed teams would have alleviated integration issues and set expectations for interactions and deliverables. The varying IPT/Center CM tools introduced unnecessary complexity into review processes. Thus, reviewers had to obtain access to different systems, which reduced time available to review the technical content and made data retrieval difficult and challenging. The use of technical discipline reviews and assurance that review board members, or their designees, assess the supporting technical data are vital to successful reviews and mission success. An early face-to-face review covering system-engineering expectations including models, testing, factors of safety, etc. is needed for future projects.

SE&I requirements management was not adequate at the outset of the mission, which resulted in differences in IPT implementation. The Windchill application was an extremely poor choice for a lifecycle management tool and did not lend itself to rapid retrieval of key information. Using an appropriate Product Life Cycle Management (PLM) toolset would help ensure requirements definition and environments are properly addressed and linked. This would ensure proper flow-down of requirements that can be traced as the mission priorities change.

Due to the accelerated pace of the mission, requirements from some sources such as range safety (e.g. triboelectrification) were overlooked and not properly accounted for in the design, reducing the available launch window. Verification of system-level requirements was rushed. Adequate scheduling and linkage of verification activities and supporting events was a concern. This led ultimately to additional unquantifiable risks that were accepted by mission and program management. Interface verifications were not adequately defined in terms of who was ultimately responsible for pulling together all necessary data to ensure that the interfaces would be verified. More involvement and control should have been exercised by SE&I in this area.

[*This summary was prepared by the Ares I-X Deputy Chief Engineer, MSFC, and coordinated with the Chief Engineers participating in the February 2010, ThinkTank knowledge capture session*.]

APPENDIX A: KNOWLEDGE CAPTURE METHODOLOGY

The knowledge capture activity was designed as a story telling-based, “high yield – low impact” effort that imposes minimal impact on busy program/project teams. Knowledge capture process features included:

- Structured engineering management thematic framework for knowledge capture
- Rigorous time-management
- Storytelling interview format
- Telephone – one hour interviews with IPT Leads
- On-site, face-to-face, 3-Hour IPT Knowledge Capture process with 5-15 IPT members

The thematic framework used in the knowledge capture process included:

- Engineering Management
- Technical Authority (S&MA and Engineering)
- Systems Engineering
- Schedule
- Requirements Management
- Design
- Organization
- Manufacturing
- Test and Verification
- Communication
- Resources

The knowledge capture process focused on eliciting mini-stories or vignettes from integrated product team (IPT) members relevant to each of the thematic areas. To initiate the thought process, each participant was asked to consider three questions:

1. Up-front, early on we should have ______.

2. Our team really did well with ______ because of _____.

3. If I were “King/Queen,” the top three things I would change are ______.

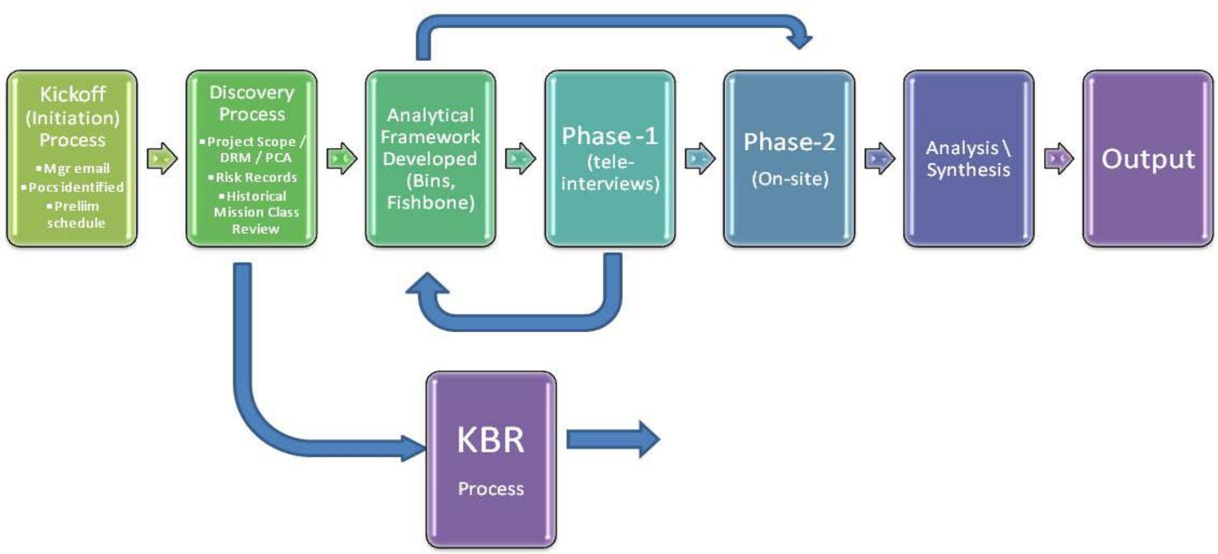
Each lessons learned (ideally) can be considered to incorporate a challenge, a management response/and or outcome combined in a contextual short story. The Ares I-X knowledge capture process has pulled together nearly one thousand individual “issues.”

Knowledge Capture Process

The ESMD knowledge capture process begins with a series of “kickoff” activities, including coordination with project management, identification of key contacts, and preliminary schedule planning. The second step “discovery,” is when the knowledge-capture team comes up to speed on the project background, including Design Reference Mission (DRM), success criteria, Centers, contractors, and existing Risk Records or other documented issues.

At this step, a wiki-space will typically be established to assist in document management and planning. The discovery process also provides the necessary background to initiate the Knowledge Based Risk (KBR) process that may be conducted in parallel with the knowledge capture process. Step 3 involves development of the analytical framework for the analysis. This framework can be considered a taxonomy used to stimulate and guide knowledge capture discussions (telephone interviews). The framework may be represented as a fishbone diagram and/or "bins or buckets" within the ThinkTank tool used in the on-site interviews. Step 4 involves one-hour telephone interviews with IPT-leads, or equivalent subsystem-managers.

Feedback from telephone interviews is used to refine the analytical framework in preparation for on-site activity. The on-site team interviews will typically involve 7-10 members of the IPT or equivalent subsystem team. A powerful laptop-brainstorming tool, ThinkTank, is typically employed to assist in gathering issues and opportunities for improvement. Following the fieldwork is a period of analysis and integration followed by a report and a series of knowledge transfer products (see Appendix B).



APPENDIX B: KNOWLEDGE TRANSFER & COMMUNICATION

Delivery and communication of Ares I-X knowledge capture content will employ multiple modalities including:

Ares I-X Briefings: this methodology would involve presentation slide briefings to ESMD Level I/II/II management (HQ, Constellation, Ares, Orion, Ground Ops, etc.) as well as Mission Support Offices (Office of Chief Engineer (OCE) / Office of Safety & Mission Assurance (OSMA). Further partnering with OCE and OSMA will involve providing links to the OCE, Lessons Learned Information System (LLIS) and the NASA Safety Center PBMA-Knowledge Management System (PBMA-KMS).

Ares-I Critical Design Review: Some Ares I-X lessons may be deemed critical enough to be used as part of the Ares-I Critical Design Review (CDR). These lessons will be provided to the Ares-I Project as a checklist to be considered as part of the CDR entry/exit criteria.

Peer Assists: This methodology involves making available specific Ares I-X team members to Constellation or Level II projects upon request for the purpose of a very specific knowledge exchange between peers. These problem-solving sessions can last between ½ to 2 days.

Interactive Cafés: This methodology leverages small group brainstorming and problem solving and is normally a facilitated event. Multiple topics may be addressed by Ares I-X personnel with Constellation or Level II projects with participants rotating among topics after short (usually 30-40 min) focused discussions. Topics would align with the knowledge capture themes.

ICE Wiki implementation (multimedia): This methodology involves a long-term, passive delivery process of Ares I-X knowledge captured and codified in the ICE wiki environment. It would preferably be accompanied by video interviews and other Ares I-X artifacts (documents, reports, etc.).

Knowledge-Based Risks: This methodology also provides a long-term preservation of Ares I-X knowledge in the form of a risk record and storytelling narrative that includes how the risk was mitigated--what worked or did not work.

Ares I-X Managers and IPT Lead Briefings: This methodology called upon Ares I-X Managers and IPT Leads to "hit the road" with storytelling/conversation briefings for program and project teams within ESMD and across the Agency sharing those lessons with broad crosscutting applicability.

Ares Projects Assessment: Because of the difficulty in getting already busy project teams reading lessons learned and figuring out how to incorporate them, an assessment may prove a more effective approach at actually transferring lessons learned. For example, the lessons learned from Ares I-X could be turned into an assessment guide and knowledgeable Ares I-X personnel could "audit" the Ares-I program to identify where the lessons learn best fit and identify the specific activities that need to happen to effectively incorporate the lessons.

Multimedia Case Study: There is a great opportunity to create a multimedia-based case study. This would feature lessons learned across several engineering disciplines, and incorporate video of the Ares I-X key participants to emphasize these lessons. The course is designed as a half-day classroom course where project teams identify their approach, which is then compared to that of the "experts" via video. Conducting these sessions throughout the Ares Project would enable the lessons to be tailored to the needs of each particular group.

APPENDIX C: ARES I-X KNOWLEDGE TRANSFER ACTIVITIES

C1. Ares I-X Knowledge Based Risks and Video Nuggets

Knowledge Based Risks (KBRs) capture risks that have been successfully mitigated in the past that are relevant to many current topics including: project management, systems engineering, design and development, integration and test. Additional information is also bundled with KBRs, such as subject matter expert video interviews, white papers, articles, and presentations.

KBRs are one of the most important techniques ESMD is employing to capture and effectively transfer knowledge to future programs.

Each KBR contains a discussion of the risk statement, background or detail concerning the risk, a discussion of control and mitigation strategies, and finally lessons learned in addressing the risk.

The KBRs are organized into five sections:

- Risk Statement – The condition and consequence of the risk stored in the risk management tool
- Video – A video nugget captured from an interview with a subject matter expert.
- Transcript – Written version of the video displayed
- Related Knowledge Bundles – These are other KBRs that are relevant to the KBR that is currently displayed
- Related Content – View other supporting documentation, presentations, and Web content that support this risk statement
- KBR Forum – Post comments, questions (or answers), or thoughts on a KBR

KBR home page URL: https://ice.exploration.nasa.gov/ice/site/km/kbr_home

Screen shots from COPV (Composite Overwrap Pressure Vessel) KBR

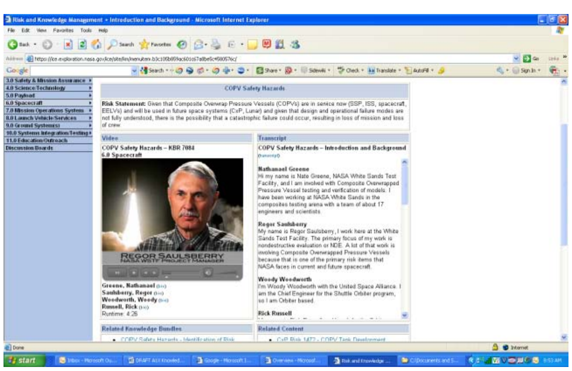


Table C.1 Ares I-X KBRs in development as of February 2010		
Risk Record	**Topic**	**Interviewee**
3142	Flight termination system safe and arm	Jim Price (Range Safety Lead)
	Heritage software controlling heritage hardware	Robert DeCoursey (LaRC S&MA Lead)
4530	Manufacturing and Assembly – use of metallic tape to wrap cable harnesses	Chris Calfee (1st Stage IPT Lead
	Parachute Issues / maturity test	Chris Calfee (1st Stage IPT Lead)
2503	Loads and environments	Curt Detweiller (S&EI Lead)
4267	Thrust oscillation impacts to the thrust vector control system	Mike Bangham (S&EI)
2821	1st Stage nose-first re-entry	Mike Bangham (S&EI)

Video Nuggets

Video Nuggets (VNs) are video clips based around a structure or taxonomy designed to elicit specific experience-based knowledge from project participants. Multiple VNs are planned for implementation in the first quarter of 2010 with Ares I-X mission managers and IPT Leads. Preliminary interview outline:

- Introduction / name, title, IPT, location, role in Ares I-X mission
- Outline the most significant accomplishments of the Ares I-X mission
- Describe the most significant accomplishments of your IPT
- Discuss the greatest challenge your IPT faced
- Tell me a good story related to accomplishments and/or challenges
- Discuss mission management (approach and process) issues and areas in which
- improvements could be made in future fast-track technology demonstration projects
- Discuss anything that you, as an IPT manager might have done differently

C.2 ARES I-X Knowledge-Share Wiki

ESMD has implemented the Ares I-X Knowledge-Share Wiki, a wiki-space devoted to the communication and sharing of knowledge capture artifacts associated with the Ares I-X project, providing insights for NASA. The wiki-space was deployed in mid February 2010 and will undergo further development through the 2nd Quarter of 2010. The wiki-space design includes:

Intuitive Knowledge/Information Architecture

Alternatives under development

Documents

- ESMD Knowledge Capture Process Documents
- Ares I-X Knowledge Capture Volume I
- Ares I-X Knowledge Capture Volume II – IPT ThinkTank Knowledge Capture
- Sessions
- Ares I-X Knowledge Capture Volume III – Compendium of Other Lessons Learned
- Documents
- PAO Documents

Links

- Links to Ares I-X documents, drawings, schedules, and data packages in Windchill
- Links to other Ares I-X wiki spaces

Video Content

- Knowledge Based Risks
- Video Nuggets
- PAO Videos
- Other Project Video

Calendar of Events

- KBR and Video Nugget Schedule
- Outreach Events (seminars, road shows, presentations)

Membership / Social-Networking Function

- Contains membership profiles and contact information for participants

Threaded Discussion Forum

- Opportunity for open discussion of thematic issues related to Ares I-X implementation
- Open forum for submission of contextual, storytelling-based lessons learned concerning Ares I-X implementation

APPENDIX D: KNOWLEDGE CAPTURE INTERVIEWS AND IPT SESSIONS

Ares I-X IPT Lead Telephone Interviews

IPT Leads were interviewed using a risk-informed question set in a one-hour timeframe. Results of these interviews were used to build the IPT "story" – they were also used to frame the discussion at the IPT "team-level."

Team / Interviewee	Date
CM/LAS IPT – Jonathan Cruz / LaRC	May 27, 2009
Roll Control System IPT – Ron Unger / MSFC	May 29, 2009
Upper Stage Simulator IPT – Vince Bilardo / GRC	June 25, 2009
Avionics IPT – Kevin Flynn / MSFC	July 24, 2009
Ground Systems IPT – Mike Stelzer / KSC	July 24, 2009
First Stage IPT – Chris Calfee / MSFC	August 5, 2009
Grounds Operations IPT – Tassos Abadiotakis / KSC	August 6, 2009
SE&I IPT – Marshall Smith	September 23, 2009
Technical Authority – Glen Jones	September 25, 2009
Project Integration Manager – Bruce Askins / MSFC	September 29, 2009
Deputy Mission Management Team - Jon Cowart / Steve Davis	September 30, 2009
Mission Manager – Bob Ess	October 6, 2009

Ares I-X IPT On-site and Virtual Knowledge Capture ThinkTank Sessions

Phase 2 involved structured interviews of 6-15 IPT team members at their Center.

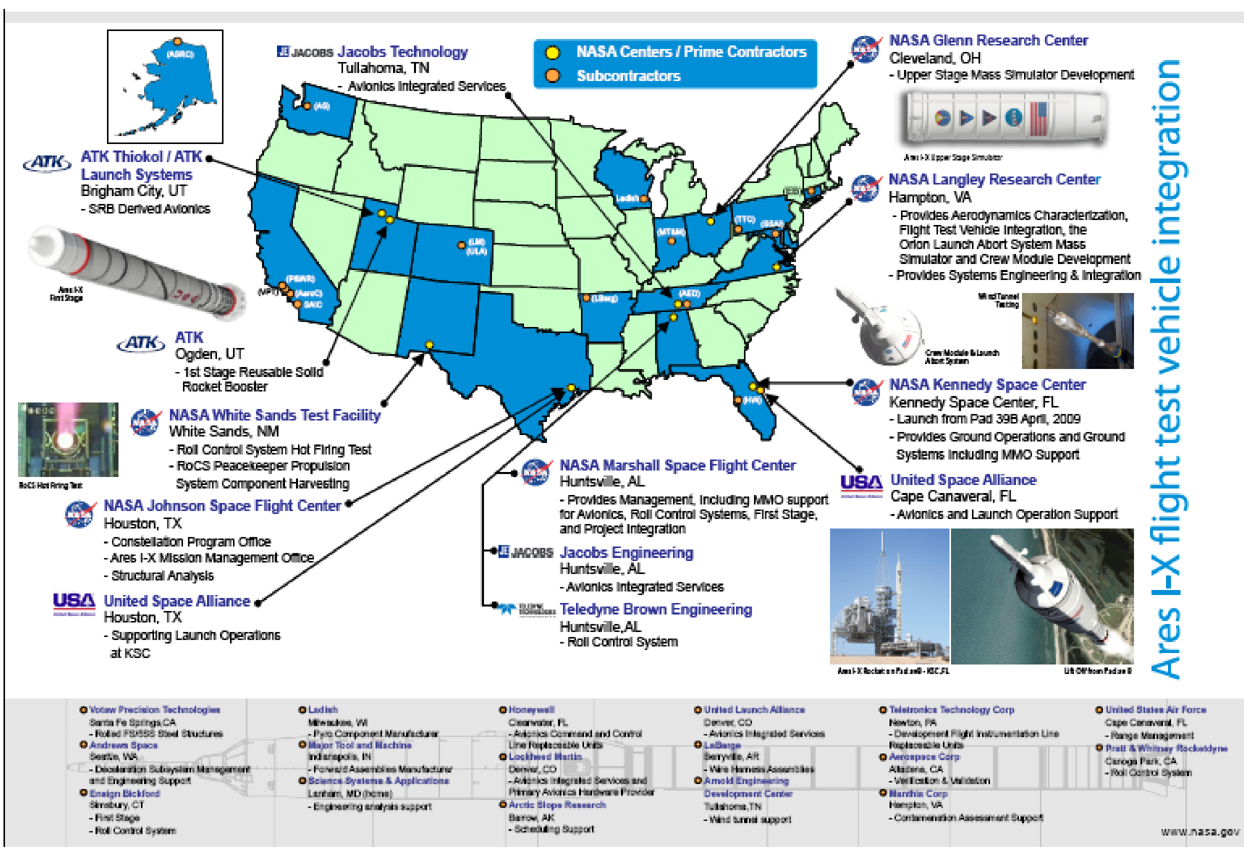
Team	Date
Ground Operations (KSC)	November 4, 2009
Ground Systems (KSC)	November 4, 2009
S&MA (MSFC)	November 9, 2009
RoCS (MSFC)	November 9, 2009
First Stage (MSFC)	November 10, 2009
Avionics (MSFC)	November 10, 2009
Upper Stage Simulator (GRC)	November 13, 2009
CM/LAS (LaRC)	November 16, 2009
SE&I (LaRC)	November 16, 2009
Engineering (Technical Authority)	February 16, 2010

APPENDIX E: ARES I-X PROJECT ORGANIZATION

The Knowledge Capture activity was conducted across the Ares I-X Project Integrated Product Teams (IPT). This section provides a brief contextual summary of key organizations participating in the activity

The Ares I-X mission was managed from the NASA Johnson Space Center. NASA's Glenn Research Center in Cleveland, Ohio, developed the Ares I-X upper stage mass simulator. NASA's Langley Research Center in Hampton, Virginia, provided aerodynamic characterization, Ares I-X Systems Engineering & Integration (SE&I), and Orion/launch abort system mass simulator development. NASA's Marshall Space Flight Center in Huntsville, Alabama, provided management for the development of Ares I-X avionics, roll control, and first stage systems as well as project integration. NASA's Kennedy Space Center, Florida, provided operations, systems and associated ground activities.

ATK Space Systems of Promontory, Utah, is the prime contractor for the first stage reusable solid rocket boosters. Jacobs Engineering in Tullahoma, Tennessee, is the prime contractor for Ares I-X avionics, with Lockheed Martin of Denver, Colorado, as subcontractor. Teledyne Brown Engineering of Huntsville, Alabama, is the prime contractor for developing the roll control system. United Space Alliance of Houston, Texas, is the prime contractor supporting launch operations at Kennedy Space Center.



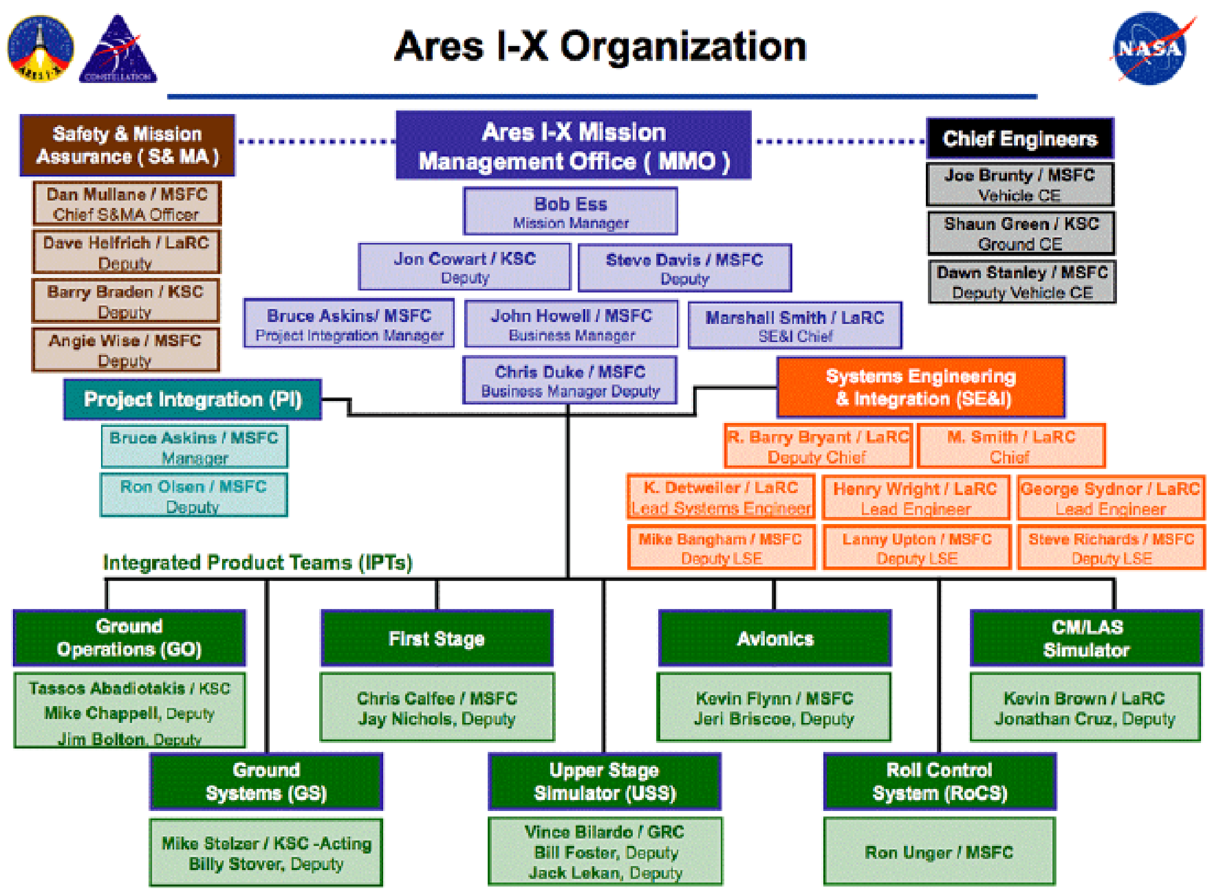
Integrated Product Team (IPT) Approach

Ares I-X employed the Integrated Product Development (IPD) approach used extensively by the Department of Defense (DoD) which is designed to accomplish concurrent engineering and horizontal integration by including life-cycle stakeholders on each of the IPTs designated to design, develop, and test key system elements.

Ares I-X Integrated Product Teams included:

- First Stage
- Ground Operations
- Ground Systems
- Avionics
- CM/LAS Simulator
- Upper Stage Simulator
- Roll Control System

The Systems Engineering & Integration (SE&I) and Project Integration organizations also play key roles.



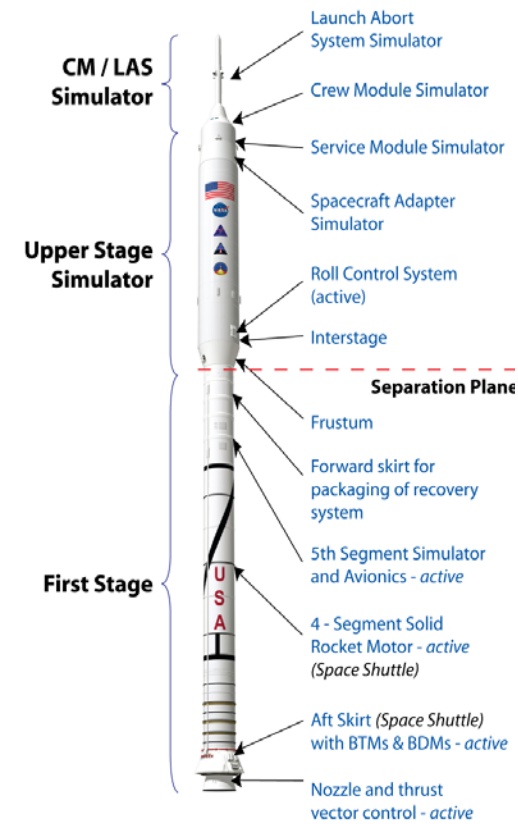
APPENDIX F: BACKGROUND ON CONSTELLATION PROGRAM

[*Excerpted from NASA web sites*]

The Constellation Program (CxP) is developing new systems and vehicles to support the next generation of space exploration. These vehicles will support the International Space Station after the Space Shuttle is retired, as well as missions to the moon, Mars, and beyond. Unlike earlier programs, CxP will directly inherit the legacies of both Apollo and the Space Shuttle, using parts and concepts of these earlier programs to build more dependable and economical craft.

The Orion crew exploration vehicle will take astronauts to the International Space Station. It will be able to rendezvous with the Altair lunar lander and Ares V Earth departure stage in low-Earth orbit to carry crews to the moon and, one day, to Mars-bound vehicles assembled in low-Earth orbit. Orion will be the Earth entry vehicle for lunar and Mars returns. Orion's design will borrow its capsule idea from the capsules of the past, but it takes advantage of 21st century technology in computers, electronics, life support, propulsion, and heat protection systems. Orion is scheduled to fly its first missions to the space station by 2015 and carry out its first sortie to the moon by 2020.

The Ares launch vehicles, named for the Greek god associated with Mars, will carry into orbit astronauts, cargo, and the components needed to go to the moon and later to Mars. Ares I will be an in-line, two-stage rocket topped by the Orion crew vehicle and its launch abort system. Ares V cargo launch vehicle will be the heavy lifter of America's next-generation space fleet. The two-stage, vertically stacked launch system will have a 206-ton capacity to low-Earth orbit and 78-ton capacity to lunar orbit. The Altair lunar lander will be capable of landing four astronauts on the moon, providing life support and a base for week-long initial surface exploration missions and returning the crew to the Orion spacecraft that will bring them home to Earth. Altair will launch aboard an Ares V rocket into low-Earth orbit, where it will rendezvous with the Orion crew vehicle.



Ares I-

Ares I-X Project

Ares I-X, which flew October 28, 2009, was the first suborbital test of the rocket that will replace the Space Shuttle and ultimately carry astronauts to the moon and beyond. The Ares I-X flight test vehicle launched from NASA's Kennedy Space Center. The flight of Ares I-X was designed to simulate the first two minutes of Ares I flight. A broad range of performance data was relayed to the ground and stored in the onboard flight data recorder. The solid rocket motor separated after the boost phase and was recovered at sea for later inspection. The simulated upper stage and Orion's crew module and launch abort system splashed down in the Atlantic Ocean downrange and were not recovered as planned. The Ares I-X flight provided NASA an early opportunity to test and prove some hardware, facilities, and ground operations associated with the Ares I. The test also allowed NASA to gather critical data during ascent of the integrated stack, which includes a simulated Ares I vehicle and simulated Orion crew module and launch abort system. Data collected will be used to improved models, look at the effectiveness of the rocket's design and ensure that it is safe and stable in flight before astronauts begin traveling into orbit.

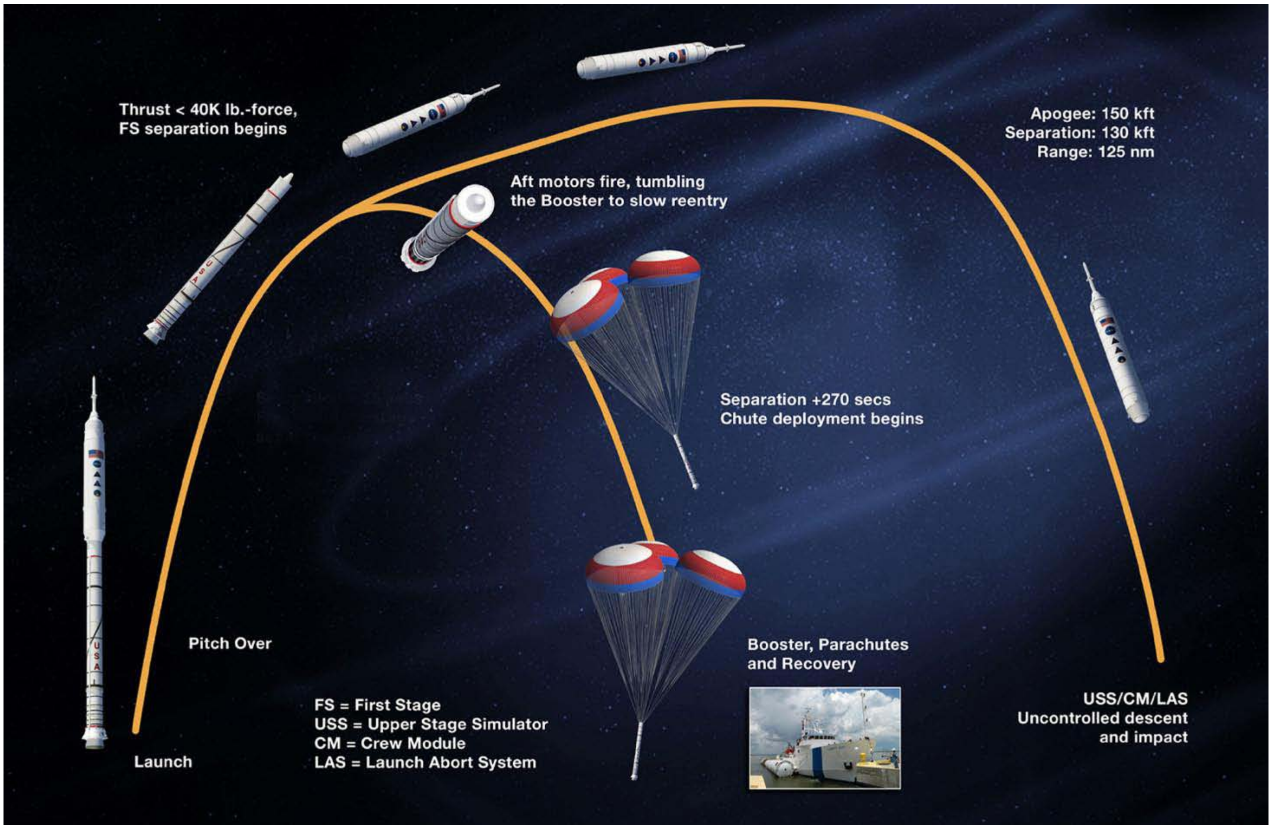
The Ares I-X flight test is part of a larger flight test program that will include three flight tests of the Orion launch abort system between 2009 and 2012, a follow-on Ares I-Y test, and an integrated test of both the launch vehicle and spacecraft, called Orion 1, in 2015. The Ares I-X flight test vehicle will be similar in mass and size to the actual Orion and Ares I vehicle systems but it will incorporate a mix of proven spaceflight and simulated, or mockup, hardware. The test vehicle was powered by a single, Space Shuttle four-segment reusable solid rocket booster – flight hardware from in the Space Shuttle inventory – modified to include a fifth inactive spacer segment to simulate the Ares I five-segment booster. Mockups of the upper stage and the Orion crew module and launch abort system were used to simulate the integrated spacecraft. The flight test profile closely followed the flight conditions to be experienced by the Orion/Ares I vehicle through Mach 4.7 – more than four times the speed of sound. Approximately two minutes into flight, at approximately 130,000 feet, the launch vehicle's first stage separated from the upper stage. The maximum altitude, or apogee, of the flight test was about 150,000 feet.

Ares I-X assembly, testing and launch used existing facilities at Kennedy Space Center, Florida. The first stage motor segments arrived by rail car and were prepared for assembly on top of a mobile launch platform in the Vehicle Assembly Building. The upper stage simulator was shipped by the *Delta Mariner* while the Orion simulator was sent by air (C-5). These components were assembled into super segments and then integrated atop the first stage. The completed Ares I-X flight test vehicle rolled out to Launch Complex 39B October 17, 2009. From the Launch Control Center, the launch team performed final checkout and launched the Ares I-X rocket October 28, 2009.

Ares I-X Flight Test Profile

During the Ares I-X flight test, the vehicle's first stage separated from the upper stage simulator and the Orion crew module and launch abort system mockup and fell into the Atlantic Ocean.

The first stage booster continued through its complete recovery sequence, releasing its Ares I prototype three-stage parachute recovery system, falling safely into the ocean and floating until the hardware was retrieved for inspection and analysis. Data gathered from the first stage will provide vital information on hardware and software performance and also will be used to fine-tune ground operations.


Thrust < 40K lb.-force,
FS separation begins
Apogee: 150 kft
Separation: 130 kft
Range: 125 nm
Aft motors fire, tumbling
the Booster to slow reentry
Separation +270 secs
Chute deployment begins
Pitch Over
Booster, Parachutes
and Recovery
USS/CM/LAS
Uncontrolled descent
and impact
Launch
FS = First Stage
USS = Upper Stage Simulator
CM = Crew Module
LAS = Launch Abort System

APPENDIX G: TABLE OF ACRONYMS

A&S	Aging and Surveillance
ACWP	Actual Costs Work Performed
ADMS	Automated Data Management System
ADP	Acceptance Data Package
AF	Air Force
AFSCM	Air Force Systems Command Manuals
AFSOP	Ares I-X Florida Safety Operating Plan
AG	Attitude Gyro
AIT	Assembly, Integration, and Test
AIX	Ares I-X
AMS	Automated Material System
APO	Ares Project Office
ARF	Assembly Refurbishment Facility
ASA	Altitude Switch Assembly
ASME	American Society of Mechanical Engineers
ASOC	Atlas Space Operations Center
ATP	Acceptance Test Procedure; Authority to Proceed
ATVC	Avionics Thrust Vector Control
AVIO	Former organizational name for LaRC SE&I
BCWP	Budgeted Cost Work Performed
BCWS	Budgeted Cost Work Scheduled
BOE	Basis of Estimate
BRCU	Booster Remote Control Unit
BSM	Booster Separation Motor

BW	Bandwidth
C&C	Command and Control
C&DM	Configuration and Data Management
CAD	Computer-aided Design
CADD	Computer Aided Design and Drafting
CADM	Core Architecture Data Model; Computer-Aided Design and Manufacturing
CAM	Computer Aided Manufacturing
CAT 1	Category 1
CAT 2	Category 2
CCC	Command, Control, & Communications
CCLS	Computer Controlled Launch Set
CDM	Configuration and Data Management
CDR	Critical Design Review
CE	Chief Engineer
CEQATR	CxP Environmental Qualification & Acceptance Testing Requirements
CFD	Computational Fluid Dynamics
CI	Conformance Inspection, Configuration Item
CIL	Critical Item List
CIPS	Computer Integrated Process Systems
CLV	Crew Launch Vehicle
CM	Configuration Management; Crew Module
CM/LAS	Crew Module / Launch Abort System
CMP	Configuration Management Plan
CMQC	Configuration Management Quality Control
CofC	Certificate of Conformance
CoFTR	Certification of Flight Test Readiness

ConOps	Concept of Operations
COTS	Commercial Off-the-Shelf
CPAR	Corrective Preventive Action Request
CPR	Cost Performance Report
CR	Change Request
CRADLE	(requirements management software)
CRM	Continuous Risk Management
CSERP	Constellation Safety and Engineering Review Panel
CSO	Chief Safety Officer
CSRP	Constellation Program Safety Review Panel
Cx	Constellation
CxCB	Constellation Program Control Board
CxP	Constellation Program
CxPRACA	Constellation Problem Reporting and Corrective Action
CxSECB	Constellation Systems Engineering Control Board
CxSERP	Constellation Safety Engineering Review Panel
DAC	Design Analysis Cycle
DCMA	Defense Contract Management Agency
DCR	Design Certification Review
DD 1149	DoD Form 1149 – Requisition or Invoice Shipping Document
DD 250	DoD Form 250 – Material Inspection and Receiving Report
DDT&E	Design, Development, Test, and Evaluation
DE	Design Engineering
DEV	Development
DFI	Development Flight Instrumentation
DGA	Designated Government Authority

DM	Data Management
DMP	Data Management Plan
DoD	Department of Defense
DOF	Degree of Freedom
DOL	Day of Launch
DR	Discrepancy Report
DRM	Design Reference Mission
DWP	Digital Wave Processor
DWV	Dielectric Withstanding Voltage
DXCB	DFI Control Board
ECB	Engineering Change Board
ECN	Engineering Change Notice
ECS	Environmental Control System
EDF	Electronic Development Fixture
EELV	Evolved Expendable Launch Vehicle
EEE	Electronic, Electrical, and Electromagnetic
EGLS	Exploration Ground Launch Services
EGSE	Electrical Ground Support Equipment
EIS	Environmental Impact Statement
EMB	Engineering Management Board
EMI	Electromagnetic Interference
EMP	Environmental Management Plan
EO	Earth Orbit; Earth Observation
ER	Explanation Report
ERB	Engineering Review Board
ERD	Element Requirements Document; Environmental Resources Document

eRoom	(collaboration software for distributed work teams)
ES	Engineering Specification
ESA	European Space Agency
ESD	Electrostatic Discharge
ESDS	Electrostatic Discharge Sensitive
ESMARR	Engineering and S&MA Readiness Review
ESMD	Exploration Systems Mission Directorate
ESS	Executive Summary Schedule
ESTS	Engineering Support and Technical Services
ETZ	Eastern Time Zone
EVM	Earned Value Management
FAM	Functional Analysis Model
FAR	Federal Acquisition Regulation
FCS	Flight Control System
FEC	Field Engineering Changes
FEM	Finite Element Method
FLUINT	(NASA standard tool for thermo-hydraulic analysis)
FMEA	Failure Mode and Affects Analysis
FOD	Foreign Object Damage; Flight Operations Directorate
FOM	Figures of Merit
FOS	Flight Operations Support; Factors of Safety
FR	Flight Rule
FR1	Firing Room 1
FS	First Stage
FSAM	First Stage Avionics Module
FSE	Flight Support Equipment

FSOP	Florida Safety Operating Plan
FSS	Fixed Service Structure
FTE	Full-time Equivalent
FTP	Flight Test Plan
FTINU	Fault Tolerant Inertial Navigation Unit
FTRR	Flight Test Readiness Review
FTS	Flight Termination System
FTV	Flight Test Vehicle
GC3	Ground Command, Control and Communications
GCE	Ground Chief Engineer
GCEL	Ground Control Experimental Laboratory
GCS	Ground Communications System
GFE	Government-Furnished Equipment
GN	Ground Network
GN&C	Guidance, Navigation, and Control
GO	Ground Operations
GOP	Ground Operations Project
GRC	Glenn Research Center
GS	Ground Systems
GSE	Ground Support Equipment
GSRD	Ground Support Requirements Document
HAWG	Hazards Analysis Working Group
HB	High Bay
HMF	Hypergolic Maintenance Facility
HOSC	Huntsville Operations Support Center
HQ	Headquarters

HW	Hardware
HWL	Hardware in the Loop
I/O	Input / Output
ICBM	Intercontinental Ballistic Missile
ICD	Interface Control Document
ICE	Integrated Collaborative Environment
ICM	Interim Control Module
ICMC	International Cryogenic Materials Conference
ID&A	Integrated Design and Analysis
IDA	Integrated Design and Analysis
IDEAS	Initial Design and Evaluation Analysis System
IDOS	Integrated Development and Operations Systems
IFTS	Integrated Flight Test Strategy
IG	Internal Guidance; Instrumentation Group; Inertial Guidance
IHR	Integrated Hazard Report
ILS	Integrated Logistics Support
IM	Instant Messaging
IMS	Integrated Master Schedule; Information Management System
INS	Inertial Navigation System
IPD	Integrated Product Development
IPM	Integrated Project Management
IPPD	Integrated Product and Process Design
iPRACA	Integrated Problem Reporting and Corrective Action; Interim PRACA
IPT	Integrated Product Team
IRD	Interface Requirements Document
IRIS	Incident Reporting and Information System

IRMA	Integrated Risk Management Application
IRT	Incident Response Team; Icing Research Tunnel; Integrated Real Time
IS	Information Security
IT	Information Technology
ITA	Independent Technical Authority
ITAR	International Traffic in Arms Regulation
IV&V	Independent Validation and Verification
JCL	Joint Cost Level
JDMTA	Jonathan Dickinson Missile Tracking Annex
JSC	Johnson Space Center
KBR	Knowledge Based Risk
KC	Knowledge Capture
KDP	Key Decision Point
KSC	Kennedy Space Center
LaRC	Langley Research Center
LAS	Launch Abort System
LAT	Launch Team
LC	Launch Complex
LC39B	Launch Complex 39B
LCC	Launch Commit Criteria; Launch Control Center
LCRSP	Launch Constellation Range Safety Panel
LDE	Lead Design Engineer
LE	Lead Engineer
LLIS	Lessons Learned Information System
LM	Lockheed Martin
LMA	LM Aeronautics

LMCO	LM Corporation
LPE	Launch Package Engineer
LSC	Launch Service Contractor; Linear Shape Charge
LSE	Lead Systems Engineer
LST	Launch Support Team
LTDT	Launch Team Design Team
M&P	Materials and Processes
Max Q	Maximum Dynamic Pressure
MFG	Manufacturing; Major Functional Group
MCC	Mission Control Center
MILA	Merritt Island Launch Area
MIP	Mission Implementation Plan
MIUL	Material Identification Usage List
MK	(Space Shuttle Program Launch Integration [MK] organization)
MLP	Mobile Launcher Platform
MM	Mission Manager
MMO	Mission Management Office
MOA	Memorandum of Agreement
MOD	Mission Operations Directorate
MPE	Maximum Permissible Exposure; Mean Percent Error
MPR	Monthly Progress Report
MR	Material Review; Material Request
MRB	Material Review Board
MRCAP	Mishap Response Contingency Action Plan
MS	Microsoft
MSC	With Random – Approach/Tool to Random Analysis from MSC company

MSF	Mission Success Factors
MSFC	Marshall Space Flight Center
MVP	Master Verification Plan; Most Valuable Player
NAR	Non Advocate Review
NASA	National Aeronautics and Space Administration
NASTRAN	NASA Structural Analysis Program
NC	Non-conformance
NESC	NASA Engineering and Safety Center
NISN	NASA Integrated Services Network
NPR	NASA Procedural Requirement
NSD	NASA Standard Detonator
NSTS	National Space Transportation System
NX	NASA/Xerox Knowledge Network
O&M	Operations and Maintenance
O&SHA	Operating and Support Hazard Analysis
OCE	Office of Chief Engineer
OCIO	Office of Chief Information Officer
OEL	Orbiter Electrical
OFI	Operational Flight Instrumentation
OIO	Operation Integration Office
OJT	On-the-Job Training
OML	Outer Mold Line
OMRSD	Operations and Maintenance Requirements and Specifications Document
OPF	Orbiter Processing Facility
ORCA	Ordnance Remote Control Assembly
OSHA	Occupational Safety and Health Administration/Act

OSMA	Office of Safety & Mission Assurance
OTR	Operating Time Record
PATRAN	(Prototype Development Associates Engineering finite element analysis [FEA] software)
PBMA	Process Based Mission Assurance
PBMA-KMS	PBMA-Knowledge Management System
PBS	Program Breakdown Structure
PDF	Portable Document Format
PDL	Ponce De Leon (Tracking Station)
PDR	Preliminary Design Review
PERT	Program Evaluation and Review Technique
PK	Peacekeeper
PLT	Production Lead Time
PM	Project Management; Project Manager
PMB	Performance Measurement Baseline
POC	Point of Contact
POP	Program Operating Plan
PP&C	Program, Planning, and Control
PRACA	Problem Reporting and Corrective Action
PRD	Program Requirements Document
ProE	Professional Engineering (used with PATRAN)
QA	Quality Assurance
QC	Quality Control
QE	Quality Engineer
QPRD	Quality Planning (or Program) Requirements Document
QTP	Qualification Test Plan

R&D	Research and Development
R&R	Roles and Responsibilities; Remove and Replace; Rendezvous and Recovery
RAC	Reliability Action Center
RAM	Random Access Memory
ReSync	Reorganization
RF	Radio Frequency
RFA	Request for Action
RFI	Radio Frequency Interference; Request for Information; Remote Facility Inquiry; Remote File Inquiry
RFID	Radio Frequency Identification
RID	Review Item Disposition
RM	Risk Management
RMP	Risk Management Plan
ROC	Request of Change
RoCS	Roll Control System
ROR	Rate of Return
RPE	Reliability Project Engineer
RPSF	Rotation Processing and Surge Facility
RRGU	Redundant Rate Gyro Unit
RSRM	Reusable Solid Rocket Motor
RT-455	Trowelable Thermal Ablative Compound
S&MA	Safety and Mission Assurance
SA	Spacecraft Adapter
SAR	Safety Analysis Report
SAP	Systems Applications and Products (financial data processing software)
SBU	Sensitive But Unclassified

SDP	Safety Data Package
SE	Systems Engineering
SE&I	Systems Engineering and Integration
SE&IE	Systems Engineering and Integration Engineering (LaRC)
SEA	Scanning Electrostatic Analysis
SECB	Systems Engineering Change Board
SEI	Systems Engineering Integration
SEMP	Systems Engineering Management Plan
SEP	Systems Engineering Process
SERF	Systems Engineering Review Forum; Space Environment Research Facility
SIL	Software Integration Laboratory
SIM	Scientific Instrumentation Module
SM	Service Module
SMA	Safety and Mission Assurance
SMAW	Shielded Metal Arc Welding
SMSR	Safety and Mission Success Review
SOW	Statement of Work
SOWG	Science Operations Working Group
SPOC	Shuttle Payload Operations Contractor
SQ&MA	Safety, Quality and Mission Assurance
SR&QA	Safety, Reliability, and Quality Assurance
SRB	Solid Rocket Booster
SRD	Systems Requirements Document
SRM	Solid Rocket Motor
SRR	System Requirements Review
SSAS	STS/SSPE Attachment System

SSC	Stennis Space Center
SSP	Space Shuttle Program
SSPE	Space Station Program Element
SSPF	Space Shuttle Processing Facility
STD	Standard
STS	Space Transportation System
SUX	(Tied to Primavera Scheduling)
SW	Software
SWRD	Software Requirements Document
T&E	Test and Evaluation
TA	Technical Authority
TBD	To Be Determined
TBE	Teledyne Brown Engineering
TBR	To Be Resolved
TD	Thermal Desktop
TIG	Time of Ignition
TIM	Technical Interchange (Interface) Meeting
TLYF	Test-Like-You-Fly
TPM	Technical Performance Measurement
TPS	Thermal Protection System
TQR	Technical Quality Review
TR	Technical Report
TREP	Technical Representative
TSMA	Transition Safety Mission Assurance
TTA	Technical Task Agreement
TVC	Thrust Vector Control

TxRB	Transition Review Board
ULA	United Launch Alliance
URCU	Upper Stage Remote Control Unit
USA	United Space Alliance
USAF	United States Air Force
US	Upper Stage
USS	Upper Stage Simulator
VAB	Vehicle Assembly Building
VCE	Vehicle Chief Engineer
VI	Vehicle Integration
VPN	Virtual Private Network
VRD	Verification Requirements Document
VSS	Vehicle Stabilization System
WAD	Work Authorization Document
WBS	Work Breakdown Structure
WG	Working Group
WGC	(the Lockheed Martin equivalent to Windchill)
WO	Work Order
WRT	With request to
WSTF	White Sands Test Facility
WYE	Work Year Equivalent
XCB	Ares I-X Control Board