National Aeronautics and Space Administration

Ares I-X Flight Data Evaluation

Executive Overview

FEBRUARY 2011 APO-1096

Approved for Public Release - Distribution is Unlimited

TABLE OF CONTENTS

LIST OF CONTRIBUTORS

Lawrence D. Huebner, MSFC, JP10

David A. Waits, MSFC, EV93

Donny L. Lewis, Jacobs, MSFC, EV93

James S. Richards, Bangham Engineering, MSFC, JP60

R.H. Coates, Jr., MSFC, EE03

Wendy D. Cruit, MSFC, EE03

Elizabeth J. Bolté, SAIC, MSFC, JP02

Michal E. Bangham, Bangham Engineering, MSFC, JP01

Bruce R. Askins, MSFC, JP60

Ann N. Trausch, MSFC, EV93

Introduction

NASA's Constellation Program (CxP) successfully launched the Ares I-X flight test vehicle on October 28, 2009. The Ares I-X flight was a developmental flight test to demonstrate that this very large, long, and slender vehicle could be controlled successfully. The flight offered a unique opportunity for early engineering data to influence the design and development of the Ares I crew launch vehicle. As the primary customer for flight data from the Ares I-X mission, the Ares Projects Office (APO) established a set of 33 flight evaluation tasks to correlate flight results with prospective design assumptions and models. The flight evaluation tasks used Ares I-X data to partially validate tools and methodologies in technical disciplines that will ultimately influence the design and development of Ares I and future launch vehicles. Included within these tasks were direct comparisons of flight data with preflight predictions and post-flight assessments utilizing models and processes being applied to design and develop Ares I. The benefits of early development flight testing were made evident by results from these flight evaluation tasks.

This overview provides summary information from assessment of the Ares I-X flight test data and represents a small subset of the detailed technical results. The Ares Projects Office published a 1,600-plus-page detailed technical report that documents the full set of results. This detailed report is subject to the International Traffic in Arms Regulations (ITAR) and is available in the Ares Projects Office archives files. For more information about how to obtain the full report, please contact Betty Bolté at Elizabeth.J.Bolte@nasa.gov.

Ares I-X Flight Test Background

As part of the Constellation Program, NASA planned a series of development and validation test flights. The first flight test of relevance to the Ares I crew launch vehicle was the Ares I-X flight test. Ares I-X was an unmanned, developmental flight test vehicle. One of the purposes of Ares I-X was to acquire flight data early enough to influence and impact the design and development of the Ares I in key areas such as vehicle control, induced external environments, thermal environments, thrust oscillation, roll torque, and aerodynamics.

The Ares I-X was sufficiently similar to the Ares I to meet test flight objectives, to provide significant data to validate models and processes used in the Ares I design, and to influence the Ares I design and development. Ares I-X was defined such that the vehicle external shape and detailed protuberances (known as the outer mold line (OML)) and other key features were an acceptable representation of Ares I. The Ares I-X vehicle was composed of four major elements:

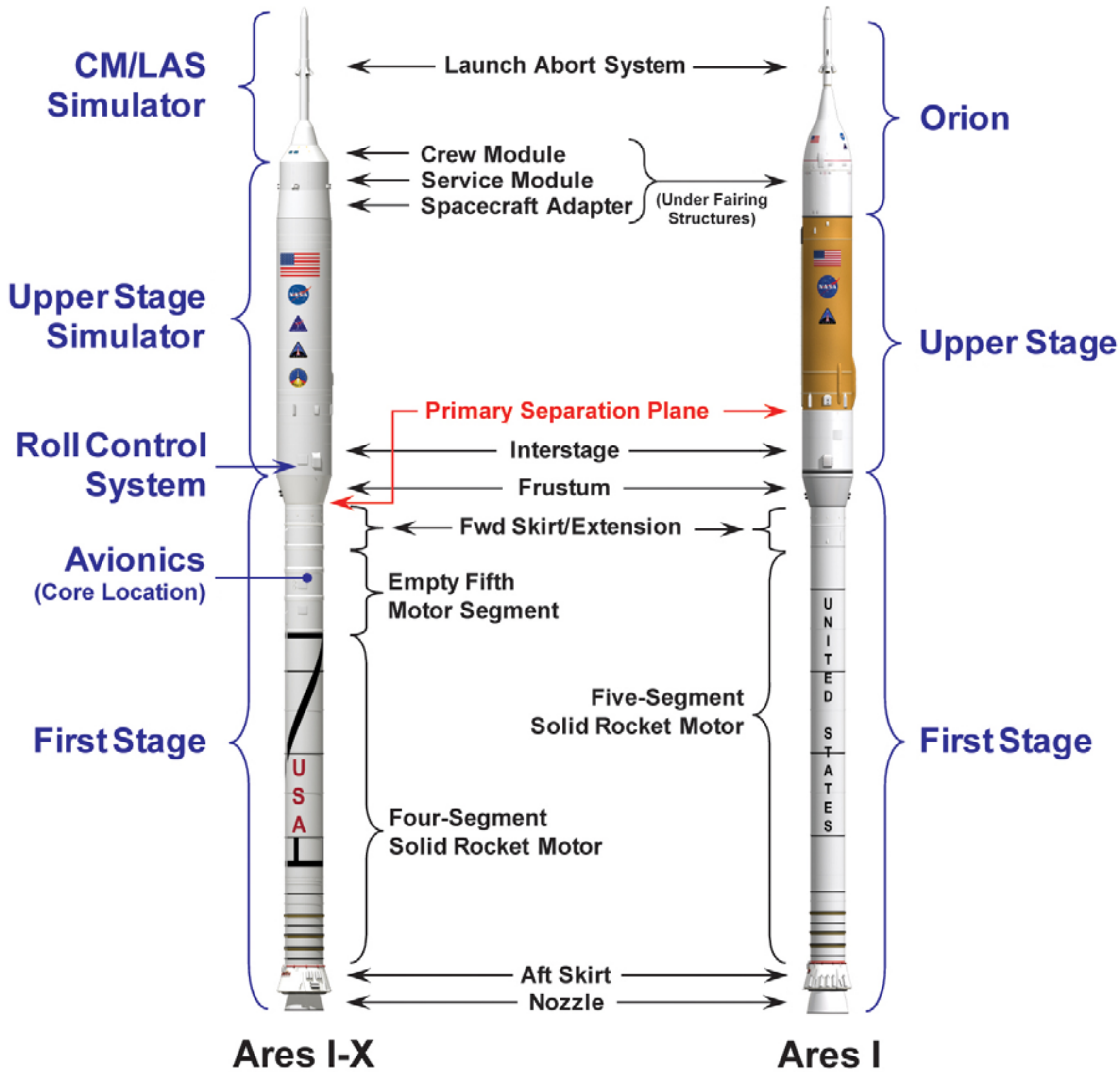
- **First Stage**: Consisted of a modified space shuttle four-segment reusable solid rocket motor (RSRM), a simulated fifth segment of the solid rocket motor (SRM), a first stage forward assembly, the frustum that connects the first stage with the upper stage simulator, and the prototype Ares I parachute system.

- **Upper Stage Simulator**: Consisted of a representation of the Ares I upper stage OML, mass, and center of gravity when loaded with propellants, as well as the Orion service module, spacecraft adapter, and interstage.

- **Crew Module/Launch Abort System (CM/LAS) Simulator**: Consisted of a representation of the Orion CM/LAS OML, mass, and center of gravity.

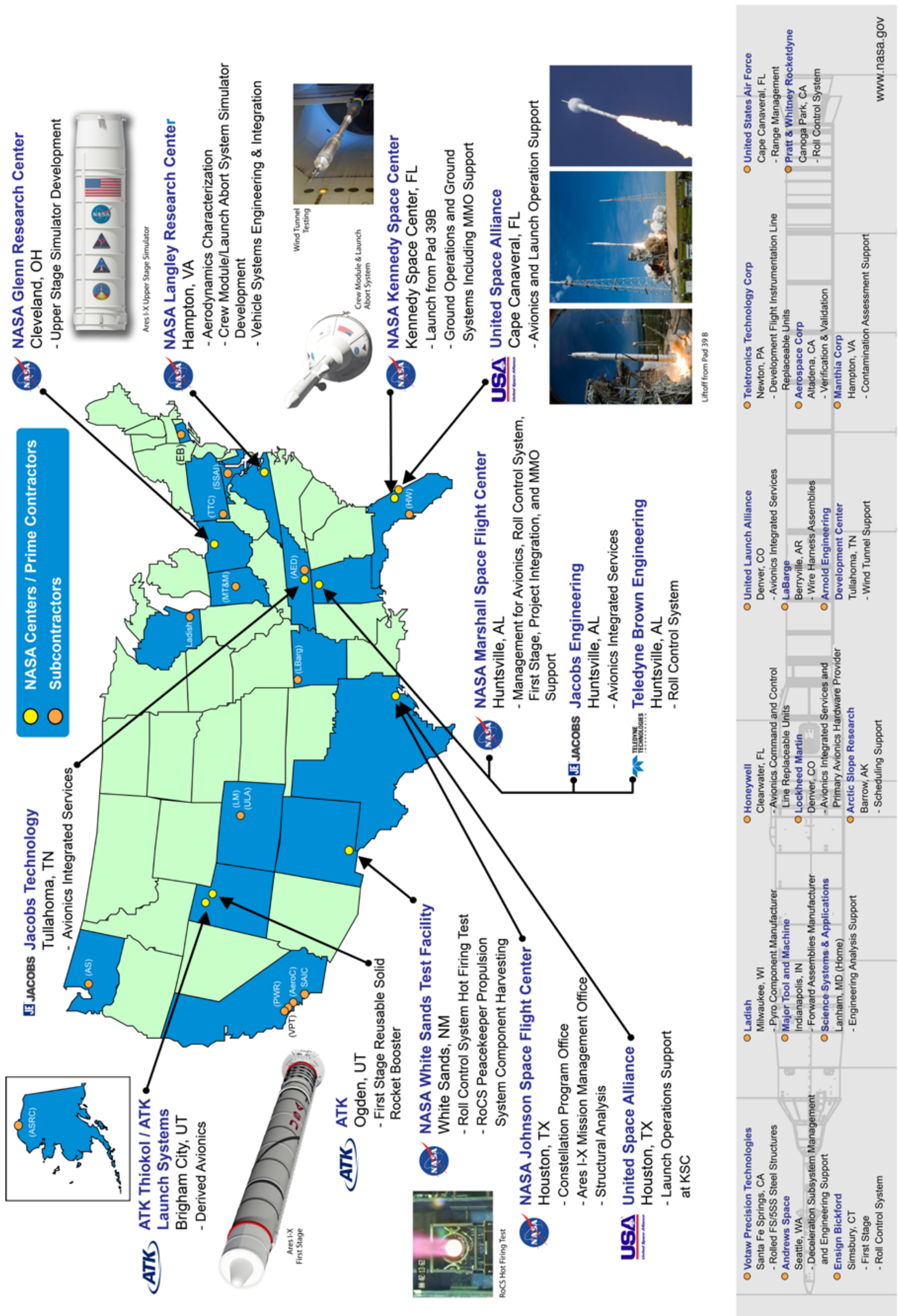
- **Roll Control System (RoCS)**: Consisted of two modules with two pairs of thrusters mounted 180-degrees apart in the interstage designed to counter the maximum predicted roll of Ares I.

A pictorial comparison of the Ares I-X and Ares I vehicles is shown in the figure below.



Overview of Ares I-X and Ares I Configurations.

The Ares I-X team was truly a national team, as is evident in the following figure, with multiple NASA centers, prime contractors, and subcontractors from 18 different states. The team designed, fabricated, and delivered the flight software and hardware components; performed assembly and checkout of the vehicle; prepared the vehicle for flight; performed the flight; recovered the first stage; and analyzed and evaluated the flight data. The test flight successfully met its flight objectives and provided very valuable data to support the design and development of the Ares I. The development activity was accomplished in under three years, demonstrating that NASA can successfully implement complex programs under a highly accelerated schedule when required.



Ares I-X National Team.

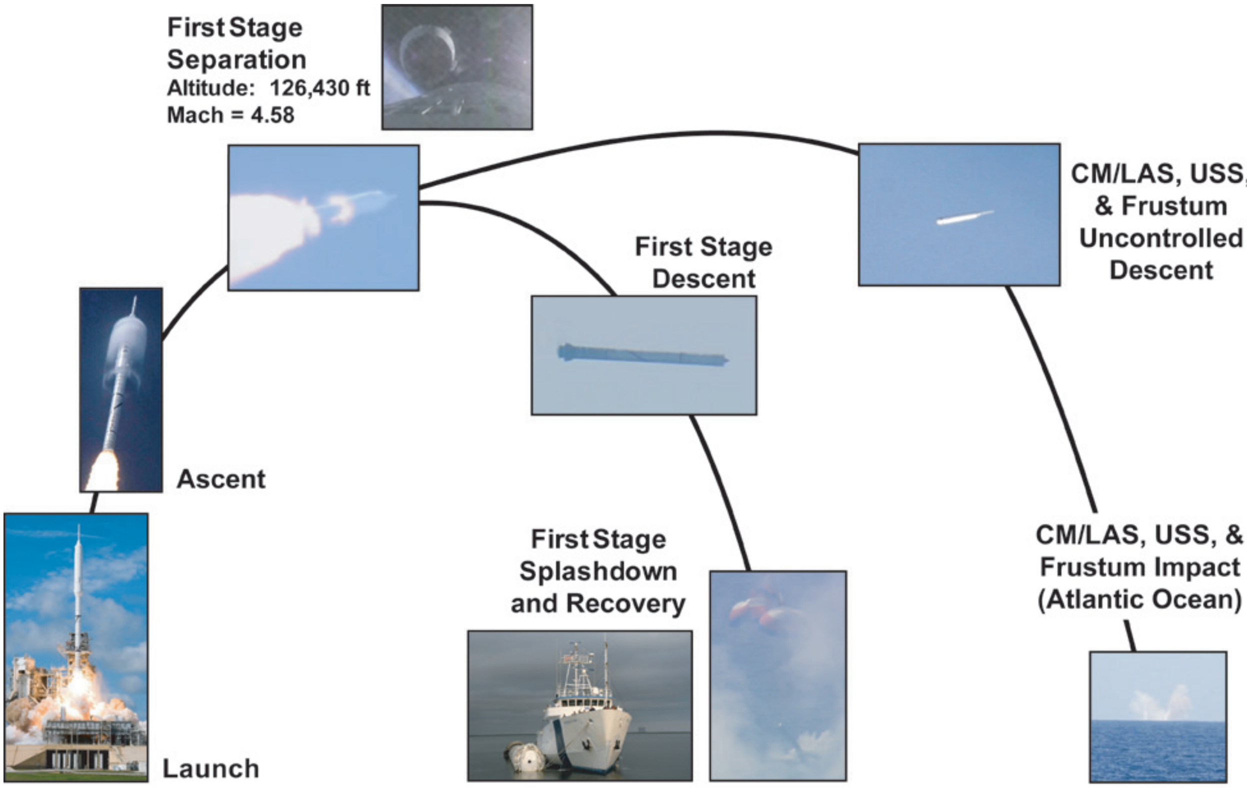
Ares I-X Flight Test Overview

The Ares I-X was launched on October 28, 2009 from the Kennedy Space Center Launch Complex 39B, at 11:30 a.m. EDT. A photograph of the Ares I-X liftoff is shown at right.

Ares I-X Launch.

The Ares I-X flight scenario is shown in the figure on the next page. Ares I-X flew a trajectory that simulated the trajectory planned for Ares I during first stage motor combustion; however, the flight profile simulation was limited by the available energy from the four-segment shuttle RSRM used in Ares I-X. The Ares I system uses a five-segment RSRM that has more energy than the four-segment shuttle motor. Thus, the Ares I-X flew essentially the same as Ares I during its powered flight but did not reach the maximum altitude or velocity that would be provided by the Ares I first stage. The acceleration profile matched the Ares I vehicle by adjusting the ballast mass in the upper stage, allowing the Ares I-X flight profile to match the velocity and dynamic pressure profile for Ares I.

The Ares I-X first stage fired for approximately two minutes prior to separation from the simulator portions of the vehicle. After separation, the first stage descended, splashed down in the Atlantic Ocean, and was recovered. Meanwhile, the simulator portion of Ares I-X—comprised of the CM/LAS, the upper stage simulator, and first stage frustum—continued in an uncontrolled, ballistic trajectory until impacting the Atlantic Ocean downrange from the separation point and was not recovered.



Ares I-X Flight Scenario (Using Ares I-X Mission Images).

Flight Evaluation Planning

A flight evaluation plan was created to collect, analyze, and document the results from the Ares I-X flight evaluation effort. This plan is entitled “Flight Evaluation Plan for Ares I Use of Ares I-X Flight Data,” CxP 72312. The Flight Evaluation Plan defines 33 technical tasks that utilize Ares I-X flight data to partially validate models and ground test data scaling used in the design of the Ares I flight vehicle. The technical tasks included assessments of Ares I-X vehicle characteristics of interest to Ares I. These tasks were performed in support of the Ares First Stage Element and Ares Vehicle Integration Offices. The tasks are categorized as integrated vehicle analysis tasks and first stage tasks. The completed flight evaluation is documented in “Final Flight Evaluation Report for Ares I Use of Ares I-X Data,” APO-1041 which consists of 5 volumes totaling more than 1,600 pages of technical data, analysis, and evaluation on the tasks that were performed. The report also contains an executive summary, flight overview, brief summaries of each task, and a summary of data quality and archival that provides a level of detail this overview cannot.

Ares I-X at KSC Launch Complex 39B.

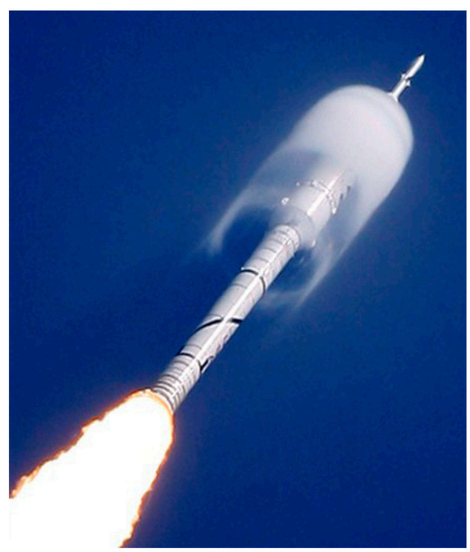
Integrated Vehicle Analysis Task Summary

The Ares I-X flight test successfully demonstrated control of a long, slender, integrated flight vehicle with a low fundamental structural frequency; provided an overall assessment of crucial design and induced environments; and partially validated selected Ares I design models and processes for a number of technical disciplines. The integrated vehicle evaluation tasks were categorized into six technical discipline areas: structural, aerodynamic, thermal, acoustic, venting, and vehicle control.

View towards Launch Complex 39B Taken from Ares I-X Shortly After Liftoff.

Structural Tasks

Seven vehicle tasks were focused on assessment of structural design models and processes. These tasks assessed the structural loads and dynamics during five phases of operation: rollout (including wind and transport loads), prelaunch (ground wind loads), liftoff (including wind, ignition overpressure, and thrust loads), ascent (buffet and vehicle maneuvering loads), and separation (aerodynamic and thrust loads). The sixth task evaluated the vibroacoustic analysis methods at liftoff, the transonic speed regime, and maximum dynamic pressure conditions. The final structural task assessed the separation pyrotechnic device shock (pyroshock) attenuation (dissipation of the shock) through the vehicle structure. Among the findings from these tasks: the Ares I simulation tools produced slightly conservative rollout loads when applied to model the Ares I-X rollout; the reconstructed ground wind loads agreed well with measured data and the model provided a realistic wind environment for assessing prelaunch loads; the ascent loads comparison results have been used to update the models and processes being used in Ares I design analysis; and the pyroshock extrapolation methodology was validated using the Ares I-X structural path.



Condensation Pattern at Transonic Conditions During Ascent.

Aerodynamics Tasks

Two tasks addressed aerodynamic analyses. The first of these tasks provided an assessment of the vehicle aerodynamic database generation process comparing Ares I-X flight data to preflight database values. These database values were generated from Ares I wind tunnel data and adjusted for OML differences using computational fluid dynamics (CFD) and additional post-flight CFD data. The second task evaluated aeroelastic fluctuating pressure (buffet) environments based on Ares I-X measured data from flight and comparative wind tunnel analysis.

Thermal Tasks

Seven tasks addressed integrated vehicle thermal environments. These tasks assessed the analysis methods and tools for: ascent aerodynamic heating, first stage tumble reentry aerodynamic heating, first stage plume radiation, first stage plume convection, first stage plume-induced flow separation, small motor (booster deceleration motor and roll control system) plume impingement, and first stage shutdown thermal transient. Based on the findings from the integrated vehicle thermal environments tasks: ascent aerodynamic heating models have been updated; the first stage reentry aerodynamic heating was updated to account for vehicle attitude; plume convection models were updated to reflect early onset of first stage base convective heating that occurred during flight; and plume impingement models were partially validated along with accurate prediction of flight conditions using CFD.

Image from On-board Video Camera During Ascent.

Acoustics Tasks

Two tasks dealt with acoustic environments. The first task provided an assessment of the liftoff acoustic environment generation and analysis methodology. The second task evaluated the acoustic analysis and environment generation process during ascent. Based on the results of the comparisons and discrepancy analysis from these two tasks, the Ares I acoustic environment prediction models and processes will be updated.

Venting Tasks

The launch vehicle is required to vent the air from the vehicle as it ascends from the launch pad. Otherwise, significant weight penalties are imposed and the possibility of vehicle damage exists due to excessive pressure in the vehicle structure. The venting task assessed the vehicle venting analysis tools and methods used to predict internal vehicle compartment pressures during ascent. Results of the task identified modifications needed for the venting models and processes, particularly in understanding the detailed vent design parameters and geometry.

Vehicle Control Tasks

The final four integrated vehicle tasks addressed evaluation of design tools and methods for the flight control system and vehicle performance related to guidance, navigation, and control (GN&C). The primary task dealt with the tools being used to design and develop the Ares I flight control system. The evaluation used the measured response of the Ares I-X vehicle to the flight environment and to preplanned maneuvers during liftoff, transonic, and supersonic ascent flight conditions. Also grouped under the GN&C area were three vehicle performance tasks.

The first performance task evaluated the methodology and modeling techniques used in predicting the vehicle thrust knockdown factor. This knockdown factor has been observed consistently in space shuttle flights and was hypothesized to affect the Ares I. Ares I-X flight data show that the phenomenon is not unique to vehicle configuration and should be expected on Ares I. The knockdown factor directly affects vehicle payload capability. The second performance task assessed the processes and tools for predicting and analyzing stage separation dynamics and ensuring no stage recontact. The final performance task evaluated the tools and process for modeling vehicle liftoff and analyzed liftoff clearance between the vehicle and launch structures.

Successful completion of the various vehicle tasks provided noteworthy progress toward validating the models and processes as they are applied to Ares I design. The knowledge gained from this experience will also be useful for any future launch vehicle development.

First Stage Analysis Task Summary

The initial expectation for the Ares I-X First Stage Element was to have a simple, robust design with minimal design modification from the shuttle RSRM. As Ares I-X evolved, it became evident that aspects of the first stage were different from the shuttle. A wide variety of design, analysis, and shuttle processes also had to be updated as a part of the Ares I-X design and development activity. Of primary concern were changes from the shuttle baseline induced environments, changes to the hardware configuration (forward structures, deceleration system, flight termination system, aft skirt, and the new parachute system), differences in trajectory, and changes in integrated vehicle configuration. These changes resulted in modeling and analysis updates to support verification that the Ares I-X design was suitable for a test flight. Most of these updated models and analyses are applicable to Ares I.

Ares I-X as seen Launching From Rotating Service Structure.

Six tasks were performed by the First Stage Element. Three of these tasks apply to Ares I first stage models developed using similar models, analyses, and databases to those that were required by Ares I-X. Data review provided partial validation of these Ares I models and analyses.

The first task partially validated modeling techniques used for the first stage high-altitude deceleration system. Although the Ares I deceleration subsystem is not identical to the Ares I-X flight system, most of the key Ares I-X parameters used in the modeling have direct application to Ares I.

The next two tasks addressed first stage thermal environments and aft skirt vibration environments. At the time of the Ares I Preliminary Design Review, conservative thermal modeling resulted in non-heritage thermal protection system heat rates. The thermal environments task evaluated the accuracy of highly complex thermal models and their application in Ares I analysis. The other task provided model validation for aft skirt vibration. The Ares I aft skirt vibration environments continue to be of concern to first stage due to high anticipated liftoff and ascent loads. The aft skirt and thrust vector control are heritage shuttle design and manufacturing. Due to predicted environments severity, hardware subject to predicted induced environments that exceed shuttle will require qualifying the hardware to the higher environments. The predicted induced vibrations could require testing beyond the capability of test facilities; thus, this task was a key factor in determining the validity of the environment predictions.

Two tasks addressed thrust oscillation. The thrust oscillation phenomenon has been historically observed in many solid rocket motors including the shuttle SRM. Forces associated with thrust oscillation can be transmitted to the rest of the vehicle and is an area of key concern for Ares I. The Ares I in-line configuration (versus the shuttle configuration where the solid rocket motors are side-mounted) poses unique vehicle design challenges to damp the solid rocket motor-induced thrust oscillations. The worst-case oscillations were predicted to cause significant additional vibration that could affect the crew. Ares I-X gave engineers a unique opportunity to obtain data from the solid rocket motor thrust/pressure oscillations and the effects on the vehicle without the complication of shuttle structures and propulsion systems. Data were successfully collected during the Ares I-X flight that validated thrust oscillation prediction and modeling techniques used in the Ares I design process and provided insight into vehicle reactions during flight.

The final task evaluated the effects of motor age on first stage performance. Although Ares I-X used a shuttle heritage motor, the motor was older than any shuttle motor ever flown or ground tested. Assessments were made for effects of motor age including the performance of the Ares I-X motor compared with its "sister" motor (the second motor in the pair was originally intended for a shuttle flight and subsequently used as a ground test motor). These data are important to the solid rocket motor community to determine the effects of aging on large motor performance, especially if there is a need to delay use of flight assets in future programs.

First Stage During Recovery Operations.

Conclusions

The Ares I-X flight clearly demonstrated the benefits of early developmental flight testing. The flight proved that the vehicle could be controlled and fly on a precise trajectory. Ares I-X flight data were used to support validation of tools and methodologies for technical disciplines that will greatly influence the design and development of Ares I and other future launch vehicles. Prominent in this evaluation is the significant improvement in our ability to predict the environments seen by the launch vehicle. Specifically, the key areas where Ares I-X flight test data influence design and development include:

- Flight control system algorithms to predict liftoff clearance, ascent, and stage separation of a long, slender launch system including accounting for vehicle structural dynamics.

- Large launch system ascent powered by a single solid rocket motor including direct performance comparisons for a single RSRM used as a flight stage with ground test.

- Frequency domain validation for a launch vehicle using real flight data obtained from preplanned in-flight maneuvers (a first for NASA).

- Structural modeling from rollout to stage separation.

- Thermal modeling including the effects of rocket plumes and aerodynamic heating.

- Extrapolation of historical methodologies to predict the dissipation of the structural response produced by pyrotechnic devices.

- Complex flow fields prediction using computational fluid dynamics during time-varying conditions including plume interactions.

- First stage deceleration systems, including the use of vehicle orientation at high altitude, prototype main parachutes (that are larger than those used for shuttle first stage deceleration), and parachute packaging and release design modifications.

Future Launch Vehicle Development Implications

Ares I-X was the first flight of a new NASA launch vehicle system since the first launch of the space shuttle in 1981. The legacy of the Ares I-X flight test includes partial validation of many current design tools and processes. These design tools and processes are essential to the successful design and development of future launch vehicles. Validated tools and processes coupled with the workforce experience gained from the Ares I-X flight data will benefit future vehicle in-house design and development and provide more informed oversight of any contractor-led design and development.

The Ares I-X flight test provides NASA with a core group of individuals who have taken a launch system from concept through flight and post-flight evaluation. Additional NASA personnel were involved in peripheral activities that were required to define, develop, verify, launch, and assess the results of the flight. The Ares I-X mission provided a significant addition to NASA's workforce experience that will be invaluable in any new launch vehicle development.

Ares I-X flight data included many special measurement and instrumentation features that make the Ares I-X data set unique and world class. These data combined with data from space shuttle and Saturn will make significant contributions to any future launch system design and development. Archiving these assets for future use is critical to the success of future launch vehicle development.

Based on the Ares I-X experience, the following recommendations are presented for any future launch vehicle development:

- Early flight tests should be planned as a part of future launch system development. Early flight tests can illuminate flight and ground system weaknesses, provide experience in operating the systems, and expose "unknown-unknowns."

- Test flights are, by necessity, fast-paced activities. The stand-alone project model worked well for the Ares I-X test flight. This organizational approach streamlined project efforts but at the expense of a wider involvement with the mainline engineering community. Future test flights should strive to balance a streamlined organization with closer working relationships with mainline engineering to expand both the experience and insight gained. This approach will provide a closer working relationship between the end users and the test flight design and development team.

- Mainline engineering community participation throughout the flight test vehicle life cycle is critical. In addition to normal design, vehicle analysis, and system verification activities, areas such as flight instrumentation definition, data capture rates, data timing, on-board data processing, and post-flight data processing and archival are key and require persistent engineering participation.

Recommendations for Future Analysis

The flight evaluation experience has provided recommendations for subsequent flight tests and for extended activities to maximize learning from Ares I-X. These recommendations include:

- **Data Analysis**: Plan and allocate resources for post-flight analyses early in the flight test development in order to establish a definitive T–0; time-synchronize all data; support rapid generation of the Best Estimated Trajectory; and exercise data flow from acquisition from the vehicle to archival. The benefits of performing these include uncovering potential issues that affect the initiation of flight evaluation and streamlining the post-flight analysis activities.

- **Instrumentation**: Make a concerted effort to plan overall flight instrumentation from a requirements-based sensor list and location generation to final checkout and acceptance just prior to flight. This should include ensuring the proper understanding of instrumentation requirements between requestors and implementers including proposed designs; information expectations as manifested via installation; measurement specifications including range, frequency response, sample rates, and accuracy; calibrations and data filters; expected sensor reports; etc. During sensor installation, assure that an on-site person with awareness of analysis sensitivities is available for crucial installation/checkout steps. Utilize an arbitration process to adjudicate instrumentation issues that arise between requestors and implementers.

- **GN&C**: Include instrumentation such as video targets, inertial data, and photogrammetry on future flights to provide high-fidelity liftoff and separation clearance data to better assess modeling and simulation credibility during these crucial flight phases.

- **First Stage**: Determine the methodology to apply a four-segment derived thrust oscillation transfer function to a five-segment motor.

- **Aerodynamics**: Perform a detailed jet interaction study for reaction control jets using different methods in association with CFD. This should include strategizing when/how to make the most efficient use of CFD (because it is very useful but expensive).

- **Acoustics**: Using the latest available data, determine the need for acoustic attenuation using a mobile launcher deck water deluge system.

- **Vibroacoustics**: Continue development and use of empirical scaling and proceed with use of hybrid statistical energy analysis finite element modeling for future flight tests.

- **Loads**: Understand the contributions of vehicle rollout to fatigue analysis.

- **Loads**: Reconstruct existing four- and five-segment development and qualification motor firings with particular emphasis on axial acceleration responses.

ACRONYMS

APO	Ares Projects Office
ATK	Alliant Techsystems, Inc.
CFD	Computational Fluid Dynamics
CM	Crew Module
EB	Ensign Bickford
FS/5SS	First Stage/Five-Segment Simulator
GN&C	Guidance, Navigation, and Control
ITAR	International Traffic in Arms Regulations
KSC	Kennedy Space Center
LAS	Launch Abort System
MMO	Mission Management Office
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
OML	Outer Mold Line
PWR	Pratt & Whitney Rocketdyne
RoCS	Roll Control System
RSRM	Reusable Solid Rocket Motor
SRM	Solid Rocket Motor
USS	Upper Stage Simulator