Best Practices from the Design and Development of the Ares I Launch Vehicle Roll and Reaction Control Systems

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On April 15, 2010 President Barak Obama made the official announcement that the Constellation Program, which included the Ares I launch vehicle, would be canceled. NASA's Ares I launch vehicle was being designed to launch the Orion Crew Exploration Vehicle, returning humans to the moon, Mars, and beyond. It consisted of a First Stage (FS) five segment solid rocket booster and a liquid J-2X Upper Stage (US) engine. Roll control for the FS was planned to be handled by a dedicated Roll Control System (RoCS), located on the connecting interstage. Induced yaw or pitch moments experienced during FS ascent would have been handled by vectoring of the booster nozzle. After FS booster separation, the US Reaction Control System (ReCS) would have provided the US Element with three degrees of freedom control as needed.

The best practices documented in this paper will be focused on the technical designs and producibility of both systems along with the partnership between NASA and Boeing, who was on contract to build the Ares I US Element, which included the FS RoCS and US ReCS. In regards to partnership, focus will be placed on integration along with technical work accomplished by Boeing. This will include detailed emphasis on task orders developed between NASA and Boeing that were used to direct specific work that needed to be accomplished. In summary, this paper attempts to capture key best practices that should be helpful in the development of future launch vehicle and spacecraft RCS designs.

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ADC	=	Advanced Development Contract
CAD	=	Computer Aided Design
CDR	=	Critical Design Review
CEV	=	Crew Exploration Vehicle
CxP	=	Constellation Program
DAC	=	Design Analysis Cycle
DOF	=	Degrees of Freedom
ESTS	=	Engineering, Science, and Technical Services
°F	=	Degree Fahrenheit
FOM	=	Figures of Merit
FS	=	First Stage
FT	=	Fault Tolerant
GHe	=	Gaseous Helium
GN_2	=	Gaseous Nitrogen
GN&C	=	Guidance Navigation and Control
HFTA	=	Hot Fire Test Article
Isp	=	Specific Impulse
lbf	=	Pound Force
lbm	=	Pound Mass
LOX	=	Liquid Oxygen
MAF	=	Michoud Assembly Facility
MDC	=	Mission Duty Cycle
MDP	=	Maximum Design Pressure
MEOP	=	Maximum Expected Operating Pressure
MGA	=	Mass Growth Allowance
MMH	=	Monomethylhydrazine
MPS	=	Main Propulsion System
MSFC	=	Marshall Space Flight Center
MTO	=	Mass to Orbit
NASA	=	National Aeronautics and Space Administration
NDT	=	NASA Design Team
N_2H_4	=	Hydrazine
NTO	=	Nitrogen Tetraoxide
PDR	=	Preliminary Design Review
psi	=	Pounds per Square Inch
psia	=	Pounds per Square Inch Absolute
psid	=	Pounds per Square Inch Differential
RCS	=	Reaction Control System
ReCS	=	Reaction Control System
RoCS	=	Roll Control System
SCI	=	Source Controlled Item
SDTA	=	System Development Test Article
sec	=	Second
SRB	=	Solid Rocket Booster
TBD	=	To Be Determined
TBR	=	To Be Resolved
TPS	=	Thermal Protection System
US	=	Upper Stage
USPC	=	Upper Stage Production Contractor

I. Introduction

The Ares I launch vehicle was being developed by the National Aeronautics and Space Administration (NASA) at the Marshall Space Flight Center (MSFC) in Huntsville, Alabama, from 2006 to 2010 as part of the Constellation Program (CxP). The vehicle was slated to replace the Space Shuttle for manned spaceflight and was being designed by the NASA Design Team (NDT), with component selection, procurement, and production being handled by the Upper Stage Production Contractor (USPC), Boeing. The Ares I was configured in two inline stages: a Space Shuttle derived five-segment Solid Rocket Booster (SRB) First Stage (FS) and an Upper Stage (US) powered by a Saturn V derived J-2X engine. Roll control for the FS was planned to be handled by a dedicated Roll Control System (RoCS), located on the connecting Interstage with induced yaw and pitch moments being handled by booster nozzle thrust vectoring. The FS SRB was designed to operate for approximately two minutes after which point the FS would separate from the vehicle ending the mission of the FS RoCS. Post-separation and prior to the generation of full J-2X thrust, the US Reaction Control System (ReCS) was designed to provide three-degrees of freedom control for the vehicle. After the J-2X ignited, the US ReCS would have continued to provide roll control for the vehicle. Nozzle vectoring of J2-X would counteract any induced yaw or pitch moments. Between J2-X engine shutdown and commanded crew vehicle separation, the US ReCS would again provide 3-degree of freedom attitude control.

The focus of this paper is to relay some of the key best practices and lessons learned from the NDT design and development of the FS RoCS and US ReCS, as well as Boeing's producibility work, and the partnership between the two teams. The Ares I was somewhat unique for man-rated launch vehicle design as it was a government-led in-house design, with the NDT serving as the role of the traditional Prime Contractor. Boeing, who was competitively selected as the USPC, was responsible for the selection, procurement, and production of all of the components and hardware that the NDT had specified for the two systems. A representation of the Ares I launch vehicle in the stacked configuration with the Orion Crew Exploration Vehicle (CEV) is shown in Figure 1.

The FS RoCS flight design incorporated a distributed, pressure-regulated Gaseous Helium (GHe) pressurization system, with localized sets of monopropellant Hydrazine (N_2H_4) tanks. The FS RoCS configuration had two thruster modules that were 180^o apart, with a pair of localized propellant tanks located behind each thruster module inside the Interstage surface. The overall FS RoCS architecture included: pressurant loading, pressurant storage, pressurant regulation and isolation, propellant loading, propellant storage, consumable acquisition, propellant delivery, and thruster assemblies to deliver the required impulse and moment generation capability. This architecture provided one failure tolerance for function and prevention of catastrophic hazards, such as inadvertent thruster firing, bulk propellant leakage, and over-pressurization.

The pressurization system included two ambient-referenced regulators on parallel strings to attain the required system level single Fault Tolerance (FT) for function. A single burst disk and relief valve assembly was included to ensure single FT for must-not-occur catastrophic hazards.

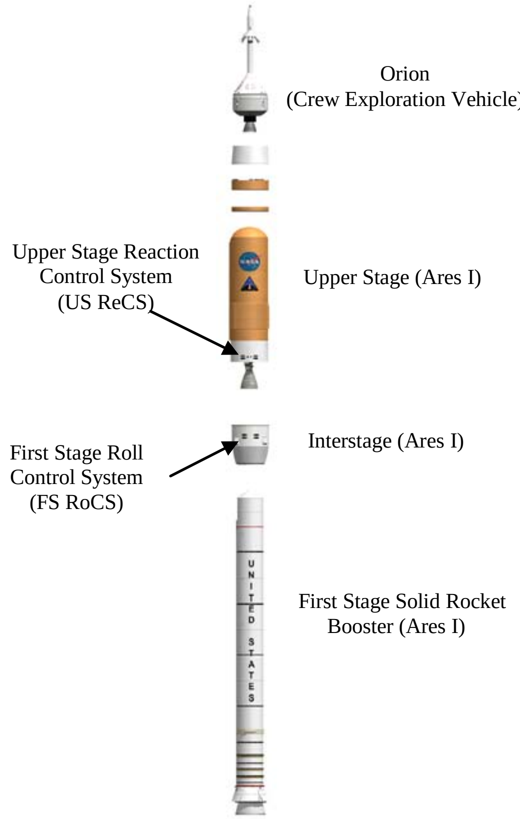

Figure 1. Layout of the Ares I Launch Vehicle and Orion Crew Exploration Vehicle

The system was designed to support the simultaneous firing of multiple thrusters as required to counteract roll torque disturbances. Each thruster module contained six 625-lbf thrusters (three each in the positive and negative roll directions), four acting as primary thrusters and two as redundant thrusters. The thruster flowrate was approximately 3.0 lbm/sec at the rated thrust. All thrusters were in an inline configuration (catalyst chamber and nozzle), with nozzle centerlines being parallel to the Y-Z plane of the vehicle. Each thruster assembly centerline was canted 20^o relative to the tangent of the interstage outer wall in order to reduce plume thermal effects and subsequent Interstage Thermal Protection System (TPS) mass. The baseline design also incorporated series redundant, pneumatically actuated thruster valves.

Propellant was stored in four supply tanks, with two located in a localized configuration behind each thruster module inside the Interstage structure. Propellant tanks were an all-metal cylindrical design, with elastomeric diaphragms being used for positive expulsion. The total propellant mass was approximately 1136 lbm with 40 lbm of that being unusable. The volume and dry mass for each propellant tank was approximately 8115 cubic inches (in^3) and 40.0 lbm with the nominal and Maximum Expected Operating Pressures (MEOP) approximately 639 and 793 psia respectively. The distributed pressurization subsystem was located along the inner wall of the Interstage, approximately halfway between the thruster modules and is comprised of three high-pressure helium storage tanks and a Helium Pressurant Module (HPM). Each of the high pressure, cylindrical composite over-wrapped GHe pressurant tanks were designed to operate at a maximum helium pressure of 4500 psia and have an internal volume of approximately 8438 in^3 and an estimated weight of 74.0 lbm. The total amount of GHe to be loaded was estimated at 35 lbm, with 21.5 lbm being unusable due to end of mission pressure and temperature constraints as well as the rapid mission usage timeline. A common pressurant system was used for both propellant tank pressurization and actuation of the pneumatic thruster valves due to commonality of operating pressure levels. Additionally, helium manual valves and service valves were added to facilitate propellant loading of the localized propellant tanks from the service panel.

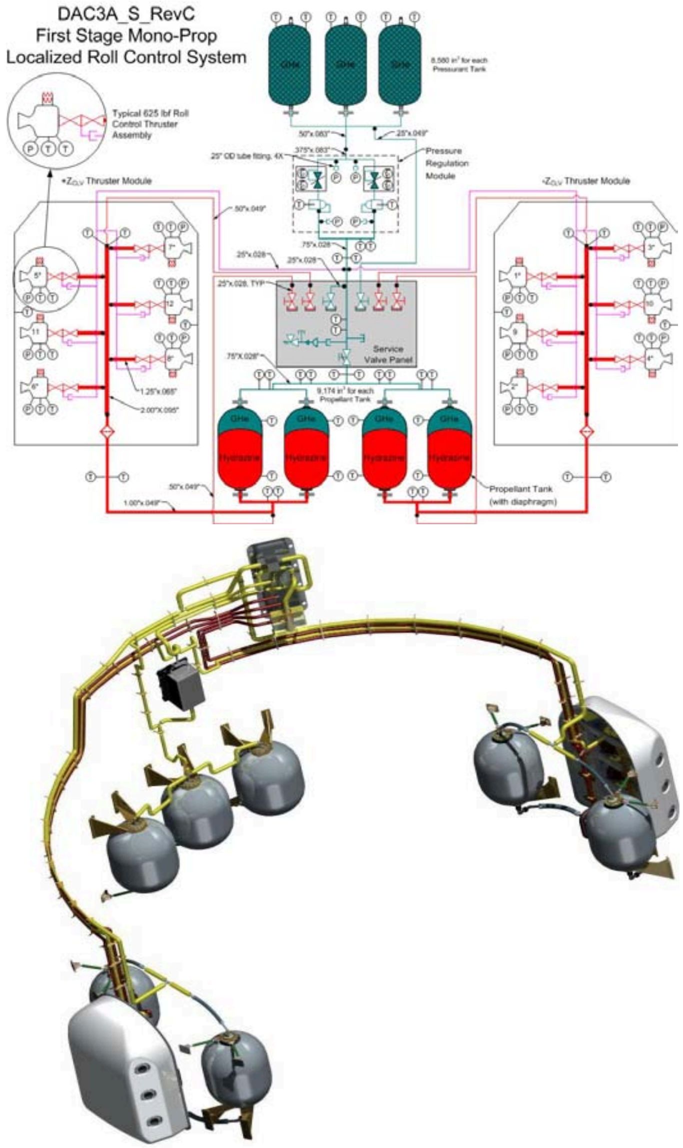

Figure 2. Fluid schematic and CAD layout of the Ares I First Stage Roll Control System

The FS RoCS configuration was designed to facilitate draining, purging, and decontamination of the propellant system. The service panel (which contains the fill/drain valves) was located on the outside of the Interstage wall to allow access to the service valves from outside the vehicle. A liquid trap/low point was located on the propellant fill/drain lines. A purge line was located at the top of each thruster module and routed back to the service panel. Two service valves, one for the $+Z_S$ thruster module and one for the $–Z_S$ thruster module, provided a continuous purge circuit for each module and was used in conjunction with the propellant manifold designed to facilitate faster draining. The outer diameter of the fill/drain line was ½" to ensure adequate drain and decontamination performance. The final configuration of the fluid system schematic and CAD representation of the FS RoCS, as configured for attachment to the Interstage, is shown in Figure 2.

The US ReCS configuration was a distributed monopropellant N_2H_4 blowdown propulsion system. It had two thruster modules 180° apart on the outer diameter of the US Aft Skirt. US ReCS architecture included pressurant loading and storage, propellant loading and storage, acquisition and delivery system, and thrusters. The thrusters utilized a catalyst bed along with a 90° turn flow nozzle due to reliability and cost. They were also sized to meet the US ReCS impulse, moment, duty cycle, electric pulse width, impulse life, impulse bit, and thrust level requirements. This architecture provided one fault tolerance for function and one fault tolerance against catastrophic hazards during ground and flight operations.

The US ReCS was designed to operate for approximately eight minutes following US element separation from the FS element. Nominal operation of the US ReCS occurred under various conditions experienced during the mission. These conditions included vibration/shock, hot environments, cold environments, and structural loads. Vibration and shock conditions would have occurred throughout the non-operational and operational phases of the US ReCS. The most intense of these conditions was the shock generated during the separation of the US from the FS.

To properly function, the US ReCS needed to survive the expected vibration conditions, which would have occurred during launch and the FS element operational phase. The US ReCS was expected to have experienced potentially large temperature variations due to proximity of the cryogenic storage tanks of the US MPS. The US ReCS was located in close proximity to the J-2X and during planned operation would have also been exposed to higher temperatures generated by the J-2X and its plume. The US ReCS propellant tank would have also experienced lower temperatures due to its location on the thrust cone of the US element. The thrust cone was located on the aft dome of the Liquid Oxygen (LOX) tank providing LOX to the J-2X. The final configuration of the fluid system schematic and CAD representation of the US ReCS, as configured for attachment to the Aft Skirt of the LOX tank of the US, is shown below in Figure 3. For additional design and development details on the Ares I FS RoCS and US ReCS see References 3-9.

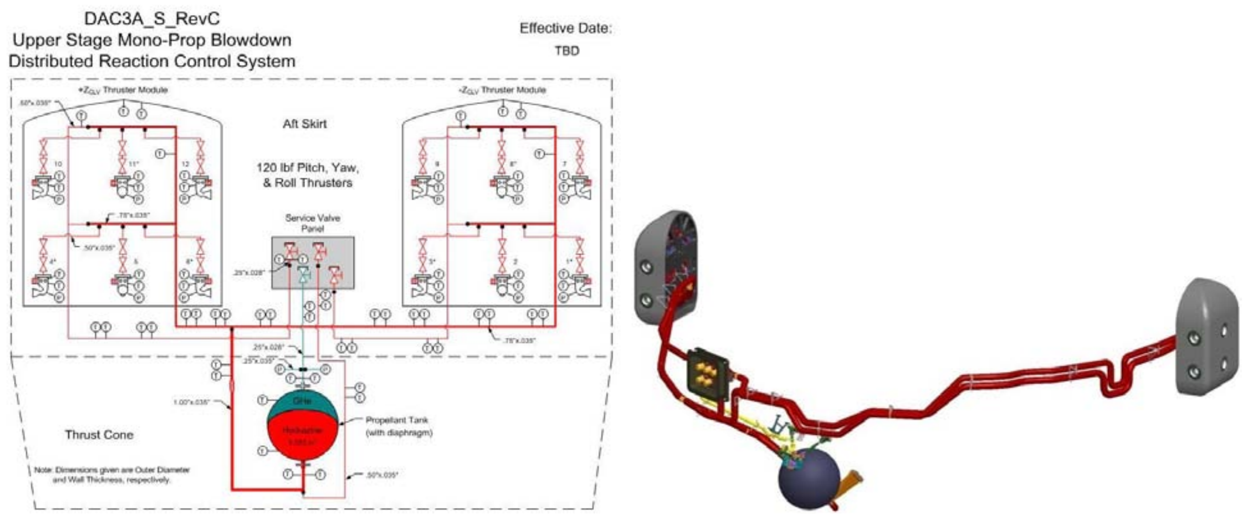

Figure 3. Fluid schematic and CAD layout of the Ares I Upper Stage Reaction Control System

II. Technical Design Best Practices

The following sections outline some of the major best practices incorporated and lessons learned during the design and development of the Ares I RoCS and ReCS. As mentioned earlier, the NASA Design Team (NDT) was responsible for the design and development of the two systems, essentially serving the role of the traditional Prime Contractor. The NDT consisted of both MSFC civil servants and contract employees from the Jacobs ESTS and Teledyne Brown technical services contract. Initial planning and conceptual design for both systems began in 2006. Preliminary Design Reviews (PDR) for the RoCS and ReCS were conducted in 2008, and an integrated Interstage-Upper Stage PDR was conducted in 2009. Design work ended approximately half way to the Critical Design Review (CDR) in 2010, with an Interim Design Review (IDR).

A. Integrated Product Team (IPT) Organizational Structure

1. The larger the program, the more authority the IPT leadership needs to have

If sufficient authority is not vested in the IPT leadership the structure can become more cumbersome with larger groups and projects, as there become more and more routes for decisions to be made and challenged. Additionally, clear delineation of ownership responsibility needs to be defined early on. The organizational structure at MSFC added complexity to the situation for the Ares I RCS designs. The IPT consisted of engineers from various disciplines including systems, components, structural, thermal, Guidance, Navigation and Control (GN&C), safety, etc. that are all independent organizations (Branches with a Division) which have their own hierarchies (i.e. branch chief, team lead, engineer). Integration of the individual disciplines into the IPT structure proved challenging, but overall was fairly effective, as there was consistent active engagement of the disciplines supporting the IPT. One of the challenges with this approach was a resultant difficulty to prevent the accumulation of design margin within each technical area of responsibility. An example of a challenge that arose due to this organizational structure was the maximum component temperature of 120°F. This value was initially established by the IPT as a conservative value to insure access to a wide variety of commercially available components and materials. However, the thermal analysis branch imposes 18°F margin for all programs based on their collective experience, leading to a very conservatively low maximum temperature. This overly conservative value ended driving aspects of component and system design that likely could have been simplified had better definition of IPT authority been made earlier in the project. Component and system level design and testing requirements also imposed an additional related qualification margin of 20°F, adding an additional level of margin and conservatism.

2. Divide and conquer

The IPT was initially comprised of both FS RoCS and US ReCS teams, in order to maintain consistent design and development approaches, but later became cumbersome due to the size of the team. Following PDR, the RCS IPT divided into separate FS RoCS and US ReCS Integrated Design Teams (IDT) to streamline the critical design of the individual systems. This proved to be a good approach and resulted in decreased meeting times with more targeted topics. To ensure consistency was maintained at a higher level, an RCS Work Package Manager position was created to oversee continued development.

3. As much as possible, push decision making authority down to the level of the subject matter experts / responsible discipline engineer

To facilitate effective delegation, spend adequate time defining expectations and interfaces, as well as the reporting process and content, then focus on reviewing the results and not the detailed process. Make decisions and mature designs. Don't be afraid to make initial decisions, based on all inputs available at that time; and don't be afraid to revise those decisions, based on re-evaluation of all available updated inputs, even if there are impacts. Failure to make a decision is a bigger impact that making a decision that later needs to be updated.

4. *Establish working capabilities and functionalities, including margin, with major interfacing subsystems early, and constantly update*

For example, levels and margin for propulsion performance with GN&C need to be initially set well before GN&C is ready to commit formally to propulsion performance requirements, such that RCS propulsion design can start to mature. Define required/expected products for reviews (and associated content) enough in advance to allow product generation.

5. Independent Technical Experts with a tremendous amount of industry experience, frequently referred to as greybeards, can be very valuable in the early design process

Seasoned, highly experienced RCS subject matter experts with decades of experience were brought in early in the design phase to provide invaluable guidance, lessons learned, and independent assessments for all aspects of the development of the RoCS and ReCS. The greybeards were both integrated into the design process to provide frequent feedback, and available for separate consultation while performing various assessments and analyses. The overall influence and impact of the greybeards led to a higher fidelity, more technically sound design.

6. *Configuration management is critical for diverse teams to stay up to date on system iterations*

Configuration management via a share site was instrumental in keeping the IPT up to date on the latest system configurations. In addition to a log of decisional packages documenting system changes, the latest fluid system schematics, mass properties, power budgets, and pressure budgets were consistently updated to the most current version. Notifications were sent to the entire IPT when any major product was updated. The implementation of intermittent, formal Technical Interchange Meetings (TIM) ensured thorough and consistent products at reasonable intervals (6 to 9 months for this project) was invaluable for surfacing problems and issues that needed resolution. These meetings were conducted as internal reviews for synching up the integrated products for each subsystem, and not under the banner of a PDR or CDR. Finally, it is recommended to continue to implement new and improved technologies to facilitate communication for remote meetings, such as dynamic video conferencing, and improved share-tool training. However, webex/telecons for local team members should be minimized as much as feasible as this typically results in multi-tasking, which can decrease the efficiency and effectiveness meetings.

B. System Design and Analysis

1. Proactive coordination between disciplines was helpful in addressing areas of potential conflict early on to minimize unforeseen issues down the road

An example was RCS offering the TPS team the opportunity to test candidate materials in RCS thruster plumes during early development tests. This expedited the selection of candidate TPS materials with no real technical impact to the thruster test and relatively low cost for the TPS team. The interface between the RCS IPT and the GN&C team was strong and facilitated rapid turn around for system impacts to fluctuations in the vehicle and mission requirements. However, the interface with Avionics was an example of an interface that could have used more

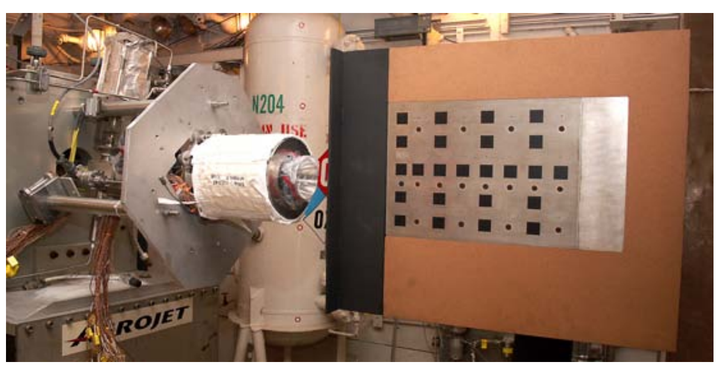

Figure 4: Insulated FS RoCS development thruster in hot-fire test cell with instrumented TPS plume impingement panel

nurturing. Establishment of lighting strike and electromagnetic interference (EMI) requirements resulted in disjointed efforts to try to resolve the impacts to vehicle capability and component complexity. To streamline the interface for analysts, consider including a technical liaison between designers and analysts to maintain consistency and minimize potentially conflicting inputs and interfaces. Similarly ensure integration between subsystem and respective component expertise to ensure component designs support planned subsystem requirements and operations. Also, early integration with the ground servicing and operations group is important - even early in the design process.

2. *Frequent changes in higher-level requirements led to frequent trade studies and there was not always sufficient time for adequate review*

An example was the thrust level and ultimate roll torque requirement for the RoCS. As this requirement fluctuated, the RCS IPT would try to be proactive and assess changes to the system and component designs that could support the changes in the roll torque requirement. However, because the requirement was undergoing frequent changes, it became difficult to continuously make changes to the RoCS design while still meeting overall schedule and milestones, so a line in the sand needed to eventually be drawn and agreed to by both GN&C and RCS. Additionally, some trades appeared to only be making incremental improvements when there may not have been sufficient rationale for reassessment. Be sure to consistently be aware of the old adage - better is the enemy of good enough. Time is always a critical resource and the more iterations that are required for review there will be an increased need for resources, less time to progress a functional design that meets requirements to CDR, or lead to not enough time for review which presents the risks of the design requiring even more iterations farther (and cost increase and schedule slip) down the road.

3. High technical risk items were identified early on and advanced development or development programs were put in place to mitigate those risks

Examples included RoCS thruster proof-of-concept testing, component advanced-development, prototype thruster development, tank study contracts, system development test articles (SDTA), and thruster module and service valve panel vibration test articles. See the Development Testing section below for more details.

4. By PDR, initial flexibility stress analyses should be completed on lines and assemblies to identify problem areas

This effort should also include initial assumptions and basis for build tolerances in order to capture manufacturing and producibility aspects. Delays and a lack of manpower on RCS effort deferred these efforts with design impacts further along in the program.

5. Launch vehicle applications and other special RCS applications (e.g., re-entry) need to have conservative vibration and shock levels defined early and the vehicle architecture should work to stay within these levels as it matures

Ares I subjected the vehicle to a significant vibration level increase following PDR, for which the RCS architecture really wasn't designed. This introduced significant RCS and US primary structure design complications to try to reduce vibration levels, translating into greater RCS assembly and US design complexity and sensitivities in other areas. For example, if vibration levels are at risk for a significant increase or are out of family for a particular RCS architecture, RCS design should likely choose a conservative or more capable design to handle this vibration level.

6. The vehicle should work to insure timely establishment of design-to interface requirements

Specifically, important RCS to primary structure requirements include thermal environments, physical deflections (static and dynamic, as well as thermal and other loads), and interface mating specifics and tolerances. These parameters were still not fully established and controlled by the vehicle at the time of US IDR for RCS interfaces, introducing significant design risk and schedule risk for the RCS CDR. Deflection of the primary structure could significantly impact both RoCS and ReCS, and in particular pressure vessel design, and therefore should be captured in procurement specifications to avoid significant cost and schedule impacts.

7. Know and understand the safety and mission assurance requirements.

Address them in the subsystem and component designs, and when planning to deviate for these requirements, formulate a strong and thorough rationale for deviation and coordinate with all Safety stakeholders.

C. Component Design

1. RCS systems should carefully consider series redundant thruster valve configurations, particularly where non-heritage valve applications and/or high flowrates are incorporated

The RoCS application had significant cost, mass, envelope and schedule ramifications immediately upon incorporation. In many instances there are other options to meet the standard fault tolerance requirements including manifold or tank isolation valves, pyro valves, and burst disks to name a few. It is recommended that all reasonable options be explored prior to committing to a single architecture.

2. Determine a reasonably conservative filter sizing methodology and implement it early in the design

After a very conservative initial sizing estimate was made, a significant amount of time was spent in developing a sizing methodology that was not overly conservative. However, before a final methodology was determined, impacts from the initial approach and assumptions had led to ramifications in the system design that were too embedded in the system design to rationalize refining it (i.e. affected manifold layouts, thruster module and fairing footprint, and component specifications).

3. Carefully determine maximum pressurization system component flowrates as well as capabilities of off-the-shelf hardware for demanding applications

In order to keep the Burst Disk, Relief Valve (BDRV) assembly to within heritage sizing (which was being sized for maximum failed regulator flowrate plus margin), a maximum flowrate had to be specified. As the FS RoCS was a relatively high flowrate system, the maximum failed open regulator flowrate was near the boundary of existing heritage BDRV components capabilities. This resulted in the supplier selecting a BDRV design at the top end of heritage flowrate capacity and incorporating a fairly complex flow limiter to the outlet of the GHe pressure regulator to stay within the selected BDRV's operating range. The flow limiter design then incurred additional challenges to system operation, requiring that the system would need to modify various modes of operation to insure that full performance and fault tolerance were maintained. Due to the flow limiter design not being incorporated into the system until sometime after PDR, the system needed to make concessions as it was too far along in the contractual process to make the necessary component design changes to negate this issue.

D. Requirements Definition And Planning

1. Too much emphasis was placed on detailed requirements in the component specifications, which detracted from the overall progress of the system designs

Vendor contract provisions need to be in place to allow specification updates quickly, with low impacts, and allow for cost increases as the vendor interacts with NASA or a prime on requirements. As requirements evolve, make sure to fully understand cost and schedule implications on the components. Additionally, from the development of the detailed component specifications:

- Deviation from initially defined documentation formats (specifically specifications) can lead to a significant amount of rework later in the program, which can be avoided.
- When vendors cannot meet procurement spec requirements, flexibility both at the subsystem level and at the vendor levels is needed (both effectively incurring cost impacts) in order to best solve the related design issues; this may also include relaxation of imposed requirements in the best interest of both the subsystem and vendor to achieve a workable product.
- Consider the use of a Technical Writer for grammatical and consistency comparison of technical documents and let the engineers focus on the technical content.
- Ensure consistent integration of the designers throughout the specification formulation process, with specific emphasis on interfaces.
- Use study contracts as surveys for initial design information until such time that selected flight component vendors can be placed on contract – fills gaps in understanding of available and new designs on components.
- Emphasis on qualification planning and test article configurations should be dedicated to support PDR and elevated to the appropriate levels for release to support CDR.
- Account for planned test and build activities (qualification, acceptance, and manufacturing/ground processing) in the design and capabilities of the subsystem and its components – don't wait to consider and address these factors until CDR or even PDR.

2. Many early-derived requirements ended up being treated as though they were "set in stone" – allow for the iteration and evolution of derived requirements as higher-level requirements become more refined

It is good to set early derived requirements to keep the design process moving along, but they can add unnecessary complication farther down the road if not sufficiently allowed to evolve. Frequently, more time was spent incorporating greater complexity into the RCS designs rather than challenging or relaxing the requirements.

3. Thoroughly establish success criteria for completion required for each design milestone

If there are other IPTs that have interfacing influence (such as the RoCS and the Interstage), insure they are onboard with the approach and assumptions early to assist with creating achievable success criteria at the integrated vehicle-level. Ensure that any discrepancies are closely tracked to closure.

4. The system should progress to the development of detailed drawings around the time of PDR in order to mature details of design

CAD models are difficult to interpret in terms of manufacturing tolerances and manufacturing requirements, and details of drawings will better provide this manufacturing information (tolerances and requirements).

5. Spend the time early in the program to develop a realistic budget margin

It became more and more apparent as the program progressed that very detailed and well thought out planning had gone into the initial (and revised) overall budget. Sufficient margin consistently appeared to be present as difficulties and complexities arose, requiring more resources. Budget and definition is almost always a challenge and expending substantial effort early in the program to allow for anticipated margin can be a strong deciding factor in the program's success and the system's ultimate performance margin. The FS RoCS did not have a strong heritage and historical precedence, and thus necessitated thorough planning to account for additional design, development, test and engineering that would be required. Finally, when developing the budget margin, be sure to thoroughly assess the available skills base and factor in any needed variations to account for available resources and capabilities.

E. Development Testing

1. Utilize a strong in-house test program to facilitate the generation of component specifications, flesh-out system design issues, and anchor analytical models – place an early emphasis on "Test like you fly, fly like you test"

For components where there is limited heritage consider parallel development paths. Especially for the RoCS, for which there was little historical precedence for a similar system, parallel design paths were pursued on higher complexity components like the series-redundant thruster valve and high pressure GHe regulator. If the experience base with the selected technology or approach is limited, it is worthwhile to develop tools through development testing.

A series of advanced development and formal development test programs were pursued to improve the fidelity of the early component and system designs, facilitated thorough the anchoring of analytical models to data using flight-like components. Development programs included:

- ***Advanced Development Hardware (ADH) Testing -*** Critical components were identified early and a test program was put in place to work with component vendors to build flight-like designs, based on top-level "fly-sheet" requirements, and test at MSFC. For RoCS the GHe regulator and series-redundant thruster valve were identified as the most critical components and multiple sets of respective designs (4 regulator designs and 2 valve designs) from different vendors were designed, built and tested. For ReCS the series-redundant thruster valve was deemed most critical and three separate vendor designs were built and tested to help identify design constraints for the flight designs. This work was conducted prior to PDR and greatly contributed to the development and generation of the detailed component specifications.
- ***Vibration Test Articles –*** Due to the unique configuration of the Ares I, the predicted vibration and shock environments were relatively high compared to other manned launch vehicles. The selection of monopropellant architectures for the RoCS and ReCS systems led to particular sensitivities for the thruster designs, which rely on a somewhat brittle catalyst to generate thrust. This lead to various design features that were implemented into the system designs to reduce the vibration levels to the thrusters, which the catalyst would ultimately experience. Such features included the use of elastomeric vibration isolators at the thruster module level, propellant manifold line routing that minimized loads into the thrusters, and high-temperature flexible closeouts that attached from the thruster nozzles to the fairings. Separate RoCS and ReCS thruster module vibration test articles were manufactured, following as close to the flight designs as possible. They were then subjected to predicted flight random vibration and shock levels on vibration

shaker tables at MSFC, per the test setup shown below in Figure 5. Test results demonstrated that the vibration isolation features would be sufficient to maintain levels at the thrusters similar to the vendors' maximum heritage experience.

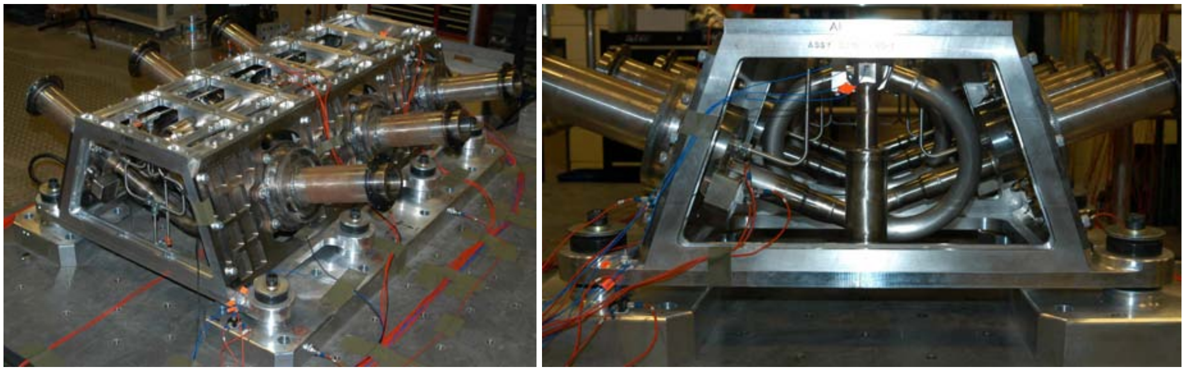

Figure 5. Thruster module vibration test article for FS RoCS on a vibration shaker table at MSFC

- ***Thruster Prototype Development –*** Very early in the decisional process to select a monopropellant Hydrazine architecture over a bi-propellant architecture, it was decided to perform a proof-of-concept test for the FS RoCS thruster. The primary rationale for the test was that there was very little historical precedence for a pulsed Hydrazine thruster at the intended flowrates. The Marshall Roll Control Thruster (MRCT) program was therefore conducted in 2006, and upon completion and demonstration of feasible pulsing using a relatively large Hydrazine thruster, the decision was made to baseline the monopropellant RoCS architecture. Following the MRCT program the RoCS Advanced Prototype Thruster program was put in place to optimize the MRCT design for pulsing operating, high vibration levels, and integration of a series-redundant valve design. This program concluded with the successful development and testing of a thruster suitable for the demanding environments and mission requirements of the FS RoCS thruster, as shown below in Figure 6.

Figure 6. Vibration and hot-fire testing of the prototype FS RoCS thruster

- ***System Development Test Articles (SDTA) -*** Full-scale system representations, using very similar volumes, materials, and layouts to the flight tanks and manifolds, incorporating components specifically designed for RoCS and ReCS, from the preceding component Advanced Development program were incorporated into the RoCS and ReCS SDTAs. Both test articles, as installed in the test stands at MSFC, are shown below in Figure 7. Helium was used as the pressurant along with water to simulate the propellant. Testing encompassed integrated system performance across a broad range of duty cycles, a variety of simulated mission profiles, and multiple simulated failure scenarios. See References 5-9 for more detail on the Ares I RCS SDTA programs. SDTA's can be expensive, but if implemented into the program very early can save significant cost later in the program if issues arise and redesign / rework is required. Typically the most complex and difficult to predict interactions occur at the integrated system level, and the more testing that can be done to identify the system sensitivities early on, the less likely costly needed redesign will be discovered farther along in the design cycle. Early integration of the system analysts during the test-planning phase is crucial. The analysts were integral in the design of the test articles, definition of the test procedures, and test and checkout on the test stand. The close familiarity with the test articles allowed for rapid modification of the test matrices and reconfiguration of the test articles based on test results. This approach minimized costly down time on the test stand and maximized the usefulness of the test articles and impact on the flight designs, including benchmarking of analytical models.

Figure 7. FS RoCS SDTA pressurization system and thruster module (left and middle) and ReCS SDTA thruster modules (right) at MSFC

2. *Other best practices used and lessons learned during the FS RoCS and US ReCS SDTA test programs:*
   - Insure the use of localized filtration to protect sensitive and critical components
   - Specify the inclusion of daily, in-place calibration (also known as "shunt" calibration) into the requirements for the Data Acquisition and Control System (DACS). This can greatly reduce down time to verify instrumentation over multiday / week / month test programs.
   - The ability to rapidly turn around data from the DACS to the Test Requestor, during long continuous test programs is important for tracking the real-time completion of test objectives
   - Specify response characteristics of instrumentation in fast-acting systems to avoid interference with test article harmonics
   - Specify accuracy of instrumentation and/or intent of measurement with test facility to insure selected instrumentation can satisfy objectives
   - Design test schedule to be flexible in order to deal with problems as they arise and not result in lengthy schedule delays
   - Schedule repeated data reviews throughout testing, even if you can only afford short review periods, to minimize the amount of re-testing or uncompleted test objectives
   - Maintain and update a sequential test log and include any daily notes / observations. It is much more difficult to recall after the fact and best done while results and observations are fresh in your memory
   - Insure early pre-coordination with Safety and Stress / Structural organizations to avoid lengthy schedule delays for required detailed assessments
   - Make sure all development hardware has well documented prior test history, material properties, operational constraints, etc. For limited life item components, be sure to accurately track cycles and usage conditions
   - As much as is feasible, arrange test matrix in groupings of hardware changes to minimize the required number of changes
   - The number one issue with planning a test, especially when pressurized vessels are involved, is safety. Safety protocol must be implemented into test procedures early, because test article access may be limited when the system is pressurized.
   - Real time data collection should be reviewed by a system analyst to ensure that data on ensuing tests is acceptable.
   - When troubleshooting one issue, be aware of additional issues and work in parallel if possible.

- Include voltage measurements when trying to understand solenoid valve performance criteria.
- When troubleshooting, communicate to key stakeholders the reasoning behind each new action.
- Identify all expectations to the test conductor up front and in writing to prevent miscommunication.
- Ensure that all technical advisors are involved during the planning phase to provide input before testing begins. Provide adequate time for advisors to review test plans.
- Prepare contingency plans to continue the testing flow with alternate test sequences should data results differ from what was expected. The SDTA configuration allowed for multiple test configurations for various areas of the system. If an issue were to arise with a particular measurement or set of data the test procedure could be altered to continue testing on a different area of the system while the unexpected data was reviewed.
- Document, Document, Document! An enormous amount of useful data can be recorded, but test conditions and procedure changes must be documented in order to understand and utilize the data. Prior to testing clear and organized documentation prevents miscommunication between the test facility and the test requestor.

III. Boeing Producibility Best Practices

A. Scope

The Boeing Company was selected by NASA on August 28, 2007 to be the contractor providing manufacturing support for design and construction of the Ares I Upper Stage (US). This put into motion the Ares I Upper Stage Production Contract (USPC), which resulted from a full and open competition with a period of performance beginning September 1, 2007 through December 31, 2016. Boeing was tasked to provide support to a NASA-led design team during the design phase with responsibility for the production of the Ares I US. This including the manufacturing of a ground test article, three vehicle flight test units and six production flight units to support NASA's flight manifest through 2016. Final assembly of the US would have taken place at NASA's Michoud Assembly Facility (MAF) in New Orleans, Louisiana.

B. Source Control Items

In support of the FS RoCS and US ReCS NDT, Boeing began a source selection process with vendors for all components, also known as Source Control Items (SCIs), specified by the NDT for each system. The vendors for each component were selected by Boeing and put onto contract to begin development of each SCI using the provided SCI specification. Using the design information provided in the SCI specification, the vendors began the necessary Design, Development, Test and Evaluation (DDT&E) needed to meet the requirements. Upon, completion of the flight development phase, the SCI flight qualification phase was planned to begin and a full shipset of each FS RoCS and US ReCS SCI was planned for delivery to the NDT for use in the subsystem environmental and full system level hot fire qualification testing.

Boeing was responsible for the following specific roles in the development of the FS RoCS and US ReCS SCIs:

- The design, development and/or procuring, qualification and certification of each SCI while providing the NDT insight for all SCI DDT&E.
- The hardware required to manufacture, assemble, checkout, and test all FS RoCS and US ReCS integrated test articles, simulation of test article operation including SCIs commanded by the US Avionics system, and the flight units.
- Providing inputs aiding the NDT in the development of the SCI specifications.
- Maintaining the configuration control of all SCI specifications and related interface documents.
- Providing certification data for all FS RoCS and US ReCS SCIs.
- Ensuring verification of all SCIs are conducted in accordance with the US Verification and Validation Plan (USO-CLV-SE-25703).

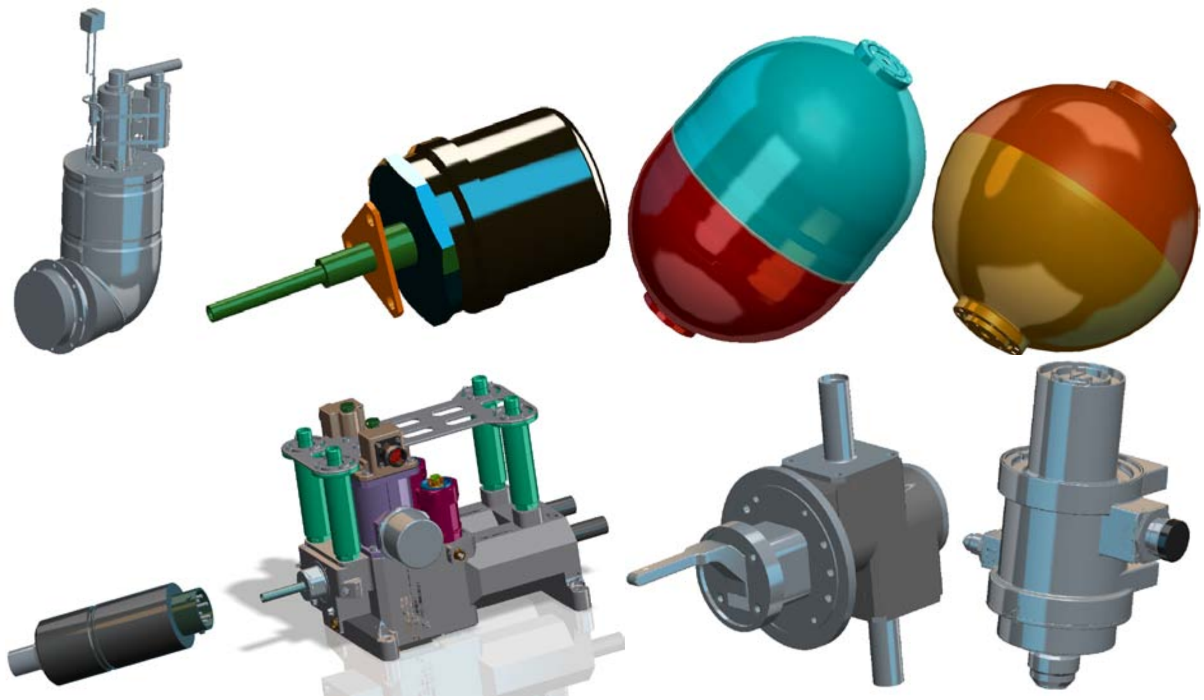

Figure 8. CAD representations of the various RoCS and ReCS components. Clockwise from the top left: US ReCS thruster assembly, service valve, RoCS propellant tank, ReCS propellant tank, RoCS BDRV assembly, RoCS GHe manual valve, RoCS GHe pressurant module, and manifold pressure transducer

C. Producibility, Manufacturing And Test Support

The other primary role that Boeing played in support of the FS RoCS and US ReCS NDT was in the areas of producibility, manufacturing and test. Boeing was well suited to support the NDT in these roles based on their vast knowledge of producing large scale products such as commercial airplanes, military aircraft, satellites and rockets. Weekly meetings were held focusing on producibility of both the FS RoCS and US ReCS in an effort to streamline their designs, making them easier to manufacture and more affordable to assemble and test. Specific focus was place on the details of how each system would be assembled, which included taking into account the total number of welds, tubing bends and fittings used attempting to make these areas lean. To further support this work, Boeing, applied knowledge gained from the Space Shuttle and Delta programs in an attempt to drive down unnecessary touch time and cost.

Boeing was responsible for the following specific roles related to the producibility, manufacture and test support of the FS RoCS and US ReCS:

- Providing producibility engineering support to the FS RoCS and US ReCS IDTs through participation in the design and development process.
- Participating in the design and development process of the FS RoCS and US ReCS, including: development of analytical models, development of CAD designs which define the subsystem/vehicle/SCI interfaces, maintenance of subsystem requirements documents and subsystem development plans and supporting documents.
- Providing inputs to the NDT via a series of Technical Interchange Meetings.
- Manufacture and assemble the FS RoCS and US ReCS Hot Fire Test Articles (HFTA) in accordance with the NASA design. Deliver HFTAs to the NDT for testing of all components along with both test articles.
- Manufacture and assemble the FS RoCS and US ReCS Thruster Module Qualification Test Assemblies in accordance with the NASA design. Deliver both Thruster Module Qualification Test Assemblies to the NDT for testing.

D. Task Orders

Over the course of the Ares I program, Boeing was requested by the NDT to performed additional technical work in support a variety of goals that the NDT did not have the manpower to complete in a timely manner. The process used to complete this technical work for the NDT was called task orders. Task orders included specific technical direction that bounded the work Boeing was requested to complete in the scheduled timeframe. Requested NDT task order direction included the following detailed work:

1. FS RoCS and US ReCS Component And Verification Assessment

Assessments of component verification early in a propulsion system design provide a significant head start in the verification process, which often is an area that lags behind on programs. A component survey was performed to assess the feasibility of component procurement for the Ares I program. Request for Information (RFI) packages were released for all SCI components to evaluate overall design feasibility, identification of specification requirements that carry significant technical risk or verification difficulty, identification of heritage hardware that might be used to reduce development cost or risk, and the feasibility of the Boeing hardware delivery schedule required to meet key NASA milestones. Draft NASA specifications accompanied the RFI packages in order to gain valuable feedback on the requirement and verification sections in an attempt to help the specification authors produce a cleaner product. In general, all of the SCI's were considered feasible with the exception of the Burst Disk/Relief Valve and the Helium Regulator. The concern with these two components was that some tolerances were excessively tight, with the burst disk being the worst.

Both of these issues have been brought to the attention of NASA, and Boeing and the NASA ER33 Component Group have been working together to adjust the tolerance bands of the regulator-burst disk-relief valve system within the limitations of the system design to alleviate excessive development risk. This effort is improving the tolerance range, but is still on-going. The other remaining system components were all considered feasible with a typical level of effort in-line with components used in past manned flight applications. Numerous comments were provided, but there were no requirements that were considered a significant risk of technical failure. Evaluation of heritage hardware potential was difficult. Due to the unique launch environments, high flow rates and system pressures, it was difficult to identify existing components that met the Ares I requirements. The SCI with the highest likelihood of heritage commonality are the Service Valves, Helium Tank and the Upper Stage Propellant Tank. Most suppliers indicated that a heritage design would likely be a starting point for the Ares I component, and this could potentially result in schedule and cost savings, although the impact will likely be minimal.

Finally, Boeing support was provided to assist in the definition of verification methods for all subsystem requirements. Tasks accomplished included:

- Populated verification methods (Analysis, Demonstration, Inspection, and/or Test) in both the FS RoCS and US ReCS Subsystem Design Specifications Verification Cross Reference Matrices (VCRM).
- Populated sections 4.2 through 4.4 of the two subsystem specifications with verification objectives and identification of success criteria,
- Developed an excel spreadsheet that will be used as a preliminary tool to further mature both the subsystem and component verification methods, definition of verification work to be performed, and the success criteria that determines when the verification is complete.

Completion of the above tasks has afforded the NDT with a significant head-start in the verification process which on other programs has often been an area that lags behind. Identifying verification methods, objectives, and success criteria early in the program can only help reduce the chances of costly "I-forgots" in terms of dollars and schedule. Then Boeing conducted a line-by-line, requirement-by-requirement review to determine if each requirement was verifiable and if the verification methods and statements were adequate. A sit down, face-to-face meeting was then conducted with each NDT responsible engineer to redline the component specifications resulting in a significantly improved specification in terms of both the section 3 requirements and section 4 verification requirements.

2. FS RoCS and US ReCS Thruster Module Assessment

Early design producibility assessments have the potential to reduce propulsion system weight, number of parts, cost, production schedule along with assembly time and checkout tests. This report presents the analysis products of an Integrated Product Team of Aerodynamics, Aero-Acoustics, Aeroheating, Plume Heating, Thermal, Dynamics, Loads, Stress, Design, Materials & Processes (M&P) and Propulsion disciplines which assessed the FS RoCS thruster module design to develop PDR design tools, provide design assessments, and provide recommendations to the baseline and alternative concepts that reduce flight environments to the propulsion hardware. The Aerodynamic effort established efficient CFD models, which demonstrated similar results with respect to the NDT baseline fairings and has assessed alternate fairing shapes which offer the option of reducing the protuberance Overall Sound Pressure Level (OASPL). Wind tunnel test data was unavailable to validate the specified protuberance OASPL; therefore, an alternative approach, which entailed the application of Space Shuttle OMS Pod OASPL data, was applied to various fairing shapes and relative locations to present potential improvements in thrust module random vibration levels. A Boeing analytical methodology was applied for deriving reduced SPLs and iterations on fairing shapes indicated that improved random vibration levels to the propulsion hardware were possible.

The Aerothermal effort assessed the ascent flight trajectory and the worst case mission duty cycle to develop both aeroheating and plume heating environments for the RoCS and ReCS. These two efforts developed working models that provided a comparison to the NDT results. The aeroheating and plume heating environments for simultaneously firing thrusters were integrated based on the worst case mission duty cycle and provided for selected regions on the fairing and thruster close-out. Results revealed that the heat fluxes had the least sensitive design concerns on the thruster module relative to the random vibration environments. Recommended analyses for CDR, such as the use of wind tunnel and flight test data, were defined to assure the maturity of the results will mitigate any potential temperature violations on the fairing and thruster close-out.

Thermal modeling of the fairing structure, nozzle close-out, fairing close-out, frame structure and propellant line layout have been developed for the thruster modules. The aeroheating and plume heating environments and ablation techniques are applied to determine the peak temperature distributions on each fairing concept. Worst case temperature distributions and critical hot spots on the fairings are provided. At this time, no temperature violations have been identified. Recommendations are made to further mature the PDR results and to finalize the recommended heat flux levels that should be applied to the forward module insulation to assure that no other potential heat fluxes could cause appreciable temperature increases that may violate requirements. The establishment of these models provides the NDT with independent analytical tool to support the integrity and fidelity of the Thruster Module design from PDR to CDR.

The Dynamics and Load analysis effort utilized OMS Pod OASPL measured data and alternate fairing sound pressure level reductions to derive reduced random vibration levels at the base plate location. The analysis tool for this effort was the Statistical Energy Analysis (SEA) technique applied to the Hybrid DAC2 Model. Alternative Fairing attachment concepts were identified which changes the flow of random vibration energy resulting in reduced random vibration levels at the baseplate and to the propulsion hardware. Use of the SEA demonstrates reductions in random vibration levels over the NDT technique; however, reductions in the OASPL may not be fully realized as random vibration reductions due to the increase in alternate fairing surface area. Recommendations are to iterate on a fairing shape that defines the SPL reduction vs. increased surface area threshold to realize additional potential improvements.

A hybrid SEA model was used to assess the shock environment due to the interstage separation event. The model predicted good agreement with results from traditional empirical approaches. The model allows response recovery at specific internal locations within the RoCS and ReCS Thruster Modules. The use of constrained layer damping treatments on the fairings was investigated for reductions in the transmissibility of random vibration environment. The results indicate that significant response attenuation can be achieved through the use of specific treatments. Various isolation concepts were identified for attenuating the response at the RoCS and ReCS Thruster Modules. Two candidate isolator parameters are recommended that can help to resolve the conflicting requirements of isolation performance and the required thruster pointing accuracy.

The Stress Analysis effort began with Finite Element Models of the propellant line and thrust module structure supplied by NDT. Alternative design concepts for the thrust framing and propellant feed line routings have been explored. The team has evaluated a concept, developed a model, developed element loads and deflections as a first step in performing detail analysis. A comparison study between isolators at the thruster interface and at the baseplate interface was also performed. Results of the study indicate reduced flow in energy to the thruster, if the isolators are mounted at the baseplate interface to the interstage. The evaluated design concept shows positive margins for both the thrust module and feed line assemblies. Further detailed analysis is required to size the hardware.

A design and manufacturing assessment was performed on the baseline concept. This effort involved evaluation of the NDT CAD models and involved the analysis of the proposed design for production of subassemblies and integration of module hardware. Recommendations that enhance production of the assembly have been provided which includes alternative concepts. Specifically, in the design of the propellant manifold, several options, which assist in meeting system requirements, have been recommended. In the area of the fairing design, recommendations are offered which reduce random vibration levels on the hardware. For the engine closeout, reduction of part count and recommendations on final assembly are suggested. Forward planning is recommended in order to address the realization of reduce random vibration levels.

The integrated thermal assessment for the RoCS and ReCS presents resolvable design concerns; however, recommendations to deliver better performance are identified. The available NDT aeroheating and plume heating environments have been evaluated as satisfactory, but there are still sections of data missing, such as RoCS and ReCS plume radiation heating and J-2X and USM plume heating environments. These are recommended as forward work. Once these elements are provided, a comprehensive set of aeroheating and plume heating environment assessments can be completed with additional recommendations to improve the RoCS and ReCS design.

For the FS RoCS, a material assessment of the close-out considered Nextel/Saffil and Nextel/Dyna-flex combinations; the thermal material assessment revealed similar properties. As a result, Nextel/Saffil combinations were analyzed. The temperature limit of the Nextel/Saffil closeout material was not exceeded (< 2600 oF). Analysis of the thruster can without internal insulation revealed this is not a feasible option: the worst case conditions predicted a maximum temperature of 1722°F. At this stage of the analysis, the insulated Thruster Can exceeds the Can limit of 350 °F (~ up to 1455°F). These temperatures occur near the closeout. Additional gridding of the Thruster Can will assist the mitigation of the limit violation. With a maximum interface temperature of 120 ºF at the Fairing Close-out, a perform seal around the fairing interface with the interstage structure will prevent hot gas from entering the module during flight, maintain ambient conditions inside the module and prevent temperature violations.

The ReCS thruster module closeout design effort concluded that Nextel 312 (fabric-ceramic fiber 312) and Saffil (fibrous alumina-silica batting material) can be used to prevent high temperature thruster exhaust gases from entering the fairing cavity at the thruster nozzle penetration point. To prevent hot gases from entering the fairing module at the base plate intersection, Room Temperature Vulcanizing Elastomer (RTV-560) can be applied at this junction. An area of concern is the interface of the fairing structure and the thruster nozzle close-out. The fairing has a relatively low limit of 120°F, and the nozzle exterior interface can exceed 500°F. A comprehensive thermal model was developed with inputs from the above mentioned fairing and thruster analyses to perform the ReCS thruster fluid line analysis. The analysis determined that no fluid propellant lines exceeded their allowable upper temperature limit. Some component temperatures are near their maximum allowable upper limits, and if any changes are made to the external environments that exacerbate the overall thermal response of the ReCS, some issues may arise.

A comprehensive thermal model was developed with inputs from the above mentioned fairing and thruster analyses to perform the RoCS thruster fluid line analysis. The analysis determined that no fluid propellant lines exceeded their allowable upper temperature limit. Some component temperatures are near their maximum allowable upper limits, and if any changes are made to the external environments that exacerbate the overall thermal response of the RoCS, some issues may arise.

Thermal modeling of the fairing structure, nozzle close-out, fairing close-out, frame structure and propellant line layout have been developed for the thruster modules. The aeroheating and plume heating environments and ablation techniques are applied to determine the peak temperature distributions on each fairing. Worst Case Temperature distributions and Critical Hot Spots on the fairings are provided. At this time only a minor temperature violation of the ReCS thruster module top wall has been identified. Recommendations are made to further mature the PDR results and to assure that no other potential heat fluxes could cause appreciable temperature increases that may violate requirements. The establishment of these models provides the NDT with independent analytical tools to support the integrity and fidelity of the Thruster Module Design from PDR to CDR.

As a result of this investigation, the Boeing Team has established the technical knowledge base and modeling tools to further mature the potential benefits identified in this report. It has embarked upon the detailed analysis that will allow the NDT team to realize potential vehicle performance benefits and/or pursue alternate design recommendations. The current analytical tools are available to perform independent assessments of N_2H_4 Propellant Lines, Fairing-to- Nozzle Close-Out, Fairing-to-Interstage or Thrust Cone Close-Out, and Fairings. The objective of this assessment has been to reduce the energy transmitted to the propulsion hardware and to identify alternative design solutions that reduce weight, numbers of parts, cost, production schedule, assembly time and checkout tests.

3. FS RoCS and US ReCS Fairing Closeout Trade Study

The final closeout between the thruster and the external surface of the vehicle may require a unique design implementation, and its design should not be neglected in the early design phases. In support of the NDT, Boeing was asked to conduct a trade study that identified preliminary Fairing close-out concepts for study along with an evaluation of candidate material options. After evaluation of material used in high temperature applications (~2600 °F), three materials (BF20 (Nextel 440), AF20 (Nextel 312) 3M Products, and a Boeing AB 312) along with two close-out design concepts were considered. Materials BF20 (Nextel 440) and AF20 (Nextel 312) are commercial low cost type fabrics while AB 312 is a Space Shuttle custom weave heritage fabric. Concept 1 is a simplistic thermal fabric applied across the close-out opening which was considered with a draped feature to provide the compliance needed for the relative motion between the fairing and the Thruster nozzle. Concept 2 is a combination of an alumina fiber (Saffil) insulator wrapped within a Nextel Fabric blanket to provide a thermal barrier. The draped feature was also considered for concept 2 to provide the needed relative motion compliance. Next, these options were compared against the following criteria:

- Safety
- Operability
- Programmatic
- Technical

Utilizing inputs from a supplier, lessons learned from a prototype blanket found in Figure 9 along with thermal and structural analyses it was concluded that:

- TPS is required at the fairing close-out interface to limit the fairing temperature below 120 °F.
- The highest close-out surface temperature exhibited on RoCS and ReCS concept 1 was 1714 °F/765 °F, respectively using AB 312.
- The highest close-out surface temperature exhibited on RoCS and ReCS concept 2 was 1941 °F/875 °F, respectively using AB 312.
- Strength analysis showed two layers of either Nextel 312 or 440 (minimum 0.02" ply thickness) will be required to meet the worst case pressure loads of -7±2 psid Crush to +10±2 psid Burst.
- If a two-edge constraint attachment feature is considered with a single fabric, a 0.23" to 0.40" of Nextel material would be required for the RoCS/ReCS respectively.
- To address the current deflections between the fairing and nozzle, the close-out blanket will need to be flexible enough to provide the required compliance.
    - The RoCS compliance required are 0.313” lateral and 0.393” axial.
    - The ReCS compliance required are 0.172" lateral and 0.234" axial.

Figure 9. Prototype of Saffil Wrapped with Nextel (Donut Concept)

The thermal performance for AB312 was determined to not be better than Nextel 440 while its manufacturing cost and schedule was also expected to be much greater than Nextel 440. Based on the high FS RoCS surface temperatures (~1941 °F) and the fact that the Nextel 440 fabrics have greater strength retention than the Nextel 312 fabrics, it was determined that the Nextel 440 (3M BF20) would be the best choice material in a loose/draped blanket concept. This conclusion is based on a two-edge constraint concept which can limit the relative motion between the fairing and nozzle. Due to this finding, a single edge constraint option with the appropriate thickness for strength can be considered for a future close-out design study. This feature will allow relative motion between the nozzle and the fairing and will meet the required compliance.

Also, the single edge constrain option will required a compressive fit feature and will require a stiffness to determine a minimum load transmission to the nozzles. It should be noted that, as the Nextel material thickens, the flexibility required to meet compliance diminishes. Because the deflections are preliminary, the two candidate options were recommended for study to address compliance/flexibility vs. transmission of load to the nozzles. The thermal and compliance performances are heavily dependent on configuration, and, therefore, a correct material with proper designs would be able to resolve the thermal and compliance requirement.

4. FS RoCS and US ReCS Fairing Material Trade Study

Material trade studies based on appropriate Figures of Merit can result in the implementation of the best design material needed. A Fairing material trade study was conducted involving various metals (Aluminum, Titanium, Inconel, and AlBeMet) coupled with several fabrication process options along with the use of a composite as a separate material of choice. The trade study had primary Figures of Merit (FOM) that included Safety (10%), Programmatic (40%), and Technical (50%). Based on the initial weightings in the trade study analysis tool, which favors the mass measure FOM at 35%, the composite material would be the material of choice as noted in Table 1 (109%), Baseline Option.

Table 1: Baseline Material Option Result

Material and Fabrication Process Alternatives Scores								
	Machined Aluminum	Assembled Aluminum (Baseline)	Cast Aluminum	Assembled Titanium	Cast Titanium	Albemet	Composite	Conclusion
Baseline 4-16-09	90	100	103	85	77	72	109	Composite #1 Choice Assembled & Cast Al Close 2nd

It should be noted that this result assumes the following:

- The material database is well established and released for the choice of composite fabric, there will be no impact to the design and/or drawing release dates due to material property data not being well defined. The material database will affect the margin carried forward into the final design and thus affect the weight savings.
- A path forward to address the lightning strike requirement is in place.
- A path forward to address the ascent debris impact requirement is in place.
- A path forward to address the Proof Load test requirement for composites is in place.

Without these paths clearly identified and the issues resolved in time to meet schedule, the use of an all composite fairing would not win out in the baseline study. This is identified in Table 2 below as an option that drives risk as a critical factor.

Table 2: Emphasis on Risk Result

Material and Fabrication Process Alternatives Scores								
Parameter Changes	Machined Aluminum	Assembled Aluminum (Baseline)	Cast Aluminum	Assembled Titanium	Cast Titanium	Albemet	Composite	Conclusion
Baseline 4-16-09	90	100	103	85	77	72	109	Composite #1 Choice Assembled & Cast Al Close 2nd
Least Technical Risk Study: Weighting Changed in Technical to favor Risk: 35% Mass/6% Structural/6% Producibility/ 3% Risk to 3% Mass/6% Structural/6% Producibility/ 35% Risk	90	100	101	118	109	54	91	Assembled Titanium #1 Choice

The reason Titanium ranks better on risk is because of its resilience to strength, temperature and fabrication processes established. Should the ascent debris requirement govern, the titanium will out rank composite and aluminum in strength and impact. In addition, the fabrication processes for Titanium are less forgiving to impact damage.

Parametric trades driving either Programmatic and/or additional Technical FOMs were also performed to understand the sensitivity of the material choice to these measures. Results indicate, that as Programmatic measures vary, the use of a composite material is still the preferred choice, except for the case where additional costs get added for

In general, the three following conclusions can be drawn from the trade study:

- From a producibility standpoint, the ReCS and RoCS Fairings can be made by most of the materials studied and can be fabricated in the time frame desired.

- From a cost standpoint, the ReCS and RoCS Fairings can be made competitively by the assembled aluminum sheet metal using aluminum casting methods. The Fairings can also be made of composites competitively by composites suppliers.
- From a schedule standpoint, most of the fabrication processes for both Fairings can be met if ordered within 14 months.

Additionally, the NDT might want to consider the following options.

- A "Hybrid" fairing that produces the leading edge out of Titanium and the remaining structure out of composites. This would provide the lightest weight option with the best structural resilience.
- Producing the ReCS and RoCS fairings from different materials since each fairing has a specific value on the Mass to Orbit calculation carried at the vehicle level.

In summary, if weight is driving the material selection process (as assumed in the baseline trade summary results), the composite material option is the most favorable choice, if the least cost approach drives the material selection process then the Cast Aluminum is the most favorable choice, if structural resilience (impact resistance) drives the material selection process then Titanium is the most favorable choice. Other NDT considerations can drive the selections as well, depending on the relative importance of any one weighted measure. The measures presented in the report provide the directed response need to make the material selection given the relative importance of each of the weighted measures. With the NDTs input into the relative importance of the weighted measures, a favorable material choice can be made.

5. US ReCS Crowned Fairing And Close-Out Preliminary Assessment

Following US ReCS PDR, the NDT requested that Boeing review the Fairing design and provide a recommendation regarding material, shape, manufacturing and assembly. Based on the review, Boeing provided a recommendation that the Fairing should be made of Aluminum SP2195-T5 while also being crowned. Detailed analysis showed that the crowned aluminum fairing concept is superior to that of the o-give configuration previously analyzed in terms of being lighter along with its curved shape providing additional stiffness. The drawback to the design is that the shape of the crowed Fairing can complicates the close-out geometry and design relative to the thruster nozzles.

The crowned Fairing concept was analyzed for its impact to aero-heating derived loading conditions, aero-dynamic derived loading conditions and then assessed structurally against the new environmental loading conditions. The structural analysis of the crowned Fairing concept has shown that for the combined loading cases of enforced deflections, accelerations, and aero-dynamic pressures the design maintains positive margins in all categories (buckling/stability, stress, and deflections) using prototype factors of safety. A thermal knockdown in material allowable was used when writing margins with the maximum thermal knockdown temperature assumed to be 120 °F. This is lower than the specification value of 150 °F but is consistent with the time frame at which the maximum pressure occurs. Boeing believes the crowned Fairing concept is ideal for this application and recommends using super plastic forming as the manufacturing process. Additional detailed analyses of the side panels, mechanical close-out parts, and fastening features used throughout the design will need to be evolved and analyzed to complete the design process.

E. Best Practices

One of the biggest lessons Boeing learned from supporting the Ares I FS RoCS and US ReCS NDT is the importance of focusing on affordability throughout the duration of a program. The best way to accomplish this is to make affordability a priority from the beginning of a program. A key way of implementing this is by clearly defining the program's performance requirements early with all parties in agreement. With the program requirements understood and agreed to, the team can work together to create a design that meets performance requirements and minimizes cost without sacrificing safety. Efficiency must be a priority to everyone who is a part of the program and should be included in our every day process and hardware design choices. The following recommended best practices should help ensure affordability plays a key part in future launch vehicle propulsion designs:

- Goals should be common across the program.
  - The following items should be considered in the order listed: safety, cost, schedule and performance.
  - Consider locating key team members, such as designers, system engineers, analyst, manufacturing engineers and test engineers together to build an effective team and ensure that affordability it a key driver.
- Make all IPT boundaries efficient, where communication and support is not limited to individual groups, but is program wide. Drive synergy across IPT boundaries – efficiencies should be program wide not limited to individual groups
- Before procuring hardware clearly defined all requirements, especially key environments that can drive suppliers away from heritage engineering approaches and methods.
  - Traceable to upper level requirements using a requirements database such as CRADLE or DOORS
  - Standard method for evaluating Requests For Information (RFI) data and applying a correction factor to account for fidelity of data to avoid underestimation of costs
- Defined an executable schedule at the beginning of the program.
- At the beginning of a program key processes should be defined and in-place.
  - Also, the ability should be in place to quickly change any processes that are not meeting the required performance.
- Develop standard Supplier Statement of Work (SSOW) template, which allows custom tailoring based on specific application
  - Detailed Tailoring Guide that provides rationale for requirements as well as rationale to help guide authors to properly tailor
  - Detailed review process for SSOW release that ensures tailoring was properly performed

IV. NASA-Boeing Team

Traditionally, the Prime Contractor (the NDT in this case) has the leverage to make design changes and directly affect the contract of the component suppliers. In this instance, Boeing served as the liaison between the Prime and the vendors, and thus a more circuitous route had to be taken to flow requirements changes down to the vendors.

1. Recurring producibility meetings were instrumental in developing cost-effective, manufacturable designs

Early on meetings were incorporated that specifically focused on improving the produceability aspects of the RoCS and ReCS hardware and components. These meetings leveraged Boeing's vast corporate experience to apply manufacturing and design methodologies used in other areas such as aviation and satellite design, to the RoCS and ReCS designs.

2. Cost neutral changes were an effective approach to make critical component design modifications while not growing costs

As is the case with many programs, once component vendors are on-contract and in place it becomes more and more difficult to both request and receive new funds, as well as make technical changes without incurring significant cost. This can leave the system design in a difficult place to accept inadequacies and potentially not meet intended performance levels. For Ares the approach between NASA, Boeing, and the component vendors to prioritize design deficiencies and areas of conservative margin, and make give-and-take type changes to the component designs that would ultimately result in cost neutral changes.

V. Conclusion

In summary, there were many best practices used and lessons learned throughout the development of the Ares I FS RoCS and US ReCS propulsion systems that will be applicable to many future programs. This activity was comprised of a non-traditional structure in which the Government led the design and development of the systems and an industry partner, Boeing, was responsible for component selection, procurement, and production. It served as an invaluable opportunity for NASA to regain some of the first-hand design experience that has not be available to government design teams, on a major manned vehicle design, since before the Space Shuttle program.

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