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LESSONS LEARNED IN ARCHITECTING HUMAN SPACEFLIGHT PROGRAMS

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ABSTRACT

This paper discusses the fundamentals of architecting a major human spaceflight program and the lessons that can be learned from Constellation. Constellation is/was NASA's program to implement a new generation of human exploration missions to the moon and beyond. It is/was a tightly-coupled program where a unique set of architectural challenges can be seen and evaluated to better understand how architecting of such systems can be improved upon in the future. While the specific issues discussed in this paper derive from the current Constellation architecture they share threads with previously-crewed systems including Apollo and Shuttle and are likely to be common to any human exploration system or system of significant technical and programmatic complexity.

This paper will describe the fundamentals of system architecture, as seen in the organization of a system, as embodied in its constituent elements, the relationships between elements and stakeholders, the environment and the principles governing the design and the sustainability over time. The foundation and development of the Constellation architecture will be discussed including primary archtitectural drivers such as crew safety, performance, risk, and programmatics. Comparisons to past human spaceflight architectures including Apollo, Shuttle and the International Space Station will be made. The paper will focus on a set of the most significant challenges to creating and sustaining a human exploration architecture. Specific recommendations for developing, communicating and implementing architectures of complex systems will be made.

INTRODUCTION

The Constellation Program (CxP) was proposed for termination by the Administration in their FY11 budget submittal to the Congress. At the time of this writing, elements of the Constellation Program are part of proposed Congressional appropriations language and efforts to develop a new human spaceflight architecture are underway. While Constellation may not continue by that name, many of the architectural lessons and principles as well as design and technology maturation are likely to find their way into the human spaceflight architecture that emerges.

Constellation is developing new space vehicles and support systems which would allow continued American access to low Earth orbit following the retirement of the Space Shuttle. The program would also enable humans to return to the Moon to conduct extended exploration, establish a planetary outpost on the lunar surface and prepare for crewed missions to Mars. The Constellation Program has been phased as a stepwise capability build-up largely based upon Space Shuttle heritage components. [1]

To understand Constellation one needs to think in terms of two broad definitions. The first comes from NASA's Program and Project Management Guidelines, NASA 7120.5D, which defines Constellation as a "tightly-coupled" program. Specifically that definition is a: "Program with multiple projects that execute portions of a mission or missions, in which no single project is capable of

implementing a complete mission." Constellation also meets the definition of a complex "system-of-systems." It is a concurrent development of distributed, independent (in development, management, and sometimes operations) yet interdependent systems whose components are complex systems themselves. It is a system in which emergent, interactive and evolutionary behaviors can and often do show up that are not apparent or discoverable from understanding and/or managing the parts. In addition to the technical elements, technology, policy (politics), and economics are primary contributors to the complexity and implementation challenges.

The development, content and current status of the Constellation architecture derives from specific milestones. These milestones include cataclysmic, technical and political events. The foundations of CxP begin with the Columbia accident on February 1, 2003. This event and the detailed report of its causes directly influenced many of the developers and implementers of the CxP system architecture. In January, 2004 the Bush Administration issued the Vision for Space Exploration. This was the first significant restatement of policy for the direction of NASA since 1996. In March, 2004 NASA headquarters moved to begin their interpretation of the Vision by issuing requests for proposal to industry for a new crew launch vehicle (CLV) and a new crew exploration vehicle (CEV). The contracts were issued to ATK for the first stage of the CLV and Lockheed Martin for the CEV in 2005. In April, 2005 Dr. Michael Griffin was confirmed as NASA's 11th Administrator. Dr. Griffin moved quickly to conduct a comprehensive architecture study and released in November, 2005 the Exploration Systems Architecture Study (ESAS). At the same time as the release of ESAS the Constellation Program was established, managed out of Johnson Space Center with Jeffrey Hanley as Program Manager.

The program is designed with two complementary implementation phases, initial and lunar. The Initial Capability (IC) phase comprises elements necessary to support the International Space Station by 2015 with crew rotations, and includes the Orion Crew Exploration Vehicle, the Ares I Crew Launch Vehicle, the first configuration of a new modular spacesuit, and major new implementations of the supporting ground and mission infrastructure to enable these missions. The Constellation Lunar Capability (LC) builds upon the IC; adding the Ares V heavy lift Cargo Launch Vehicle, the Altair lunar lander, the second configuration of the new spacesuit designed for lunar surface operations and a major new mobile launch platform for the Ares V. Lunar outpost elements and capabilities would follow, including permanent and mobile habitats, rover vehicles, power and communication elements to support a sustained exploration presence from weeks to 6 months. In addition, equipment to perfect in-situ lunar resource extraction and processing techniques (e.g., on-site production of oxygen, propellants, construction materials, etc.) would be developed. In-situ resource utilization is expected to become a cornerstone technology in the human exploration of Mars and other destinations within our solar system.

WHAT IS ARCHITECTURE [3]

There is an evolving understanding of the meaning, nature and application of architecting in the broad discipline of aerospace systems engineering. Drawing from the IEEE Std 1471-2000, as applied to avionics and software systems, a working definition of architecture is that it is: the fundamental organization of a system, embodied in its components, their relationships to each other and the environment and the principles governing its design and evolution. The system in this case is the entire set of flight and ground hardware/software and all the constituent elements, organizations and stakeholders. It is also critical to consider in any system architecture both technical and programmatic constraints and drivers.

Architecture tells why a system is the way it is and how this understanding of the system is to be sustained. Architecture provides guidance as design progresses, its value is in its stability and attention to fundamentals. A sound and robust architecture ensures system integrity. A key aspect of the "goodness" or success of an architecture is its ability to engender designs that meet objectives and satisfy stakeholders over time. This is particularly true for human spaceflight programs that are developed and operated over decades where integrity must be maintained well into the development to assure success.

Architecting links management and systems engineering. It links key stakeholders within a project team and provides the guidance for unifying the technical and programmatic baseline and its implementation. The architecture must also address the objectives of all the stakeholders, some who may have different or even conflicting priorities. Stakeholders will likely share common mission objectives but may have very different views of

success criteria and implementation approaches including programmatic constraints, development strategy, and risk management. Stakeholders from outside the project/program are distinguished by the fact that they have something to gain or lose by virtue of the actions of the project/program. It is vital that we recognize all significant stakeholders.

Fundamental principles are integral to an architecture and guide the design. In engineering, the fundamental principles are the laws of nature and proven designs. In architecture the principles often take the form of heuristics, i.e. commonsense rules. Principles foster order, structure, and elegance. Principles are the basis for architectural integrity and they need to be well-crafted, documented and owned by the team. A good principle is generally well substantiated, clear about applicability and application, without qualifications or exceptions, relatively easy to explain, and the last thing you're willing to give up. Rules of thumb, prescriptive statements, and requirements are usually not good principles. They are a statement of what you really care about.

Architecture ensures that development can progress smoothly by identifying and applying carefully considered principles, rules, and patterns of good design. It establishes workable perimeters within which more detailed decisions can be made with assurance that overall system integrity is maintained. Fundamentally it explains why a system is what it is.

Designs are often confused with architecture. A design is the embodiment of an architecture. Designs address what is to be built and how. Architecture is not a broad brush effort confined to early development. Architecture dictates what possibilities are allowed, while still remaining faithful to stable concepts selected to fulfill system objectives. Architecture is not pictures, block diagrams, lists, or other schematic representations of the design. Architecture focuses on a full accounting of the structure, properties, and models that represent essential characteristics of the system and its environment. Architecture is not requirements. Architecture provides the rationale for requirements, as well as the criteria for allocating requirements and fluidly moving them from one level to the next. Architecture is not fickle, or subject to routine refinement, it provides a stabilizing influence through its well-considered form, expectations, rules, and attention to fundamentals.

ARCHITECTURE DESCRIPTION

To understand the Constellation architecture one needs to understand the principles that are its foundation.

They are derived from many sources and stakeholders including the Columbia Accident Report. While not published officially as such, the authors believe the following are the core principles of Constellation.

1. "Give overriding priority to crew safety, rather than trade safety against other performance criteria, such as low cost and reusability" [7]
2. Meet Loss of Crew (LOC) and Loss of Mission (LOM) performance, based on analysis supported by testing
3. Launch and landing crew survival must be robust
4. Human exploration starts beyond LEO and the moon is a key stepping stone
5. Establish and maintain adequate performance margins across all mission phases (Note: all margins are not equal)
6. Separate cargo from crew and provide significantly more payload than Apollo
7. Utilize heavy lift launch vehicles to maximize long term reliability by minimizing the number of needed launches
8. Minimize gap between end of Shuttle program and new system
9. Maintain and grow existing national aerospace supplier base
10. Minimize lifecycle costs for sustainability based on appropriate, stable funding

The role of principles is that they are used by the architects in making decisions in technical and programmatic trade-offs. In other words, when faced with a technical or programmatic architectural decision, and weighing the relative strengths or weaknesses against competing drivers/metrics, the architect refers to these principles, either consciously or unconsciously, in making the final decision.

The components that implement the Constellation architecture as defined by ESAS are seven projects. They are the Orion (CEV), Ares (Ares I and V), Extravehicular Activity (EVA), Ground Systems, Mission Systems, Altair (lunar lander) and the Lunar Surface Systems (see Figure 1). The transportation architecture for missions to the moon is shown in Figure 2. This architecture follows the basic Apollo approach with the significant difference of using two

launches to deliver the needed payload and crew to achieve the Constellation program objectives.

The cornerstone of the Constellation human space exploration strategy is the Orion Crew Exploration Vehicle. The Orion spacecraft consists of the Crew Module, Service Module, Spacecraft Adapter, and Launch Abort System (see Figure 3).

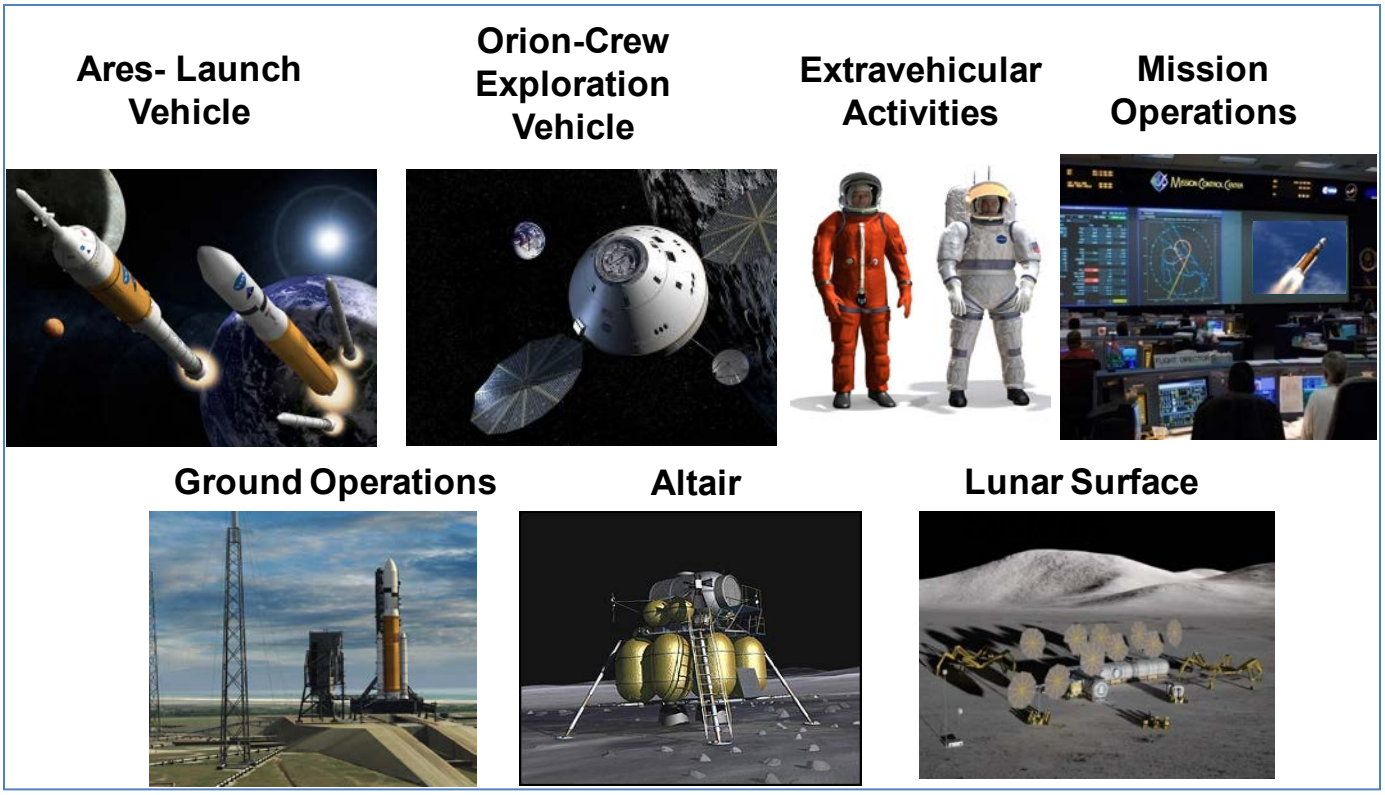


Figure 1: Seven Constellation Projects (Artists' Concepts)

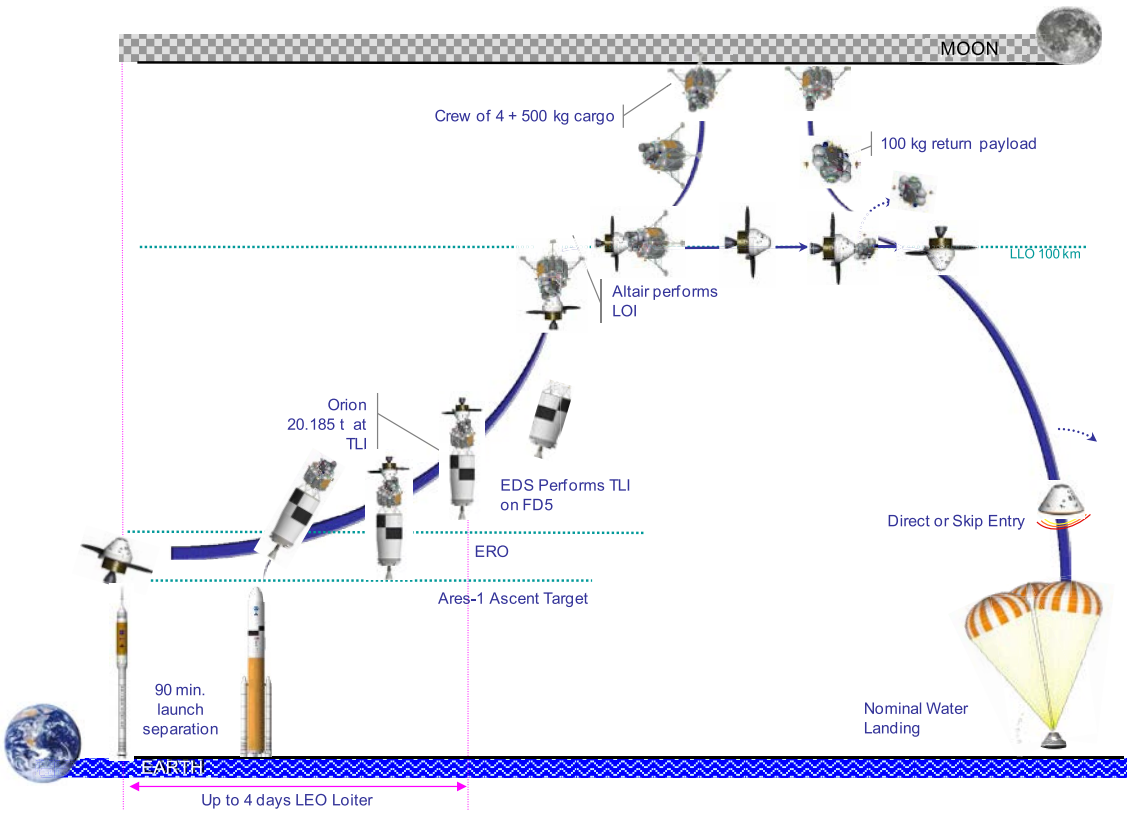


Figure 2: Lunar Transportation Architecture

While reminiscent of the Apollo Command Module (due to the physics associated with atmospheric entry, the overall shape of the Crew Module is similar to that of the Apollo Command Module), the Orion Crew Module is much larger, providing more than twice the usable interior volume and nominally carrying a crew of four, its size is sufficient to carry a crew of six. New features of the Orion spacecraft include a digital “glass cockpit” control system, derived conceptually from the systems used in today’s most advanced aircraft, and the use of high-data-rate, low-weight fiber optic systems. The spacecraft will be able to "autodock" with the ISS using onboard sensors and computers, with provision for the crew to take over in an emergency. Previous American spacecraft (Gemini, Apollo, and Shuttle) have all required manual piloting for docking. The final interior layout of the Crew Module is still being designed, but current ergonomic evaluation and crew area layout is shown in Figure 4.

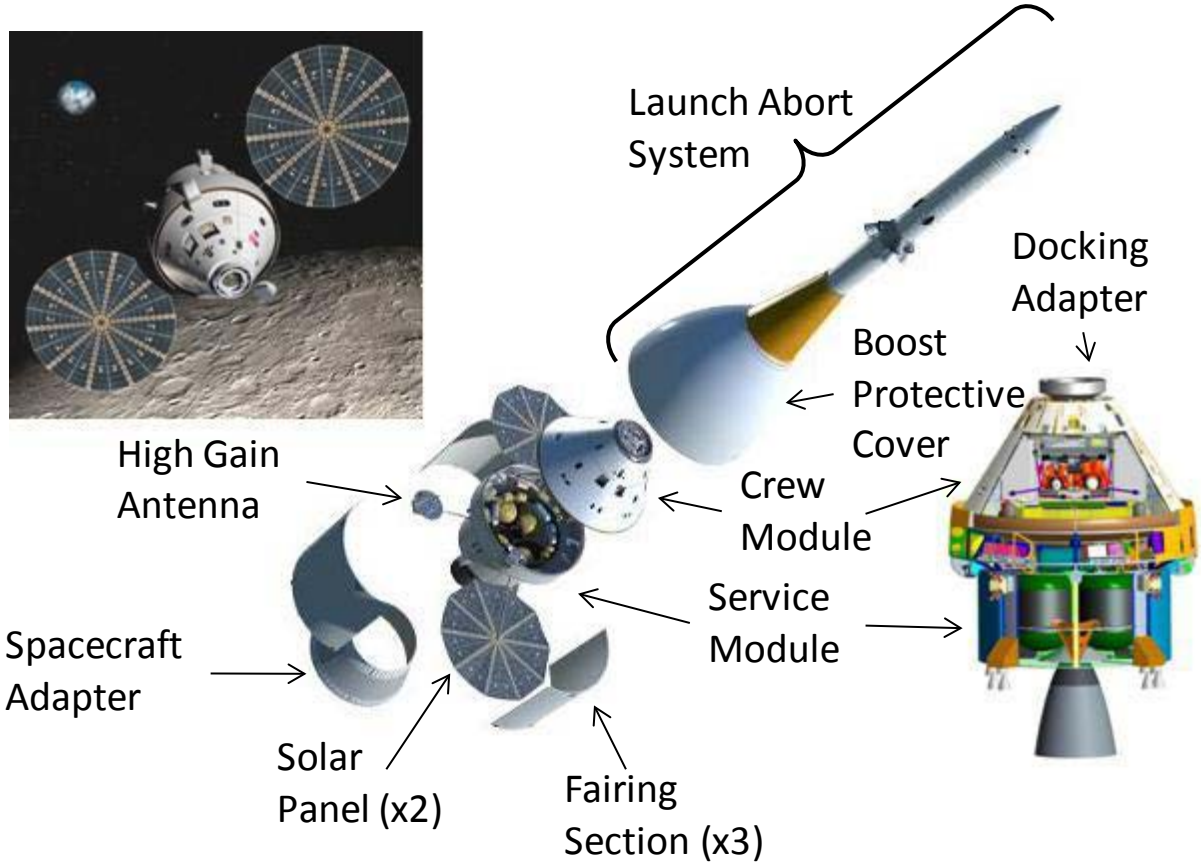


Figure 3: Orion Crew Exploration Vehicle (Artists' Concepts)

The primary landing mode for the Crew Module will be an ocean landing near the western U.S. coast supported by parachutes and inflatable water flotation airbags; however, contingency landing and recovery of the crew and capsule will be possible anywhere in the world. Current planning is focusing on a nominal water landing within 200 miles of the Navy's San Clemente Island Range Complex, using a local retrieval ship with helicopter support and cost-sharing of a Deep Submergence Rescue Vehicle with the Navy and Military Sealift Command. After recovery, various components of the Crew Module will be refurbished and reflown. Hardware associated with the Launch Abort System, Service Module, and Spacecraft Adapter is jettisoned at various points during the flight and either disintegrates during atmospheric reentry or is targeted for impact in a remote ocean location.

The Ares I launch vehicle delivers the Orion spacecraft into low Earth orbit to rendezvous and dock with the ISS or with the Altair lunar lander (previously launched by an Ares V heavy-lift rocket). Components of the Ares I and Ares V launch vehicles are being developed concurrently with propulsion

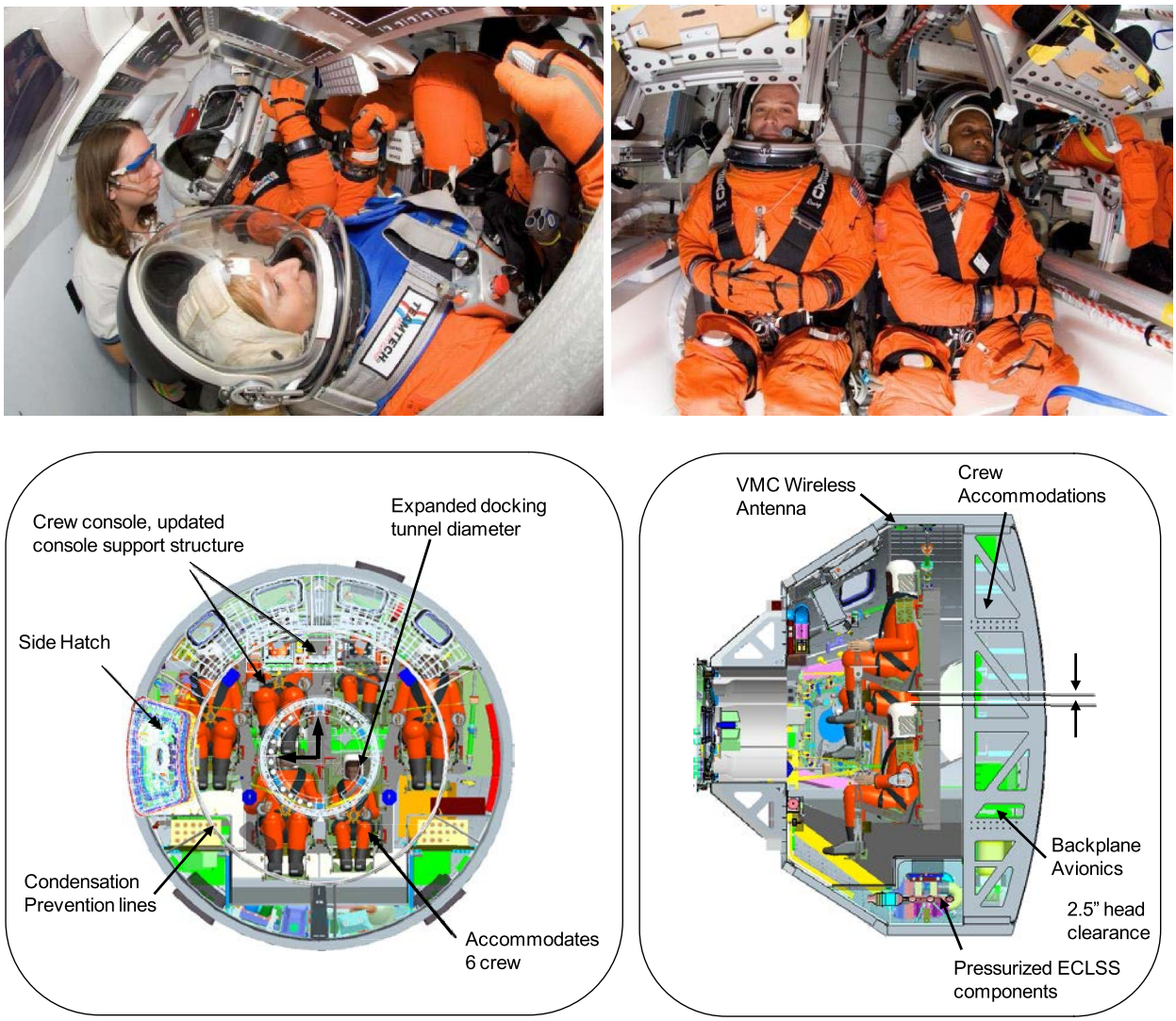


Figure 4: Orion Crew Accommodations

and structures hardware commonality, which results in significant design and manufacturing cost savings. Common elements being developed for the Ares I and Ares V launch vehicles include solid rocket motors, features of the Ares I Upper Stage/Ares V Cores Stage, and the J-2X Upper Stage engine. Cost and risk reduction are also enhanced by using existing and proven hardware and systems whenever possible. This includes Solid Rocket Booster technology from the Space Shuttle Program used as the basis for the Ares I First Stage and Ares V booster rockets. The Ares I Upper Stage J-2X engine and the Earth Departure Stage engine of the Ares V are generational upgrades of the J-2 engine used on Saturn V and Saturn IB launch vehicles during the Apollo Program. The RS-68 engines of the Ares V core stage were developed in the late 1990s and early 2000s for the U.S. Air Force"s Evolved Expendable Launch Vehicle Program (Delta IV). The primary components of the Ares I are shown in Figure 5. The Ares V launch vehicle provides heavy-lift capability. The vehicle will lift 143.4 mT (316,100 lbm) to low Earth orbit or propel a minimum of 55.6 mT (122,600 lbm) on a lunar trajectory.

The 143 mT to low Earth orbit compares to a maximum payload capacity of approximately 25 mT for the Space Shuttle. The Ares V consists of a liquid oxygen/liquid hydrogen propellant Core Stage with two Solid Rocket Boosters and an Earth Departure Stage derived from the Ares I Upper Stage. The Ares V Core Stage leverages manufacturing processes and

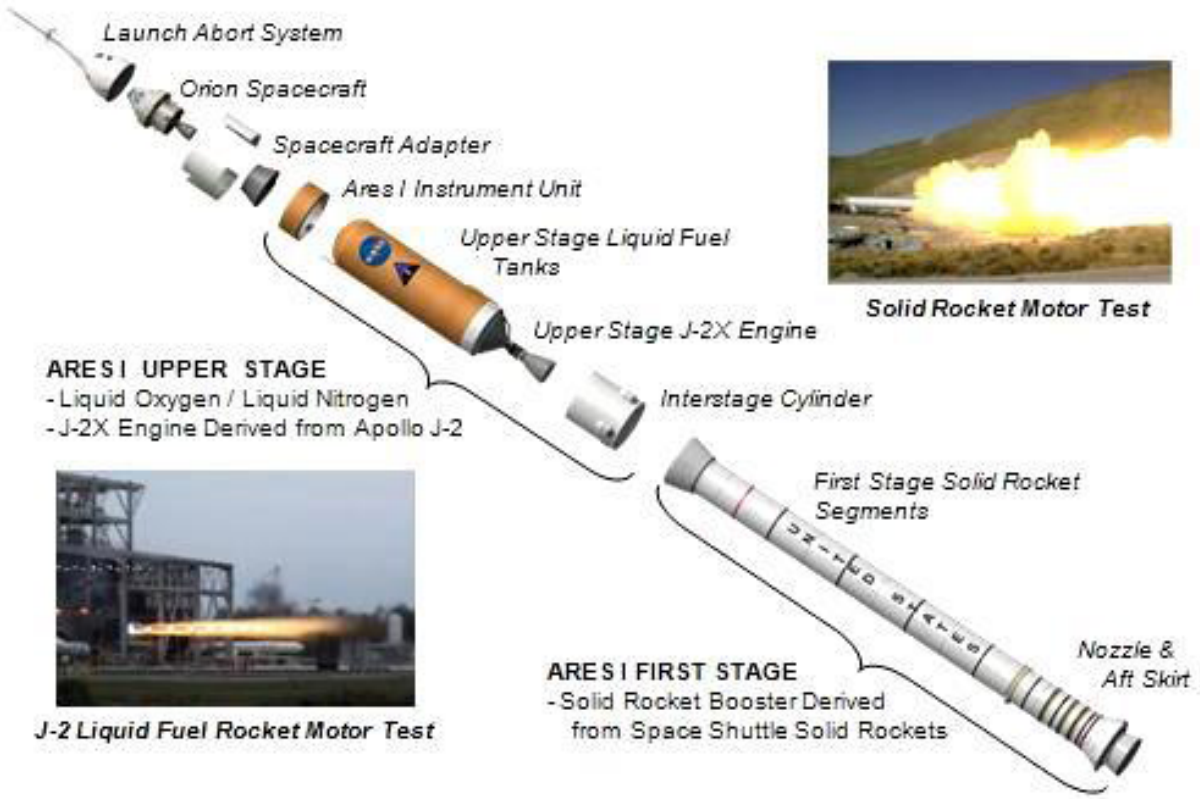


Figure 5: Ares I Crew Launch Vehicle

materials used on the Space Shuttle External Tank (ET) and uses a cluster of six RS-68B liquid hydrogen/liquid oxygen engines, each supplying about 3.1 million N (700,000 lbf) of thrust. The Core Stage is 10 m (33 ft) in diameter and 65 m (212 ft) in length, making it the largest rocket stage ever built. The primary components of the Ares V are shown in Figure 6.

The Altair lunar lander will provide access to the lunar surface for astronaut crews and/or cargo via a descent stage and will return the crew via an ascent stage to the Orion spacecraft in lunar orbit. A cargo-only version of the lunar lander will be able to transport cargo to the lunar surface and may not include an ascent stage. Basic elements of the lunar lander will include the propellant tanks and engines associated with the ascent/descent stages, a living module for the crew (i.e., pressure vessel), a landing gear system, internal power supplies (e.g., rechargeable batteries) and provisions for crew access to the lunar surface. Propellants proposed for the lunar lander include cryogenic liquid oxygen/liquid hydrogen for the descent stage and hypergolic N2O4/Aerozine 50 used in an AJ-10 rocket engine for the ascent stage. The AJ-10 is the same engine used for the Orion main engine. Later versions of the Altair module may serve as a testbed for methane-based engines which could use in-situ resources found on the Moon for fuel production. As part of the Lunar Capability phase of the Constellation program, the Altair project is currently in the initial stage of requirements development and would not select a preliminary design until the 2012-2013 timeframe. Figure 7 shows a conceptual illustration of the Altair lunar lander.

ARCHITECTURE TECHNICAL PRIORITIES

The highest architectural priority for any human spaceflight mission is crew safety. Crew safety is built on a foundation of a number of architectural elements including proven, heritage-based hardware with successful human flight history. For CxP this includes the Ares I first stage a direct derivative of the Shuttle solid rocket boosters and the Ares I upper stage J-2X engine based on the Apollo J-2S engine. Next to high inherent reliability hardware, the capability to be able to abort due to a catastrophic

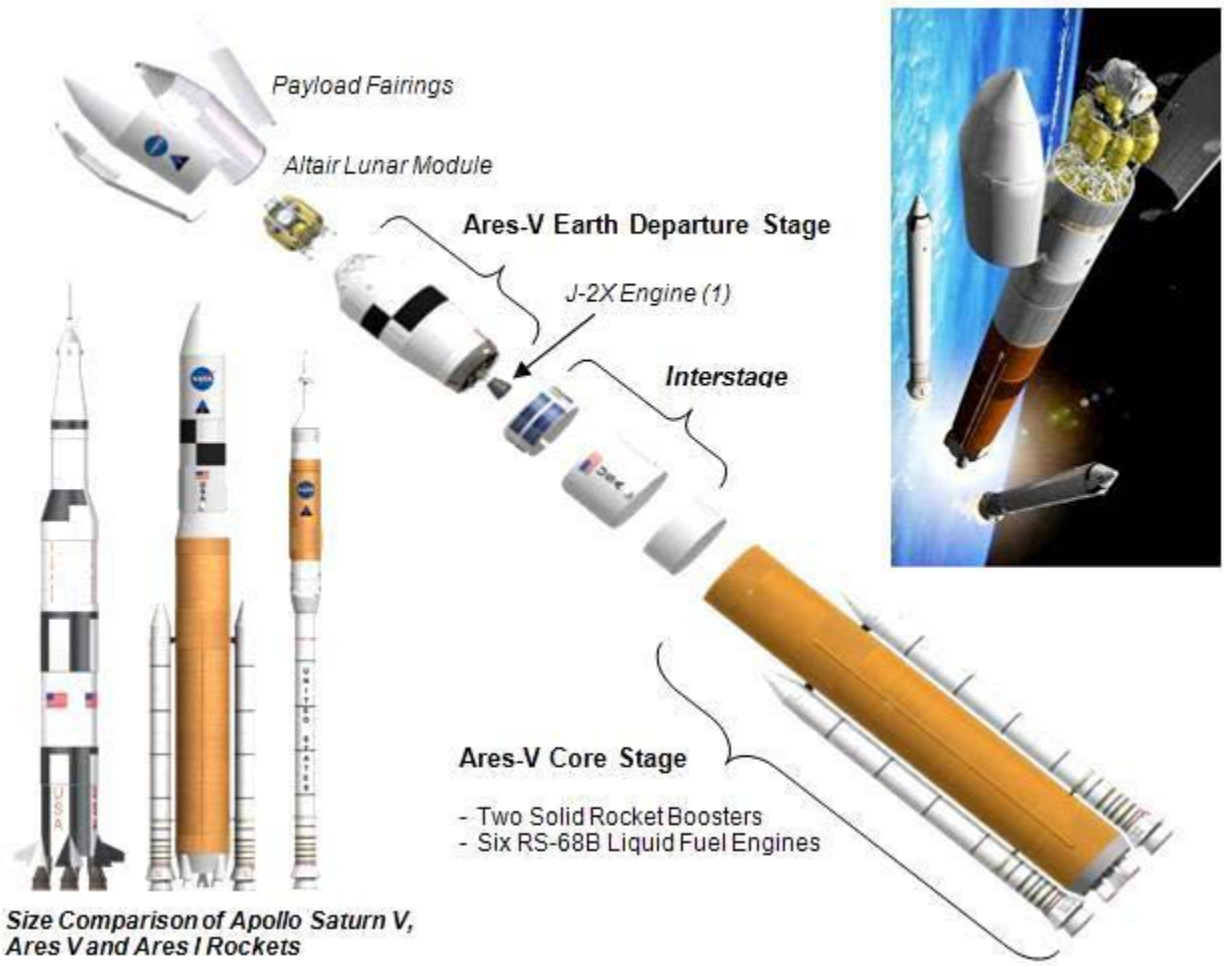


Figure 6: Ares V Heavy Lift Cargo Vehicle

event and return the crew safely to earth, during any part of the launch phase, is critical. The CxP architecture provides abort capability at all times from pre-ignition to orbit. The Launch Abort System (LAS) is a separate subsystem and is available from pre-liftoff throughout first stage flight and up until shortly after upper stage engine ignition. In particular it provides aborts capability during high–aerodynamic load regimes such as transonic and max-dynamic pressure phases. The CEV provides abort capability after the launch abort system (LAS) jettison with its own propulsion system.

Human spaceflight programs make extensive use of probabilistic risk analysis (PRA). This technique is used to calculate probabilities of loss of crew (LOC) and loss of mission (LOM). The LOC/LOM calculations are done by mission phase for the individual and integrated vehicles. The analysis of LOC and LOM are used to make design decisions throughout the program with the overall intent to provide significantly better safety than the Space Shuttle. The current ascent LOC estimates from the Space Shuttle Program is one loss of crew event in 160–270 flights. The current estimate for Ares I/Orion is one ascent loss of crew every 2,850 flights.

CxP is NASA's first program to be certified as "human-rated." This means that all the flight elements and the operations will be compliant with Human Ratings Requirements Policy, NASA 8705.2B. This policy was first established after the development of the Shuttle and was recently updated for Constellation. In the update for CxP the most significant change was to change the catastrophic failure tolerance requirement from being tolerant to 2 failures to being tolerant to at least 1 failure. This change was driven by the necessities of performance and put significant additional responsibilities on the engineering teams to show they had the safest possible designs within the constraints of the program.

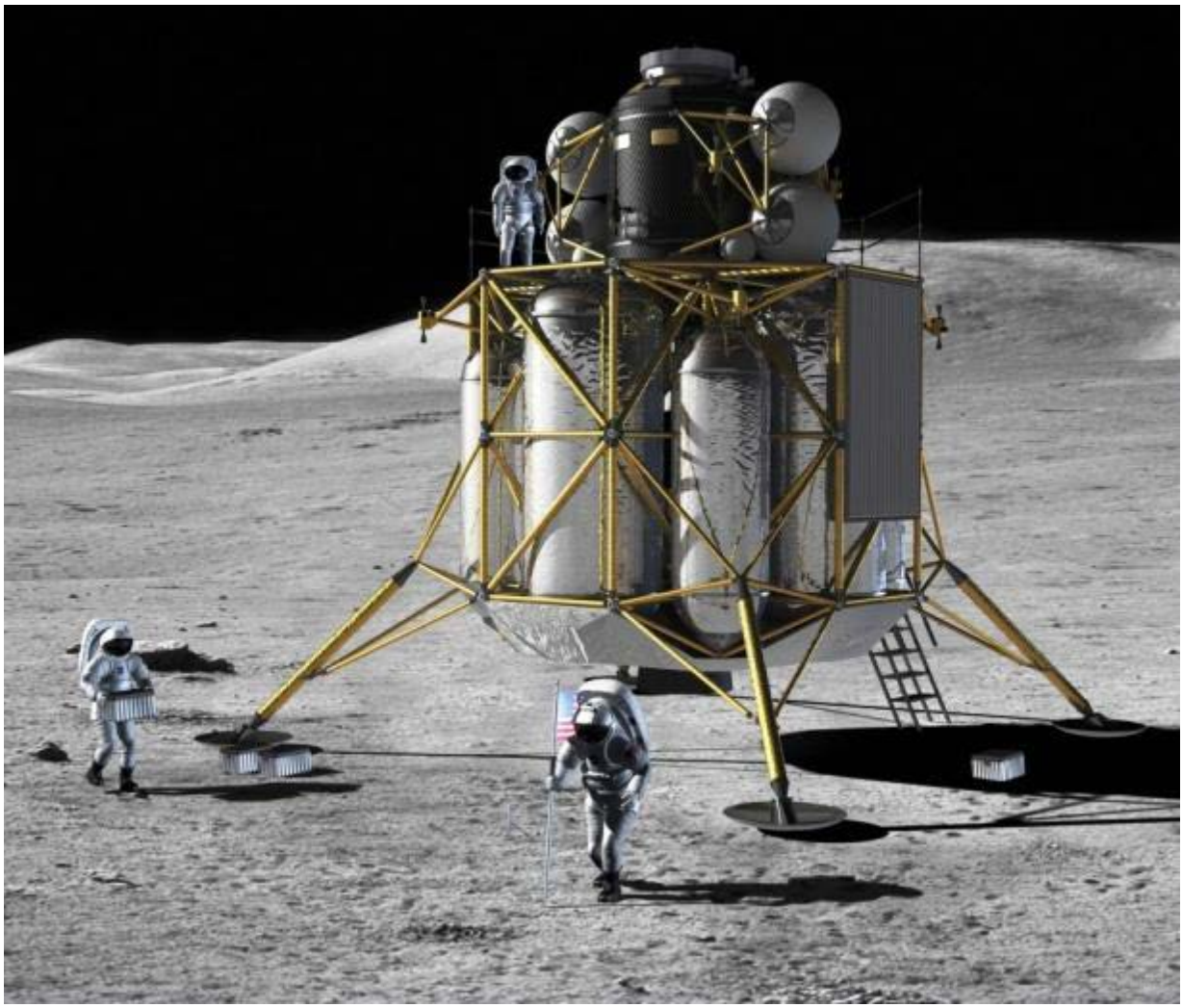
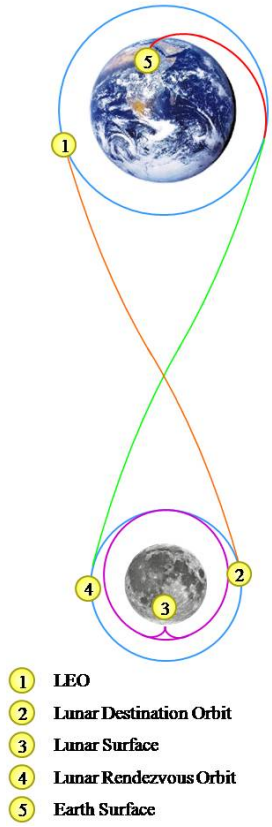


Figure 7: Altair Lunar Lander (Artist's concept)

One of the characteristics of spaceflight that makes it particularly challenging, and has parallels to the automotive industry, is the problem of mass and most specifically the ability to safely and efficiently accelerate and decelerate mass. However, for spaceflight we are working directly against gravity and must achieve very high velocities (e.g., Earth escape velocity is 11.2 km/s or ~25,000 mph) to get where we want to go. Then we need to decelerate into another gravity field (e.g., the moon or Mars) and then accelerate back out to return to Earth and finally decelerate back down to the surface of the Earth. Needless to say this is what makes spaceflight so complex and energy-intensive. In order to simplify the understanding of the performance impacts of spaceflight we talk in terms of what we call "gear ratios." A gear ratio is the multiplier times every unit of mass we want to deliver somewhere (e.g., crew or payload) that accounts for all the other things, propellant, and non-propellant (e.g., tanks, heat shields, etc.), needed for a particular phase of the mission. Just to get to low Earth orbit the gear ratio for just propellant is about 20 to 1. But to an architectural element that must travel from Earth orbit to the moon and back to the surface of Earth (e.g., the CEV) the gear ratio is 9 to 1. For those elements that we want to deliver to the surface of the moon and return to the surface of the Earth (e.g., the crew) the gear ratio is 19 to 1. Figure 8 shows a more complete set of gear ratios for lunar missions.

Given these gear ratios the ability to get a lot of mass into orbit is a major architectural driver. You have the options of one (or two) very large rockets referred to as heavy lift or a few (or many) moderate to small lift rockets. However, there is a guiding principle, driven by overall reliability, to minimize the number of launches. The probably of mission success starts



A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO
LEO to Lunar Orbit **(#1→#2)**	4.3 kg
LEO to Lunar Surface **(#1→#3; e.g., Descent Stage)**	7.5 kg
LEO to Lunar Orbit to Earth Surface **(#1→#4→#5; e.g., Orion Crew Module)**	9.0 kg
Lunar Surface to Earth Surface **(#3→#5; e.g., Lunar Sample)**	12.0 kg
LEO to Lunar Surface to Lunar Orbit **(#1→#3→#4; e.g., Ascent Stage)**	14.7 kg
LEO to Lunar Surface to Earth Surface **(#1→#3→#5; e.g., Crew)**	19.4 kg

Figure 8: Gear Ratios for Lunar Missions

to drop dramatically if more than 2 launches are required to accomplish a mission. The factors that contribute to this significant drop in mission success include individual reliability of the vehicles, the ability to launch more than one vehicle in a finite launch period (including the effects of weather and landing sea states), the ability to maintain cryogenic propellants in space, and the complexity of on-orbit operations with multiple vehicles.

Current estimates for lunar missions require the equivalent of ~200 t of mass in low earth orbit (LEO) which can be done with an Ares I and Ares V launch. For a Mars mission the mass in LEO would be in the 375-625 t range, in a higher, stable high earth orbit, which is likely to need about 6 Ares V launches. In addition, there are certain payload elements for which a single launch of at least 125 t is likely to be needed.

Mass is not the only driving performance parameter, volume is also critical. For a variety of reasons, very large payload diameters are expected to be needed. For lunar missions a payload diameter of 8 m to 10 m is needed. For Mars missions greater than 10 m diameters plus heights above 22 m are anticipated.

So how do you technically manage a complex, interdependent and evolving system of systems? In a word: margins. The need to establish and manage technical resource margins across all flight elements and all mission phases is essential. These include margins for a diverse range of resources including, mass, power, computer throughput, memory, communications bandwidth, temperature control, loads, etc. There is a set of resource margins that systems engineering establishes and manages for every flight element and for the integrated systems. The program has developed stochastic methods for analyzing margins across these multi-staged systems, particularly for mass and performance.

ARCHITECTURE PROGRAMMATIC PRIORITIES

There is an old saying around NASA – "we can lick gravity, but the paperwork has us stymied." Rocket science is not easy, but few NASA projects fail due to the difficulties of rocket science. By far, more NASA projects are cancelled before flight due to cost

growth or schedule slippage than fail during a mission. The establishment of a technical solution to perform a human or robotic mission is the first important step toward accomplishment of the mission, but must be accompanied by an equally enlightened programmatic solution that enables realization of the technical solution in finite, predictable time and money. Projects such as the Manhattan Project or the Apollo Program, accompanied by a blank check, are the exception rather than the norm. Furthermore, the development environment is dynamic, not static; for instance, vendors go out of business, technology advances render design approaches obsolete, and customer needs and desires change. The longer the timeframe needed for a system development, the more likely that some external factor will significantly impact the development effort. This is not uniquely a US Government or even NASA phenomenon; Motorola's Iridium program is a textbook example of a large corporate program done in by technology advancement in the cellular market rendering satellite telephones obsolete in the eyes of most customers. Since most NASA system developments require 3-5 years duration, and human spaceflight systems even longer, they are prone to encounter disruptive changes in the development environment.

In the case of the Constellation Program, the development effort was planned for seven years to achieve Initial Capability, then an additional five years to achieve Lunar Capability. Several technical challenges, perhaps most noteworthy thrust oscillation, emerged and were summarily addressed and resolved. The system engineering foundation provided by the ESAS, and matured within the constraints of well considered margin management proved robust, allowing technical risks to be solved without breaking the architecture.[12] The successful Ares 1-X flight test demonstrated the fundamental flight characteristics of the Ares I launch vehicle. The technical solution that was the Constellation architecture was progressing quite nicely through development.

Conversely, the programmatic solution did not prove so robust. The budget profile on which the schedule was based never quite materialized year to year, which stretched the development schedule. Still, the Constellation Program remained on track for achieving Initial Capability on schedule, albeit at higher risk because schedule margin had been consumed. For NASA, the programmatic solution also includes the political support for a given project or program. There too the programmatic solution was carefully crafted, and Congressional authorizations for NASA in 2005 and 2008 including the Constellation Program enjoyed strong bipartisan support. However, only four years into the system development the Constellation Program was proposed to be cancelled when the Human Spaceflight Policy was changed by a new Presidential Administration. In the end, the Constellation architecture was proposed for cancellation not due to technical problems but due to foreseeable funding problems, limited schedule flexibility, and ultimately to the change in priorities of a primary stakeholder. So long as complex systems take many years to complete, even carefully and robustly designed Programs are susceptible to changes in their development environment over which they can exercise little or no control.

The Constellation architecture was vulnerable because it could not achieve significant results in a short enough time. The program's focus on life-cycle cost, rather than maximizing results on an annual funding basis was its Achilles heel. The programmatic approach was a dozen years of overlapping system developments with no clear interim stopping points. Projects and programs that span Administrations are susceptible to dramatic policy changes. If one could recycle the clock to Constellation's early planning on the heels of the ESAS, a more robust programmatic approach might have been to focus on significant accomplishments which could be achieved in five years maximum, in turn followed by another 4-5 year development that achieved the next increment of capability, and so on in successive cycles of approximately 4-5 years. NASA must learn a lesson that the automotive industry has already learned – shortening the development cycle is key to successful system developments.

APOLLO PERSPECTIVE

The Apollo program architecture was created in a geopolitical environment that enjoyed enormous national support. President John F. Kennedy's historic words to Congress on May 25, 1961: "I believe this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth" set the primary objective of the program in a single sentence. While this was clearly the prime objective, from a key stakeholder, from this statement also came many of the principles that guided Apollo.

Again the principles that governed the Apollo architecture were not published as such but the

following include some of the principles, technical and programmatic, derived from various references.

1. Attend to the economic, political, and the social interfaces with key stakeholders
2. Plan well and make decisions rapidly
3. Establish and maintain an effective communication system across the program [9]
4. To minimize spacecraft complexity, weight, cost, and schedule, the level of redundancy should depend on the factors of criticality, flight experience, and technology maturity[8]
5. Share responsibility for achieving reliability between NASA and contractors. Infuse reliability into the design early in the life cycle [10]
6. Focus on the nominal and work a limited, smartly chosen set of contingencies based on probabilities of occurrence [11]
7. Test to failure to understand margins

Probably the greatest difference between CxP and Apollo was the national commitment to Apollo. It was implemented in an almost wartime mentality where the failure to meet the objective was "not an option" to borrow from Gene Kranz. The combination of the personal commitments of the Apollo team backed by the support of the nation and the willingness of Congress to fully fund the program on the profile they needed enabled success. While the personal commitment of the NASA community to its projects remains exceptional, human spaceflight has not enjoyed the Apollo level of external stakeholder support since the 60's. The lack of a clear, widely accepted and strongly supported "mission" for HSF has made it vulnerable to the vagaries of the political process.

It is probably safe to say that the Apollo managers were willing and able to take risks we can't today. In the many years since Apollo we have seen the development and successful operations of many launch vehicles and flight systems (payloads). However, the losses of Challenger and Columbia, and of the two Mars '98 missions, accompanied by the level of scrutiny of the media and other stakeholders has made the risk tolerance of NASA very low. The combination of low risk tolerance and tight cost constraints makes the challenge of architecting a robust HSF program very difficult.

SUMMARY/CONCLUSIONS

As space systems have become more complex, the need for effective architecting has become essential. Early spacecraft and rocket architectures and designs could be the work of one person or a few. For example, Max Faget was able to architect the first single-person US spacecraft, develop the design and maintain it through to the successful launches of the Mercury program. In 1965 he published "Manned Space Flight," a small 165-page book that laid out the fundamentals of the architecture of the Apollo program.[13] But as the systems have grown more complex, both technically and programmatically, the architecture and supporting processes have needed to adapt. Improving the content, understanding, communication, implementation and sustainability of mission architectures is a primary function and challenge of systems engineering, especially for ones as complex as human spaceflight. There are many and sometimes conflicting architectural drivers for human spaceflight systems but the primary ones are crew safety, performance and resources.

For architectures to be successful they need to be constructed with and for sustained stakeholder engagement, understanding and support. Establishing better understanding of what and how to construct an architecture for human spaceflight, with long term viability in the NASA technical and programmatic environment, will benefit significantly from the lessons drawn from the Constellation Program. The current efforts of the Human Exploration Framework Team (HEFT) are building on our current understanding of architecting complex systems-of-systems including stakeholder objectives and core principles. HEFT is taking advantage the lessons of CxP, Apollo and other NASA programs/projects to try and craft a robust architecture for the future of human spaceflight. The authors wish them success!

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