Lessons Learned in Architecting a Human Spaceflight Program

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Agenda

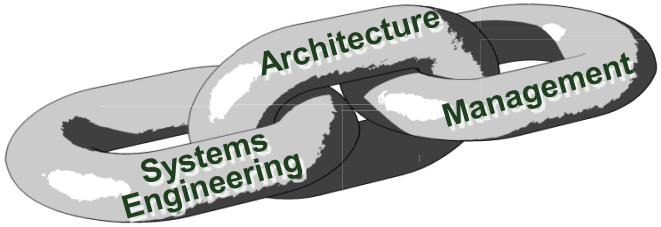
- What is Architecting
- Constellation “Architecture”
- Human Exploration Architecture Principles
- New Direction
- Summary

Constellation as a Systems Engineering Problem

"First you jump off the cliff and you build wings on the way down." **….. Ray Bradbury**

What is Architecture??

- **Architecture 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 (IEEE Std 1471-2000)**
  - Addresses both technical and programmatic considerations
- **Architecture addresses why a system is the way it is and how this understanding of the system is to be sustained**
  - It underlies the designs ability to meet objectives and satisfy stakeholders
  - Its integrity must be maintained throughout development….
  - A design is the embodiment of an architecture. Designs address what is to be built and how
- **Stakeholders, many, often with different priorities….**
  - Architecting links management/programmatics and systems engineering
- **As systems become more complex the need for an effective architecting effort becomes essential**
- **Architectures are fractal**



What Architecture Is Not!!

- **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 opaque pictures, block diagrams, lists, or other schematic representations of the design**
- **Architecture is not requirements**
  - Architecture provides the rationale for requirements, as well as the criteria for allocating requirements and flowing them from one level to the next
- **Architecture is not fickle, or subject to routine refinement**
  - Architecture provides a stabilizing influence through its well-considered form, expectations, rules, and attention to fundamentals

Exploration Architecting Process

- Establish entire set of Stakeholders, capture their concerns
- Lay out Objectives and Constraints that explicitly address Stakeholder concerns
- Establish operative Principles and related Figures of Merits (FOMs)
- Conduct trade studies and create Conceptual Designs: Design Reference Missions/Architectures (DRM/DRAs), system and technology descriptions/roadmaps, exploration strategy(s)
- Communicate products with key Stakeholders, articulating key aspects of Objectives, Principles and Concepts
- Devise encompassing sets of Views (and needed Viewpoints) to achieve all of above

Stakeholders

- **Influential "outside" people with something important to gain or to lose by virtue of project actions (i.e. their concerns/priorities)**
  - Weight can draw from many sources (legal, financial, political, etc.)
- **Not merely titles, groups, or organizations**
  - Someone architects can talk with
- **Includes future developers and operators!**
  - Hats change over time
- **Vital to get all significant stakeholder factions identified**
- **Space program/projects have many stakeholders, especially human spaceflight, and their "concerns" are not always aligned or alignable and they can/do change over time**

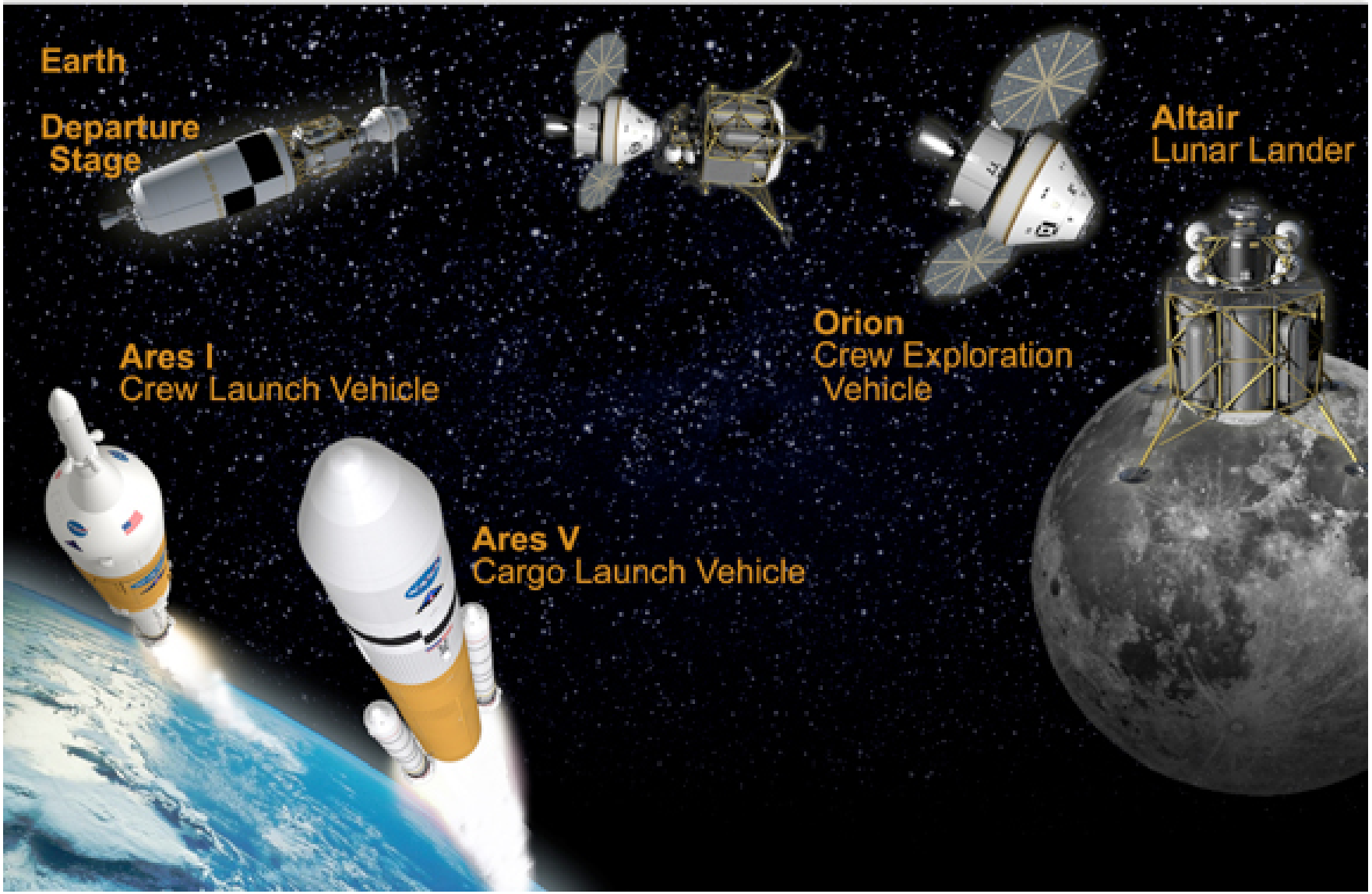
Objectives (and Constraints)

- **System costs and benefits born solely of stakeholder concerns**
  - The criteria by which success is measured
- **The architect's job is to help stakeholders express these concerns**
  - Need an actionable form that enables evenhanded evaluation
- **Objectives should be quite stable**
  - Complete, clear, and matter-of-fact
  - Architectures are never better than the quality of their objectives
- **Are as broad as the concerns of the stakeholders and includes properties such as:**
  - **Whats**
    - Performance, functionality, quality, cost, reliably…
  - **Hows,** e.g. how the system comes together, or is operated, or relates to other developments:
    - Scalability, testability, operability, maintainability, reusability, composability, modelability, and other "-ilities".

Historical Milestones in CxP

- **February 1, 2003:** Columbia accident
- **January, 2004:** Vision for Space Exploration
- **March, 2004:** CLV and CEV RFPs
- **April, 2005:** Mike Griffin becomes NASA Administrator
- **November, 2005:** Release of Exploration Systems Architecture Study (ESAS)
- **November, 2005:** Constellation Program begins
- **June, 2008:** Lunar Capability Concept Review shows a feasible architecture for lunar exploration
- **October, 2009:** Augustine Commission Report
- **February, 2010:** Proposed cancellation in FY'11 budget
- **April, 2010:** Possible redirection instead of cancellation

Constellation Architecture Elements



Constellation's Seven Projects

Ares- Launch Vehicle

Orion-Crew Exploration Vehicle

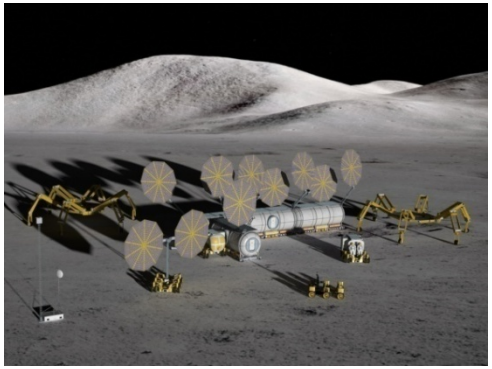
Extravehicular Activities

Mission Operations

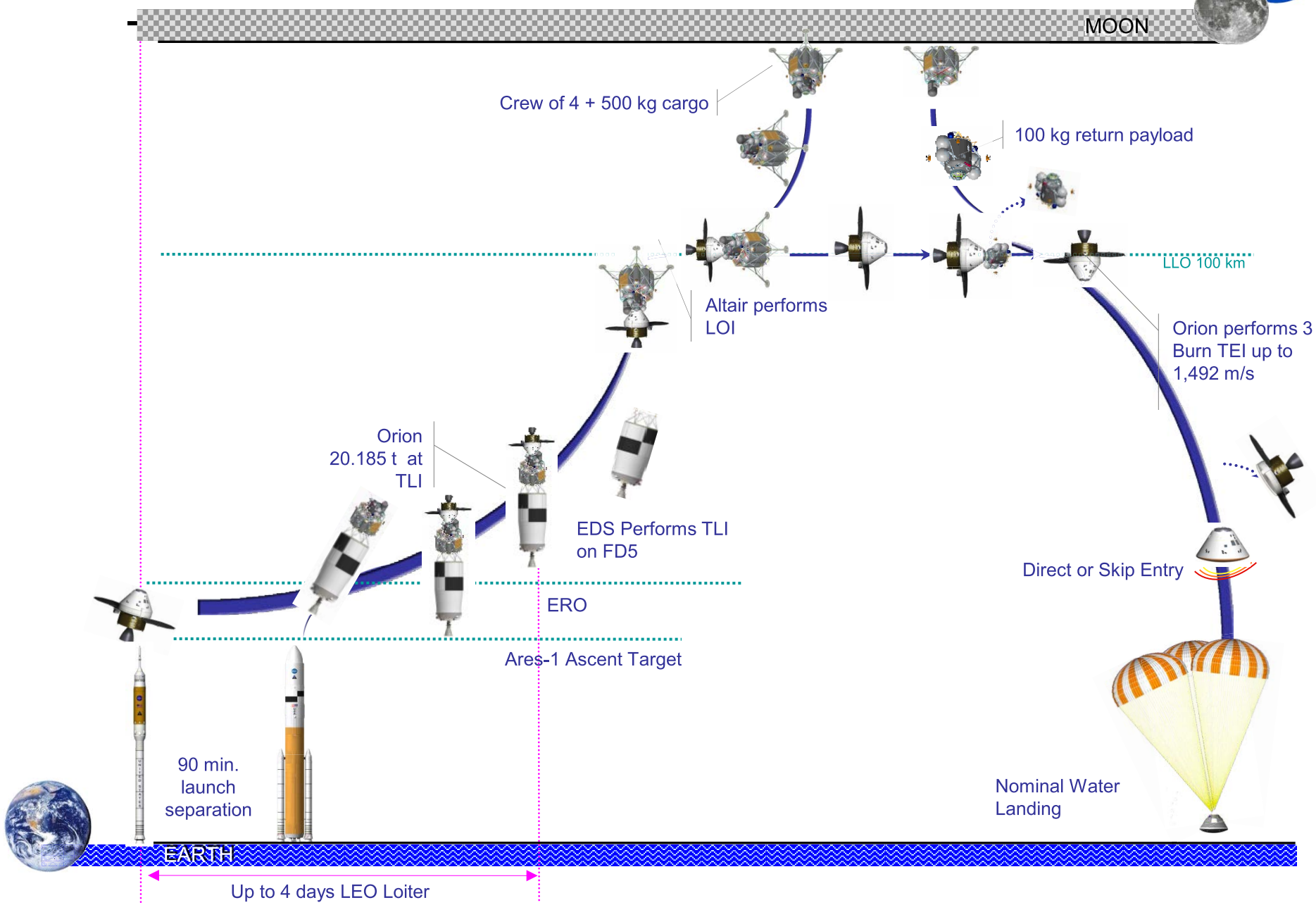
Ground Operations

Altair

Lunar Surface

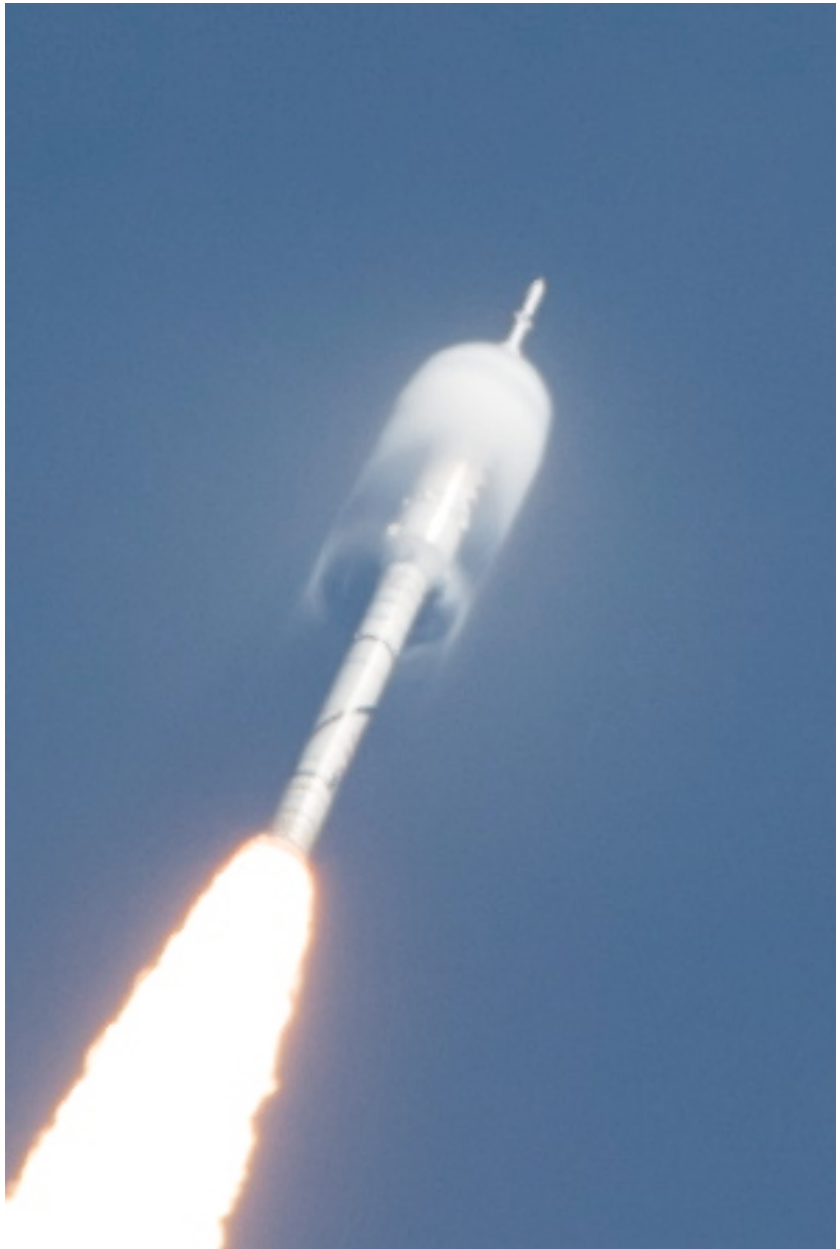


Lunar Crewed Mission Profile



Ares I-X Test Flight

Successful test flight, but only a first step



Principles

Success ⇦ Wisdom ⇦ Experience ⇦ Mistakes

- **This experience must be distilled into fundamental ideas with broad application (i.e, principles)**
  - Engineering: Laws of nature, proven solutions
  - Architecture: Usually more heuristic
- **Principles foster order, structure, elegance**
  - Commitment to fundamentals
  - Basis for architectural integrity
- **A good principle is generally… what you really care about**
  - 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**

Architecture Principles: Crew Safety

- **Use proven, heritage-based hardware with successful human flight history**
  - Ares I first stage based on Shuttle solid rocket boosters
  - Ares I upper stage J-2X engine based on J-2S engine
- **Robust abort capability**
  - Launch abort system available through upper stage engine ignition
  - High–aerodynamic load regimes are covered
  - Orion provides abort capability after launch abort system (LAS) jettison
- **Achieve 10x better loss of crew (LOC) performance than Space Shuttle**
  - Current ascent LOC estimates from the Space Shuttle Program estimate is one loss of crew event in 160–270 flights
  - Ares I/Orion estimate is one ascent loss of crew every 2,850 flights

Note: CxP is NASA's first program to formally seek to certify as "human-rated" [compliant w/NASA 8705.2B Human Ratings Requirements Policy]

Architecture Principles: Performance

- **Recognize injected mass driven by gear ratios (including non-propellant, e.g. tanks, heat shields, etc)**
  - 9:1 to lunar orbit and back to earth (e.g. Crew Exploration Vehicle)
  - 19:1 to lunar surface and back to earth (e.g. crew)
  - Current lunar mission requires the equivalent of ~200 t initial mass in LEO
  - Mars initial mass in LEO would be in the 375-625 t range in higher, stable LEO orbits
  - Need for single launch of 125 t for some elements
- **Minimize the number of launches to increase probability of mission success**
  - Maximize mission reliability
  - Simplify on-orbit operations
- **Need very large payload diameters: 8.5–12 m**
  - Lunar missions drive to 8 m to 10 m diameter
  - Mars missions drive to 10 m plus diameters plus increased heights above 22 m

Architecture Principles: Appropriate and Stable Funding

- **Budget profile must provide for adequate funding for critical early development risk mitigation, including engineering development units, ground testing, and technology maturation**
  - Cx budget reductions of $5.2B since ESAS, through FY10 put the architecture at very serious risk
  - Inadequate budget to maintain original schedule
  - As the Augustine Commission reported, to achieve most any human spaceflight objectives beyond LEO (assuming current ISS and STS commitments) in this decade, NASA would most likely need about $3B more per year for the rest of this decade

FY '11 President's Budget Proposal Overview

The President's budget will invest an additional $6 billion in NASA over the next five years - an overall $100 billion commitment to the agency

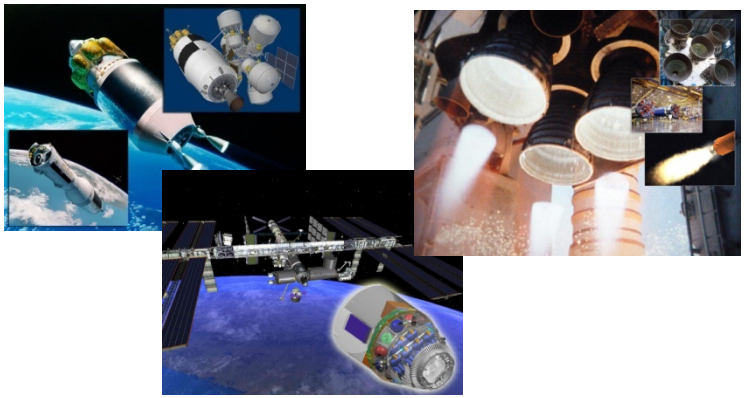
- **President's Budget challenges NASA to embark on a new human space exploration program that invests near-term in obtaining key knowledge about future destinations and demonstrating critical enabling technologies for human spaceflight and exploration, including:**
  - Research and development of heavy-lift and propulsion capabilities
  - Transformative technology development and flagship technology demonstrations to reduce cost and expand capabilities of future human exploration activities
  - Exploration precursor robotic missions to multiple destinations in the solar system to cost-effectively scout human exploration targets and identify hazards and resources for visitation and habitation
  - Expanded efforts to develop U.S. commercial human spaceflight capabilities, making space travel more accessible and affordable
  - Increased investment in Human Research to prepare for long journeys beyond Earth

Elements of Future Human Missions Beyond LEO

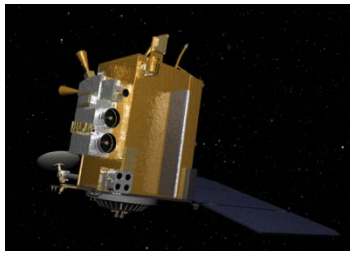
Destinations of Interest

Enabling Human Exploration

Needed Capabilities



Precursor Knowledge



Human Exploration Framework Team (HEFT)

- **HEFT Goal:** ***Create an evolvable framework for our Human Space Exploration Enterprise that drives out the knowledge, capabilities and infrastructure NASA needs to send people to explore multiple destinations in the Solar System in an efficient, sustainable way.***

- **HEFT will:**
  - Establish a portfolio of candidate DRMs to respond to Administration direction that fully integrates all human space activities and supporting robotic activities to facilitate supportable mission directorate and agency decision making concerning near-term missions, and longer-term destinations
  - Consider a wide range of missions and approaches that are consistent with the new program areas established by the President's Budget Request for FY2011
  - Leverage previous studies that have considered key knowledge and technology needs
  - Take advantage of NASA center capabilities, and proactively engage our international, commercial, and academic partners

Example HEFT "Principles" and Rationale

- **Architecture must be consistent with the business model**
  - Past architectures have failed because they took an unrealistic approach to accommodating the business model
- **Be robust to changes in stakeholder support and priorities**
  - Need flexibility and/or inertia to accommodate inevitable changes in stakeholder support and/or objectives/constraints
- **Allow for engagement of international partners (IPs) across the architecture**
  - IPs come with broadening capabilities and their own resources, provide broader political support (inertia) and can mitigate some programmatic risks
- **Use an evolutionary development strategy**
  - Allows for incorporation of advancing technologies
  - Provides for more rapid and periodic "firsts"
  - Helps deal with budget limitations/fluctuations

Final Note on Architecting

- **The practice of good architecting isn't learned quickly**
  - Even an overview course takes several hours
  - The Aerospace Institute teaches a four-week course
- **As with any art though, good architecting requires mentorship, practical experience, and willingness to keep learning**
- **Good architecting also does not occur without support and commitment**
  - It must be a recognized aspect of the project structure with appropriate authority to gather needed information, invoke the required analyses, and implement its decisions
- **Otherwise, good architecture simply will not happen, except by accident**

Summary

- **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**
- **Good architecting is more art than science and does not occur without strong support and commitment**
  - It must be a recognized aspect of the program/project structure with appropriate authority to gather needed information, invoke the required analyses, and implement its decisions
- **The robotic and human spaceflight communities are working closely together now and expect to work even closer in the future as the man-machine interface becomes more interdependent and intertwined**