FOREWORD

The material contained in this report was compiled to capture the work performed by the National Aeronautics and Space Administration’s (NASA’s) Exploration study team in the late 2002 timeframe. The “Exploration Blueprint Data Book” documents the analyses and findings of the 90-day Agency-wide study conducted from September – November 2002.

During the summer of 2002, the NASA Deputy Administrator requested that a study be performed with the following objectives:

- Develop the rationale for exploration beyond low-Earth orbit
- Develop roadmaps for how to accomplish the first steps through humans to Mars
- Develop design reference missions as a basis for the roadmaps
- Make recommendations on what can be done now to effect this future

This planning team, termed the Exploration Blueprint, performed architecture analyses to develop roadmaps for how to accomplish the first steps beyond LEO through the human exploration of Mars. The previous NASA Exploration Team activities laid the foundation and framework for development of NASA’s Integrated Space Plan. The reference missions resulting from the analysis performed by the Exploration Blueprint team formed the basis for requirement definition, systems development, technology roadmapping, and risk assessments for future human exploration beyond low-Earth orbit. Emphasis was placed on developing recommendations on what could be done now to effect future exploration activities. The Exploration Blueprint team embraced the “Stepping Stone” approach to exploration where human and robotic activities are conducted through progressive expansion outward beyond low-Earth orbit. Results from this study produced a long-term strategy for exploration with near-term implementation plans, program recommendations, and technology investments. Specific results included the development of a common exploration crew vehicle concept, a unified space nuclear strategy, focused bioastronautics research objectives, and an integrated human and robotic exploration strategy. Recommendations from the Exploration Blueprint included the endorsement of the Nuclear Systems Initiative, augmentation of the bioastronautics research, a focused space transportation program including heavy-lift launch and a common exploration vehicle design for ISS and exploration missions, as well as an integrated human and robotic exploration strategy for Mars.
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Exploration Blueprint Input: Integrated Space Plan

Doug Cooke
December 13, 2002
Briefing Objectives

- Provide initial thinking on Integrated Space Plan content
- Present examples of interim products and key architecture drivers
- Present preliminary recommendations for consideration

Gain JSAC’s commitment and participation in creating a strategy and executing an implementation plan for conducting an integrated, science-driven space program
Blueprint Assumptions

- Science driven approach for human exploration beyond Low Earth Orbit
- Derived from prior NEXT activities
- Develop roadmaps that accomplish the first steps through humans to Accessible Planetary Surfaces (Mars)
- Develop Design Reference Missions/ concepts as a basis for the roadmaps
- To drive out tall poles, set a time frame
  - TRL 6 by 2006 for Earth’s Neighborhood
  - First launch in 2012 time frame
  - Mars launch by 2020
- Recommendations on what can be done now to effect this future
Integrated Space Plan Development Process

Space Act & NASA Strategic Plan

Science: Questions, Pursuits, Activities

Requirements and Systems Engineering

Architectural Studies & Technology Trades

Technology Roadmaps

Gap analysis

Integrated Space Plan

Long term Strategy
Near term Implementation Plan
Program Recommendations
Technology Investments, New Initiatives

Established Enterprise Processes and Priorities
Results from Blueprint Activity
ACTIVITY LEADS
HQ/Code AD/Gary Martin
JSC/EX/Doug Cooke

Science & Exploration Rationale
Leads: Code S/Harley Thronson
      Code S/Marc Allen

Architecture Requirements
Leads: JSC/CB/John Grunsfeld
      JSC/DA/Wayne Hale
Participants: JPL, JSC, LPI

Architecture Design and Definition
Leads: JSC/CB/Scott Horowitz
      JSC/EX/Bret Drake
Participants: JSC, MSFC

Launch Vehicle Systems
Lead: MSFC/Vance Houston
Participants: MSFC, JSC, KSC

Vehicle Processing and Launch Operations
Lead: KSC/Cristina Guidi
Participants: KSC, MSFC, JSC

Systems Definition
Lead: JSC/DA/Jeff Hanley
Participants: JSC, MSFC, GSC, LaRC, JPL

Technology Roadmaps
Leads: JSC/MV/Fred Ouellette
      JSC/EX/Al Conde
Participants: Code S, Code M, ARC, GRC, JPL, JSC, LaRC, MSFC

Supportability
Lead: JSC/EX/Kevin Watson
Participants: JSC, KSC, LaRC, GSFC

Risk Assessment
Lead: JSC/NX/Jan Railsback
Participants: JSC
Stepping Stone Science Exploration Strategy

Solar System & Interstellar Access
- Remote Robotic Scientific Investigations & Human Precursor Missions

Sustainable Planetary Presence
- Discover Life's limits
- Sustainable scientific research on extraterrestrial bodies

Accessible Planetary Surface
- Large optical systems in deep space & Lunar science

Earth’s Neighborhood
- Biological and physical Research; Earth science; engineering testbeds

Earth and LEO
- Educational & Inspiration

Developing Capabilities
- NUCLEAR SYSTEMS PROGRAM
- BIOASTRONAUTICS RESEARCH
- EVOLVED ETO CAPABILITY
- FOCUSED TECH./ RESEARCH PROGRAMS
- COMMON CREW TRANSFER CAPABILITY
Integrated Space Plan Development Process

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Established
Enterprise
Processes and
Priorities

Space Architect
Focus
Discovery: Cosmic Origins and Destiny

Geophysical sciences and search or life

Searching for biomarkers in planetary atmospheres

The birth of stars and planets

Detailed environmental monitoring

Studying habitability around neighboring stars

Impact history and evolution of the Moon
Human and Robotic Exploration Strategies

Revolutionize technologies and capabilities to enable discovery and science return and provide the maximum return to the nation:

• **Remote observations and measurements**: reach as far into the universe as possible; understand the Earth and its processes
  – Further the incredible discoveries of Hubble Space Telescope to understand our universe, its, evolution and processes
  – Search for evidence of life on planets outside our solar system
  – Develop a scientific understanding of the Earth system and its responses

• **Robotic missions**: maximize the return from remote direct measurements of other planetary bodies
  – Further automation and virtual presence to increase the return of in-situ measurements
  – Measure the environments and test technologies preparing for follow-on missions and objectives

• **Human exploration**: enable cost effective human exploration,
  – Where human capabilities can enable and increase the rate of return of science and discovery
  – Share the excitement of first hand discoveries through virtual experience
Humans and robots have collaborated in every NASA mission
- Difference between missions is the physical interfaces and proximity of humans

Hubble Space Telescope and Apollo demonstrated significant increase in rate of science return through involvement of humans at local science site

Humans and robots represent different tools for accomplishing different jobs
- Humans have capabilities not yet attained by robotics
- Robots more efficient for repetitive tasks and expendable for high risk tasks

Understanding benefits and risks of human and robotic capabilities is complex and evolving

Objective is to optimize integration of humans and machines to maximize overall capabilities for effective scientific discovery
例：需求逐级向下流转，从高一级的目标

NASA Vision and Mission:
- To improve life here.
- To find life beyond.
- To understand and protect our home planet.
- To explore the universe and search for life.

Fundamental Questions:
- How did the universe, galaxies, stars, and planets form and evolve, and what is their destiny?
- Does life in any form, however simple or complex, carbon-based or other, exist elsewhere than on Earth?
- How can we utilize the latest findings about the Sun, Earth, and other planetary bodies to develop accurate, predictive environmental, weather, climate, natural disaster, and natural resource models to help ensure sustainable development and improve the quality of life on Earth?

Enterprise Strategic Goal (Space Science):
Chart the evolution of the universe, from origins to destiny, and understand its galaxies, stars, planets, and life.

OSS Theme Objectives: [Enterprise Strategic Objectives (Space Science)]
- Understand the structure of the universe, from its earliest beginnings to its ultimate fate.
- Explore the ultimate limits of gravity and energy in the universe.
- Learn how galaxies, stars, and planets form, interact, and evolve.
- Understand the formation and evolution of the solar system and the Earth within it.
- Probe the evolution of life on Earth, and determine if life exists elsewhere in the solar system.
- Understand our changing Sun and its effects throughout the solar system.

Science-driven architectures and requirements are derived from a variety of potential mission scenarios.

Scenarios Need To Be Developed for Code S, Y and U

Example

- Large Optical Systems
- Potential Scenarios
- Mars Human Exploration
- Many Additional Scenarios - TBD
- Near-Earth Object (NEO) Sample Return
- Humans to Asteroids - Field Exploration Beyond LEO
- Mars Sample Return

Science-driven architectures and requirements are derived from a variety of potential mission scenarios.
### Objective:
Study interstellar gas and dust over a wide redshift range.

### Derived Architecture Requirements:
- High spatial and spectral resolution imaging in the 40-500 µm range.
- Membrane reflectors, actively cooled detectors, V-groove sunshade.
- EVAs over ~weeks to assemble and deploy truss.
- Infrastructure: crew transfer vehicles, robotic aids, EVA technology.

### Rationale:
Science objectives can be achieved only by a large-aperture, far-infrared and sub-millimeter, post-James Webb Space Telescope. Because of the size of the large reflectors, it would be impractical to launch it fully assembled.
Integrated Space Plan Development Process

- Space Act & NASA Strategic Plan
- Science: Questions, Pursuits, Activities
- Requirements and Systems Engineering
- Architectural Studies & Technology Trades
- Technology Roadmaps
- Gap analysis

Integrated Space Plan
- Long term Strategy
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Established
Enterprise
Processes and
Priorities

Space Architect
Focus
Libration Points

• Libration Points L1, L2, and L3 are semi-stable locations in space oriented to orbiting planetary bodies

• Access to all locations on moon and Mars is equivalent

• Very low energy transfers between libration points are possible
Lunar Orbit

Advanced Science Instruments

Lunar Crew Prepare for Mars

Instrument Deployment, Retrieval

100,000 km

Sun-Earth L₂

Mars and Beyond

Earth-Moon L₁

Exploration Trade Space

Earth

Lagrange Crew Transportation

To Interplanetary Destinations

From Interplanetary Destinations

Earth-Moon L₁

Lunar Orbit

From Interplanetary Destinations
<table>
<thead>
<tr>
<th>Earth-to-Orbit</th>
<th>Libration Points</th>
<th>Moon</th>
<th>Asteroids</th>
<th>Mars</th>
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<tr>
<td>Existing/Planned</td>
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<tr>
<td>New</td>
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<tr>
<td>Transportation</td>
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<td>Crew Transfer</td>
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<td>Solar Electric</td>
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Architectural Drivers

• Launch Capability
• Crew Transfer Vehicle design
• Value of Applied Technology
• Artificial Gravity/ Nuclear Electric Concepts
## Exploration Launch Comparison

* Note: A launch mass packaging efficiency of 75% is assumed for on-orbit assembly

<table>
<thead>
<tr>
<th></th>
<th><strong>Telescope Assembly</strong></th>
<th><strong>Lunar Expedition</strong></th>
<th><strong>Mars Mission</strong></th>
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<tr>
<td><strong>IMLEO</strong></td>
<td>IMLEO = 150 mt *</td>
<td>IMLEO = 240 mt *</td>
<td>IMLEO = 450 mt *</td>
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<tr>
<td><strong>EELV-H</strong></td>
<td><strong>9 Launches</strong></td>
<td><strong>13 Launches</strong></td>
<td><strong>27 Launches</strong></td>
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<tr>
<td>Payload to LEO</td>
<td>23 mt</td>
<td>23 mt</td>
<td>23 mt</td>
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<tr>
<td>Probability of Launch Failure</td>
<td>1/40</td>
<td>1/40</td>
<td>1/40</td>
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<tr>
<td><strong>Shuttle-Class</strong></td>
<td><strong>3 Launches</strong></td>
<td><strong>5 Launches</strong></td>
<td><strong>10 Launches</strong></td>
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<tr>
<td>Payload to LEO (small shroud)</td>
<td>71 mt</td>
<td>71 mt</td>
<td>71 mt</td>
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<tr>
<td>Payload to LEO (large shroud)</td>
<td>60 mt</td>
<td>60 mt</td>
<td>60 mt</td>
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<tr>
<td>Probability of Launch Failure</td>
<td>1/400</td>
<td>1/400</td>
<td>1/400</td>
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<td><strong>In-Line HLLV</strong></td>
<td><strong>2 Launches</strong></td>
<td><strong>3 Launches</strong></td>
<td><strong>6 Launches</strong></td>
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<tr>
<td>Payload to LEO</td>
<td>100 mt</td>
<td>100 mt</td>
<td>100 mt</td>
</tr>
<tr>
<td>Probability of Launch Failure</td>
<td>1/400</td>
<td>1/400</td>
<td>1/400</td>
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- **Telescope Assembly** mission includes launches for infrastructure buildup
- **Lunar Expedition** includes launches for infrastructure buildup

* Assumes 4-segment SRMs
## Preliminary Concepts for Exploration
### Blueprint Launch Vehicle

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<tr>
<th>Concept Configuration</th>
<th>Shuttle Class</th>
<th>Shuttle Class- Evolved</th>
<th>In-line HLLV</th>
<th>2 Stage In-line</th>
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</table>
| **Concept Description** | • 1.5 Stage Vehicle  
• Side mount Payload Carrier  
- 4.6m x 25m Pld envelope  
• ET - LOX/LH2 Core  
• 3 SSME Boat tail on Carrier  
• 2 - Four Segment SRBs | • 1.5 Stage Vehicle  
• Side mount Payload Carrier  
- 7.6m x 27.4m Pld envelope  
• ET LOX/LH2 Core  
- 5 ft. stretch LH2 tank  
• 3 SSME Engines on Carrier  
• 2 - Five Segment SRBs | • 2.5 Stage Vehicle  
• Inline Payload Shroud  
- 9.4m x 27.4m Pld for Mars  
- 7.3m x 27.4m Pld for Near Earth  
• ET Derived, LOX/LH2 Core  
• 3 RS-68 Engines  
• 2 - Five Segment SRBs  
• Large LOX/LH2 Upper Stage  
- 2 J-2S Engines  
 or - 1 SSME | • 2 Stage Vehicle  
• Inline Payload Shroud  
- 9.4m x 27.4m Pld for Mars  
- 7.3m x 27.4m Pld for Near Earth  
• LOX/RP First Stage  
• 8 RD-180 Engines  
• LOX/LH2 Second Stage  
- 4 J-2S Engines  
 or - 2 SSME |
| **GLOW** | 2041 mt | 2449 mt | 2871 mt w/ J2S(2)  
2876 mt w/ SSME(1) | 2223 mt w/ J2S(4)  
1991 mt w/ SSME(2) |
| **Performance (Destination)** | 88.6 mt  
(30 x 150 nmi Ellipse.. @28.5°) | 93.5 mt  
(30 x 150 nmi Ellipse.. @28.5°) | 108.5 mt w/ J2S(2)  
113.5 mt w/ SSME(1)  
(30 x 150 nmi Ellipse.. @28.5°) | 102.0 mt w/ J2S(4)  
102.0 mt w/ SSME(2)  
(30 x 150 nmi Ellipse.. @28.5°) |
Example Trade Study-
XTV Vehicle Design Status

• XTV was reexamined
  – Larger launch vehicle capability
  – Sort functionality between XTV/CTV/CRV

• Work completed or in progress:
  – XTV vehicle high-level requirements identified
  – Initial vehicle mass estimation completed
  – XTV requirements comparison with previous XTV, CRV and CTV requirements

• Splinter team assessed slender body vehicle compared to other vehicle shapes
  – Aerocapture into LEO, direct entry from L1, direct entry from ISS, and direct entry from Mars.
  – Vehicle stability and aerodynamics
  – Deceleration strategy
Vehicle Shapes’ Lift-to-Drag (L/D) Characteristics

AOA ~ Angle of attack

High AOA Wing Bodies
Require advanced TPS development!

Low AOA Wing Bodies

Lifting Bodies

Slender Bodies

Capsules

Volumetric Efficiency (volume/mass)

Complexity, Development Time, $$$

Hypersonic L/D

0  0.5  1.0  1.5  2.0  2.5

Vehicle Shapes:
- Capsules: Viking, Soyuz, Apollo
- Slender Bodies: HL-20, X-38, M-2
- Lifting Bodies: Shuttle, SHARP
- Wing Bodies: X-37, Shuttle (at low AOA)
- Hypersonic L/D:
  - Shuttle
  - X-37
  - X-38
  - M-2
  - HL-20
  - SHARP
  - ELV Shrouds
  - Biconic
  - Ellipsled

Volumetric Efficiency (volume/mass): $$$

Complexity, Development Time, $$$

Hypersonic L/D

0  0.5  1.0  1.5  2.0  2.5
Shape Sensitivities

Entry G-load Limit

No return
Lunar/ L1 return: reclined
LEO return: upright & sick/injured reclined
Any return sitting upright & sick/injured reclined

LEO Return TPS
Current reusable TPS
Advanced Reusable Ceramics
Ablators (TRL5) and Flight-limited UHTC (TRL3)

Landing Sites Req’d for CRV
> 4 Landing Sites Req’d
3 - 4 Landing Sites Req’d
1 or 2 Landing Sites Required

Impact on ELV Control
Similar to current ELV launch shrouds
Within current ELV launch capability
Requires change to ELV control or OSP lift spoilers

Ascent Abort Capability
Exceeds crew load limit on hi-altitude aborts
Requires land and water landing ascent abort capability

Desirable Range

0 0.5 1.0 1.5 2.0 2.5 L/D
Lo AOA
The Value of Technology Investments
- Mars Mission Example -

- Advanced Materials (14%)
- Maintenance & Spares (21%)
- Advanced Avionics (11%)
- Closed Loop Life Support (19%)
- Advanced Propulsion (EP or Nuclear) (46%)
- Aerocapture (50%)

Today's Technology

Technology

Normalized Mass (Per Cent)
Long-Duration Human Missions

Artificial Gravity/Nuclear Electric Option for Long Duration Missions

- Alternative to micro gravity crew countermeasures
  - 1-g @ 4 rpm
- May simplify qualification of some spacecraft systems operating at 1g
- Synergism between Artificial Gravity (AG) requirements and Nuclear Electric Propulsion vehicle design
  - Booms to separate crew from reactor/ AG moment arm
  - “Nuclear Power module” as counterweight
- Impacts currently under study
- Human exploration nuclear power requirements ready to submit to Nuclear Space Initiative
Integrated Space Plan Development Process

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- Science: Questions, Pursuits, Activities
- Requirements and Systems Engineering
- Architectural Studies & Technology Trades
- Technology Roadmaps
- Gap analysis

Integrated Space Plan
- Long term Strategy
- Near term Implementation Plan
- Program Recommendations
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Established Enterprise Processes and Priorities

Space Architect Focus
Opportunities to Augment or Align NASA Programs to the Exploration Strategy

- Crew Transfer Vehicle
- Space Nuclear Program
- Bioastronautics
- Research on ISS
- Mars Program (robotic)
Common Core Crew Vehicle Requirements

- **Objective:**
  - Establish the requirements for a common core crew vehicle which satisfies multiple, long-term, needs.

- **Approach:**
  - Initiate a process to develop common requirements
  - Crew vehicle requirements should include needs for:
    - CRV- ISS Crew Return Vehicle- Priority 1
    - CTV- Crew Transfer Vehicle- Priority 2
    - XTV- Exploration Transfer Vehicles- Priority 3

- **Status:**
  - Initial set of common core requirements have been identified
  - Capabilities beyond the scope of the core requirements can be met with additional systems to be developed as needed:
    - Service module for consumables, power, thermal control, extended duration
    - Injection stage for larger propulsive maneuvers
  - Process should be continued to further refine through OSP
Common Crew Vehicle Design Concept

Core Crew Vehicle
- Common crew element satisfying multiple mission capabilities
- Key Design Requirements:
  - Configurable for 4-7 crew
  - Independent one day mission duration
  - Autonomous / manual operations
  - Propulsive orbital maneuvering
  - Return the crew safely to Earth

ISS Crew Return
- Provides safe and expeditious recovery of astronauts from low-Earth orbit
- Core Vehicle Configuration Changes:
  - Configured for 4 deconditioned crew (7 highly desirable)
  - Medical emergency provisions
  - Emergency undock capability
  - ISS interfaces and six-month to two-year on-orbit stay
- Key Issues:
  - EELV launch compatibility including automated delivery to ISS
  - Degree of vehicle reusability

LEO Crew Transfer
- Crew transfer to low-Earth orbit and return
- Core Vehicle Configuration Changes:
  - Crew escape for aborts
  - Configured for 5 crew (3 ISS transfer)
  - 12 day mission duration for ISS support
  - Resources for extended mission duration (propellant, power, thermal control, life support consumables)
- Additional Systems:
  - EVA systems for on-orbit satellite servicing and repair
- Key Issues:
  - EELV launch compatibility and human rating
  - Degree of vehicle reusability

Near-Earth Transfer
- Transport crew to lunar vicinity and return to Earth
- Core Vehicle Configuration Changes:
  - Configured for 4-6 crew (mission dependent)
  - Crew escape for aborts
  - 12 (active) + 8 (dormant) day mission
  - Deep-space environmental protection
  - Resources for extended mission duration (propellant, power, thermal control, life support consumables)
- Additional Systems:
  - EVA systems for servicing and repair as required
  - Injection stage for trans-lunar injection
- Key Issues:
  - Lunar return velocities
  - Large launch vehicle
  - Degree of vehicle reusability

Key Issues:
- Lunar return velocities
- Large launch vehicle
- Degree of vehicle reusability
Objectives:

- Strategy should address projected robotic and human needs of the agency
- Identify desired system requirements and concepts
  - Robotic: Recent NSI studies
  - Human: NEXT Human Exploration Requirements for Future Nuclear Systems
- Assess multi-applicable technologies and infrastructure options
- Develop a roadmap linking technology and infrastructure developments

Endorsement: Nuclear Systems Initiative (NSI) is to Implement a Unified and Coordinated Development Program Leading to Nuclear Electric Propulsion and Nuclear Surface Power Capabilities for Human and Robotic Exploration
Bioastronautics

• Objective: Humans will enable, not limit, exploration.
• Issues for long-duration human missions
  – Risks and critical questions have been identified and prioritized
    • Risk reduction on-going through 2010 and beyond
    • Incremental risk reduction progressively reduces mission risks
  – Radiation concerns limit deep-space exposure
  – Micro gravity exposure can effect crew performance and health
  – Medical response plan is determined by risk level to be accepted
• ISS Program issues
  – More crew time needed for bioastronautics research
  – Larger “n” required for biomedical studies
    • Larger crew size on ISS
    • More frequent crewmember turn-over
  – The ISS centrifuge is required for artificial gravity research
Research benefits ISS as well as future programs:

- Critical need for Bioastronautics research
  - Micro gravity
  - Radiation
  - Human performance on long missions
  - Behavioral Health

- Improve performance / crew productivity and safety
  - Proper automation of systems
  - Advanced crew interfaces
  - Reduce time required for biomedical countermeasures
  - Fire Safety Research

- Reduce resupply
  - Closed loop life support minimizes consumables
  - Miniature sensors, processors and wireless technologies
  - Plasma engine could perform reboost with waste H2
  - Advanced fabrication and repair technologies

- Operational experience and systems exposure to space environment
  - Contributes to long term reliability
  - Evolution to simpler designs and better performance
Potential Augmentation

Launch Year

2001
- NASA Mars Odyssey

2003
- Japanese Mars Express

2005
- NASA Mars Reconnaissance Orbiter

2007
- French PREMIER-07 Science Orbiter

2009
- Italian NASA Science Orbiter

2011/12

2014
- NASA Compton Burst Mission

2016

2018

- Incorporating human exploration payloads and flight system technologies will increase overall science return
- Preserve science pathways responsive to discoveries
- Augment program to add human exploration content

2001-2005 mission content fixed

Precursor payload opportunities begin in 2007-2009

Mission Opportunities:
- 2007 Scouts
- Dedicated 2007/9 Mission
- 2009 MSL
- Site Survey Mission
- Mars Sample Return
- Site Survey Mission
- Site Survey Mission
- Site Survey Mission
- Comsat

Potential Human Exploration Content:
- Hazard avoidance and precision landing
- Measure Cr VI, Ph and buffer capacity
- Measure organic carbon
- Measure surface radiation
- Measure mechanical and adhesive properties of soil and dust
- Advanced entry shapes (mid L/D)
- High Mach parachute
- Deep drilling
- Sample return (required if organic carbon found by in-situ measurement)
- Landing site characterization
- ISPP, ISCP
- Water recovery
- Comm. and navigation infrastructure
Summary Recommendations

• **Endorse Nuclear Systems Initiative** - Develop technologies and capabilities that address near term robotic missions and evolve towards future human missions
  – Nuclear Electric Propulsion
  – Nuclear Power Reactors for surface applications
• **Endorse and augment Bioastronautics research** - Accelerate capability on ISS to obtain needed data for long term missions
• **Focus Integrated Space Transportation Program**
  – Provide low-cost / High Payload Earth-to-Orbit Transportation
    • Payload: 100 mt class
  – Pursue process to provide synergy in Crew Transportation
    • CRV for ISS
    • CTV for alternate access
    • XTV for lunar missions
  } Common Core Vehicle
• **Endorse and augment Augment Mars Program to increase science and address precursor needs**
  – Increased science return and further interest in exploration
  – Environmental data for science, site certification, and engineering design
  – Demonstration of key technologies
  – Miniaturization of sensors
  – Accelerate Mars Sample Return Mission
Summary Recommendations

• Coordinate roadmaps between Exploration architecture and science programs and plans
  – Office of Space Science
  – Office of Earth Science
  – Office of Biological and Physical Research

• Invest in critical key technologies
  – Pursue process to identify critical technologies and gaps
  – Implement technology development plan through re-focused existing programs/projects and new initiatives

• Develop an integrated analysis capability to evaluate options and understand synergies for NASA in space programs and research
Space Architecture Team - FY03 Objectives

- Develop integrated space plan
  - Develop rationale
  - Develop architecture concepts/approaches
  - Document level 0/1 requirements (collect science, generate technical and programmatic)
  - Update technology roadmaps and gap analyses
- Recommend technology realignments and initiatives
  - Long-term evolving strategy with near-term implementation requirements
- Seed investments in specific concepts and technologies
- Coordinate development of decision support tools
- Develop and implement external engagement plan
## Space Architecture Team – Products Schedule

<table>
<thead>
<tr>
<th>Milestone/Event</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
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<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
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<tbody>
<tr>
<td>Integrated Space Plan</td>
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<td>Level 0/1 requirements</td>
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<td>IPAPO Annual Assessment</td>
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</tbody>
</table>

- Integrated Space Plan: Initial Plan, Annual Update
- Rationale: Initial Concepts, Annual Update
- Architecture concepts: Initial Concepts, Annual Update
- Level 0/1 requirements: Initial Set, Annual Update
- Technology Roadmaps: Initial Set, Annual Update
- Investment Recommendations: Support FY03 POP
- Annual Report
- IPAPO Annual Assessment
# Space Architecture Team - FY03 Products

<table>
<thead>
<tr>
<th>Title</th>
<th>HQ Lead</th>
<th>$M</th>
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</thead>
<tbody>
<tr>
<td><strong>Integrated Space Plan</strong></td>
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<tr>
<td><strong>Rationale</strong></td>
<td></td>
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</tr>
<tr>
<td>Development of a clear and compelling set of justifications to support the pursuit of robust space exploration goals</td>
<td></td>
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</tr>
<tr>
<td><strong>Architectures, Concepts, Requirements and System Analysis</strong></td>
<td></td>
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<tr>
<td>Definition of a diverse set of human/robotic architectures based on innovative concepts to identify common technological needs and challenges. Capturing of associated upper and lower level requirements</td>
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<tr>
<td><strong>Space Transportation Architecture Requirements</strong></td>
<td></td>
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<tr>
<td>Integration of a comprehensive set of requirements and traffic models consistent with both near and long term exploration needs</td>
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<tr>
<td><strong>Technology Roadmaps, Gap Analyses and Priorities</strong></td>
<td></td>
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<tr>
<td>Develop technology roadmaps and conduct gap analysis to guide strategic decision making</td>
<td></td>
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<tr>
<td><strong>Engagement Strategy</strong></td>
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<td>1</td>
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<tr>
<td>Development and implementation of a plan for communicating NASA strategy and results while also providing opportunities for internal and external inputs</td>
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**Total (this page) = 11.5M**
<table>
<thead>
<tr>
<th>Task Title</th>
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</thead>
<tbody>
<tr>
<td>Mass Reduction (Materials)</td>
<td>350</td>
</tr>
<tr>
<td>Assessment of means to reduce vehicle launch mass and operational complexity through lightweight structural materials, wireless systems that replace vehicle cabling and cold plates, etc</td>
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<tr>
<td>Precision Landing and Hazard Avoidance</td>
<td>500</td>
</tr>
<tr>
<td>Studies that improve the ability to safely land robotic and human missions near valuable science sites (e.g. Mars)</td>
<td></td>
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<tr>
<td>Radiation Shielding Studies</td>
<td>572</td>
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<tr>
<td>Analysis of active and passive shielding technologies that support definition of reference architectures</td>
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<tr>
<td>Space Assembly, Maintenance and Servicing</td>
<td>2100</td>
</tr>
<tr>
<td>Development of concepts and technologies for robotics, EVA, autonomous systems and intelligent operations</td>
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</tr>
<tr>
<td>Observational platform concepts (Space &amp; Earth Science), Auton Reconfig Constellations (Earth Science)</td>
<td>1500</td>
</tr>
<tr>
<td>Studies of concepts for revolutionary capabilities that address important scientific goals using new technologies and operational methods (e.g. pure automation and combined human/robotic)</td>
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<tr>
<td>Earth Analogs</td>
<td>1000</td>
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<tr>
<td>Definition of requirements for a ground based facility that can validate new technologies and reduce future implementation unknowns/risks</td>
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</tr>
<tr>
<td>Development of space</td>
<td>350</td>
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<tr>
<td>Identify opportunities to leverage industry investments for scientific exploration</td>
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<tr>
<td>Decision Support Tools</td>
<td>1150</td>
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<tr>
<td>Complete ongoing updates of THREADS technology roadmaps for continued development by Space Architecture team. Further development of model of top level architecture and technology metrics to aid strategic assessments</td>
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<tr>
<td>Human/Robotic Enabled Science NRA</td>
<td>2000</td>
</tr>
<tr>
<td>Studies to identify and develop concepts for human enabled science on planetary surfaces and in space</td>
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</tr>
<tr>
<td>Mars Precursor Studies</td>
<td>200</td>
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<tr>
<td>Soil and dust characterization based on “Safe on Mars” report from NRC</td>
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</tbody>
</table>

Total (this page) = 9.72M (1M-U, 0.5M-Y, 3.9M-S, 3.32M-M, 1M-R)
Space Architecture Team
FY03 Products, Studies, & Analyses Leadership

• Space Assembly and Maintenance
  - EVA
  - Intell Ops
  - Robotics
• Development of Space
• Radiation Shielding Effects
• Decision Support Tools

• Technology Roadmaps & Gap Analyses
• Observational Platforms
• Precision Landing/Hazard Avoidance
• Space Assembly and Maintenance
  - Robotics
  - Auton Sys
• Human/Robotic Enabled Science NRA

• Earth Analogs - Integrity
• Mass Reduction Materials
• Mars Precursor Studies

• Observational Platforms
• Autonomous/Reconfigurable Constellations

• Rationale
• Architecture Concepts, Requirements & Sys Analysis
• Space Transportation Architecture Requirements

FY03 Products and Studies Leadership Assignment

• Engagement Strategy

• Ames
• Dryden
• Glenn
• Goddard
• Johnson
• JPL
• Kennedy
• Langley
• Marshall
• Stennis
Next Steps

• Develop Integrated Space Plan
• Request current goals, objectives and themes from each Enterprise
  – Develop rationale for each (as needed)
  – Integrate holistic set to support science driven exploration
• Through agency decisions, align and focus existing programs to fulfill portions of the Integrated Space Plan
• Identify and pursue new initiatives to fill gaps in technologies and capabilities
• Issues
  – FY03 funding and R&PM support
  – FY04 funding
The Exploration of Life in the Universe

To improve life here
To extend life to there
To find life beyond

... and sharing the adventure of discovery with all humanity
Why exploration of space?

Why, indeed, did we trouble to look beyond the frontier?

Our prime obligation to ourselves is to make the unknown known.

We are on a journey to keep an appointment with what whatever we are.

--- Gene Roddenberry

Exploring the grand cycle of life in the cosmos
Space provides a unique perspective on our planet, other worlds, the Universe . . . and, especially, ourselves.

As the last century closed, the United States led the world in discovering new scientific evidence and new processes that revealed our place in the Universe, by exploring new places and phenomena, leading outward beyond the vicinity of the Earth, to enhance the quality of life and share the adventure of discovery with all humanity.

At the start of a new century, we build upon past success, modern skills, and a shared vision of the future.

Only NASA can lead and manage the missions and technologies for the nation that will expand human presence in the cosmos, increase fundamental knowledge, and inspire future generations of explorers and discoverers.
NASA’s unique place within the nation, in history, in science and exploration, is embodied within the Space Act and Strategic Plans. Of all the nation’s institutions, only NASA can

*Explore Life in the Universe* . . .

*To improve life here*

*To extend life to there*

*To find life beyond*
To improve life here

Space exploration has historically inspired young people to undertake the challenging tasks required for advanced education, where all citizens have the opportunity to be literate in science and technology no matter what their goals may be.

In a competitive world at the dawn of the 21st Century, only NASA will set challenges in exploration sufficiently exciting to motivate the nation’s best students.

“Every child in America deserves to be challenged by high expectations and supported by a commitment to excellence.”

--- George W. Bush
To improve life here

Only from space, enabled by NASA, has our civilization learned to appreciate the complex interplay among the biosphere, the Earth, and the Sun.

Today our observations in low Earth orbit are limited in time and in perspective. Tomorrow, with a vista from beyond low Earth orbit, our perspective will become global in time and space, as we investigate, understand . . . and one day predict . . . the effects of our environment upon ourselves.

*NASA explores the effects of life on the environment . . . . and of the environment on life.*
To improve life here

NASA technology investment makes possible the scientific discovery today and opening the frontier for human exploration tomorrow.

The Challenges

- **Space Transportation**
  - Safe, fast, and efficient

- **Affordable, Abundant Power**
  - Solar and nuclear

- **Optimized Robotic and Human Operations**
  - Dramatically higher productivity; on-site intelligence

- **Crew Health and Safety**
  - Countermeasures and medical autonomy

- **Space Systems Performance**
  - Advanced materials, low-mass, self-healing, self-assembly, self-sufficiency…

Investing in Solutions

- **Reusable Launch Vehicles**

- **Surface Power on Mars**

- **Telerobotics and Autonomy**

- **Active Shielding (M2P2)**

- **Intelligent Spacecraft Systems**
To extend life to there

Those nations that have ceased exploring remain in the backwaters of history and are consigned to follow where others will lead.

Only NASA is developing the capabilities . . . and has the mandate . . . to use humans in space to make possible scientific exploration, discovery, and to inspire a nation.
To extend life to there

Robotic pathfinders are leading humanity’s exploration beyond low Earth orbit, preparing the way for humanity . . .
To extend life to there
To extend life to there
To seek life beyond

Life’s place on the cosmic stage will only be understood when we search for its other homes, in the Solar System . . . and beyond.

Only NASA can search for all life’s origins . . .

From extremes on Earth . . .

. . . to the deserts of Mars . . .

. . . and beyond.
To seek life beyond

And only NASA can carry humanity’s search deep into the Universe . . .

Advanced optical systems . . . seeking life’s abodes among the stars.
“Let us create vessels and sails adjusted to the heavenly ether and there will be plenty of people unafraid of the empty wastes. In the meantime, let us prepare for the brave sky-travelers . . .”

-- Johannes Kepler to Galileo Galilei
Advanced Concept Analysis in Support of the Integrated Space Plan

Section 2.2

Opportunities

November 2002
Structure of the NASA Strategic Plan for Science

- Vision
- Mission
- Agency Goals (10)
  - What we will achieve
- Themes (18)
  - Our structure to implement the Goals
- Objectives (~60)
  - How we will achieve the Goals
- Implementing Strategies
  - A foundation of sound planning and management practices
# NASA Goals

## Strategic Goals

<table>
<thead>
<tr>
<th>Understand and protect our home planet</th>
<th>1. Understand the Earth system and apply Earth system science to improve prediction of climate, weather, and natural hazards.</th>
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<tbody>
<tr>
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<td>2. Enable a safer, more secure, efficient, and environmentally friendly air transportation system.</td>
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<td>3. Create a more secure world and improve the quality of life by investing in technologies and collaborating with other agencies, industry, and academia.</td>
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<thead>
<tr>
<th>Explore the Universe and search for life</th>
<th>4. Explore the fundamental principles of physics, chemistry, and biology through research in the unique natural laboratory of space.</th>
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<tbody>
<tr>
<td></td>
<td>5. Explore the solar system and the universe beyond, understand the origin and evolution of life, and search for evidence of life elsewhere.</td>
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<table>
<thead>
<tr>
<th>Inspire the next generation of explorers</th>
<th>6. Inspire students to pursue careers in science, math, and engineering.</th>
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<td>7. Engage the public in shaping and sharing the experience of exploration and discovery.</td>
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## Enabling Goals

<table>
<thead>
<tr>
<th>8. Improve the provision of access to space for the nation by making it increasingly safe, reliable, and affordable.</th>
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<tbody>
<tr>
<td>9. Demonstrate the feasibility and develop the capabilities required to enable human space exploration beyond low Earth orbit.</td>
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<tr>
<td>10. Enable revolutionary capabilities through new technology.</td>
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</tbody>
</table>
Themes

- Solar System Exploration
- Mars Exploration
- Astronomical Search for Origins
- Structure and Evolution of the Universe
- Critical Aeronautics Solutions
- Space Launch Innovation
- Pioneering Technology
- Commercial Technology Partnerships
- Earth System Science
- Earth Science Applications
- Biological Sciences Research
- Physical Sciences Research
- Commercial Research & Flight Support
- Education Programs
- Space Station
- Space Shuttle
- Space and Flight Support
Challenges to NASA

- Increase the shared experience of space exploration (“being there”)
- Enables *new* science goals—can’t do without humans *on site*
- Increase the pace of science returns ➔ rapid “in-the-field” discoveries rarely possible today
- Reduce the loss of mission returns by rescue/repair/replanning
- Inspire new generations because “they can go!” & vicarious exploration
- Demonstrate leadership: Human/robots “on site” at tangible frontiers evokes world-class science/technological prowess
- Extend life to there while Searching for Life’s records in the Universe (let humans uncover the fossil records!…)
Human Advantage:
Benefit to America

- Encourages pride in our nation and its citizens
- Provides genuine heroes
- Inspires achievement
- Source of wonder, hope, adventure, drama
- Enables vicarious space travel

Benefit to NASA

- Adaptability and responsiveness
- On-site decision making
- Enables complex operations not otherwise possible
- Human insight and intuition
- Recovery of otherwise-lost missions

*Spaceflight is intensely human*
Human Advantage: *Planetary Surfaces*

- **Results:**
  - Humans “on site” enable technology to go and collect unique data *(Greenland ice cores, Lake Vostok access)*
    - Demonstrated here on Earth and on Moon with Apollo
  - Adaptability to real, potentially dynamic, field conditions with real-time adjustment of science activities (dynamic response)
  - Sampling: getting the ‘right stuff’ to make discoveries (humans intelligently narrow the huge sample collection trade-space most rapidly and effectively)
  - Gaining new vantage points, nimbly, and rapidly, with highest potential for breakthrough results
  - Human(in-situ)/Human (extended) interaction offers NEW approaches to challenging field problems
  - Humans naturally “extend life to there” while adaptively “seeking life in the Universe” in best places
Human Advantage: *In Space Servicing*

- Humans in space enable new technology to be inserted into existing systems
  - Extension of science capabilities and operational lifetimes
- Adaptability to real, potentially dynamic, conditions with real-time adjustment of activities (dynamic response)
- Erecting: setting up the complex robotic systems to do the science work (i.e., unfurling new apertures, etc.)
- Gaining new vantage points, nimbly, and rapidly, with highest potential for repair, rescue, and innovative servicing
- Human(in-situ)/Human (extended) interaction offers NEW approaches to challenging in space servicing problems
- Humans naturally “extend life to there” while adaptively “seeking life in the Universe” in best places
Technology: Stepping Stones in the Exploration Strategy

Solar System & Interstellar Access
Remote Robotic Scientific Investigations & Human Precursor Missions

Go anywhere, anytime

Sustainable Planetary Presence

Discover Life's limits

Accessible Planetary Surface

Large optical systems in deep space & Lunar science

Tactical science investigations on extra-terrestrial bodies

Earth’s Neighborhood

Earth and Space science investigations & Testing of human/robotic systems

Earth and LEO

• Science-Driven
• Technology Enabled
• Stepping Stones
• Sequence: Robots, humans, new markets
• Leveraging Partnerships

Sustainable scientific research on extra-terrestrial bodies

• Technology: Stepping Stones in the Exploration Strategy
Technology: Priority Areas for Investment

“Earth Neighborhood” Mission Driven
- Solar Power (High Power)
- Space Assembly, Maintenance & Servicing (Robotic, EVA)
- Cryogenic Propellant Depots
- Biological Risk (Radiation)
- Aero-Assist/Entry and Landing
  - Electric/Electromagnetic Propulsion (High Power)
  - Adaptation and Countermeasures (Gravity)
- Communications and Control
- Human Factors and Habitability

Accessible Planetary Mission Driven
- Regenerative Life Support Systems
- Surface Science & Mobility
- Materials and Structures (Manufacturing Validation)
- Space Medicine and Health Care
- Earth-to-Orbit Transportation
- In-Space Chemical Propulsion
- Nuclear Propulsion

Sustained Planetary Presence Driven
- Advanced Habitation Systems
- Nuclear Power
- In Situ Resource Utilization
- In Situ Manufacturing
- Flying Systems

Current “Top-10”
- Advanced Power (Solar, Nuclear Power)
- Biological Risk (Radiation)
- Space Assembly, Maintenance & Servicing (Robotic, EVA)
- Aero-Braking/Assist/Entry
- Regenerative Life Support / Habitation Systems
- Surface Science & Mobility Systems
- Materials and Structures (Mfg)
- Cryogenic Propellant Depots
  PLUS…
- Systems Studies, Advanced Concepts, etc.
- Technology Flight Demos
Technology: Achievements

- **In-Space Propulsion**
  - Aerocapture
  - Solar Sails
  - Solar Electric Propulsion
  - Nuclear Electric Propulsion

- **Nuclear Systems**
  - **Energy** for science, mobility, playback
  - **Time** for surface reconnaissance and discovery
  - **Accessibility** to planets (latitude & terrain)
  - **Resiliency** and adaptability

- **Space Radiation Initiative**
  - Interaction of radiation with materials and living tissues
  - Critical experiments on ISS, Mars, free flyers
  - Optimized shielding and operations
  - Pharmacological and biological intervention
The U.S. Engineering and Physical Sciences *People* “Crises”

- Rudman Report: 2000
- National Science Foundation “Indicators”: 1995-2002
- National Academy of Engineering Reports: on-going
- Space Policy Institute Report on Origins of Scientists and Engineers: 1989

**Engineering Degrees 1945-2001**

- 33% Retention Loss between Freshman and Senior years.
- At Same time University enrollment is increasing, engineering enrollment decreasing.
- Minority Enrollment decreased by 9% since 1992
- 2001: 7.4% of Undergraduate are foreign nationals, but 42.8% of M.S. and 45% of PhDs are FN
- Taiwan: 35% of undergraduates are engineering students
- China: 46% of undergraduates are engineering students
- US demographics show a shrinking pool of possible engineers without the entry of minorities and women
Catalyst for Excellence
K-12

Creating the pipeline for scientists and engineers

• Instructional materials to meet state and local curriculum standards
• Professional development programs for educators
• Educator involvement in research and development
• Inspiration and motivation

The Enablers:

Universities

The people part of technology and science

• Research Support for Engineering/Physical Sciences Departments
• Undergraduate and Graduate Student Support
• Improved support for institutional capabilities
• Developing Engineering Faculty Pipeline

• NASA needs the output of the K-16+ student pipeline to execute the national Space Exploration vision and mission.
• NASA has in the past, and can in the future, inspire entry into the education pipeline and retain participation in that pipeline for benefit of the entire nation
Best Documented Solution:  
*Hands On* Experiential Involvement

Many NASA Programs have proven successes----but many more opportunities exist

**K-12**

- **EarthKam**: Since 1996 Middle School Students throughout the US have taken pictures of the earth via Camera on Space Shuttle and ISS: Started by Dr. Sally Ride and UCSD.

- **High School Aerospace Scholars**: Pilot Project in Texas funded by Texas Legislature and Hosted by JSC. Over 400 students from throughout the state, representing a large diversity, have designed missions to Mars during a week at JSC while learning science and engineering concepts.

- **Sponsorship of FIRST Robotic Teams**

- **New Concept**: schools throughout the US issued Exploration Licenses, e.g. one square mile of Mars—a real place to study and generate excitement with real time Web linkage to rover video.

**UNIVERSITIES**

- **KC-135 Undergraduate Project Teams**

- **Undergraduate Balloon Teams**

- **Undergraduate Engineering Design Projects**

- **HEDS-UP** (Human Exploration and Development of Space-University Partners Design Teams)

- **Intelligent Synthetic Environments (ISE)** Linked Universities

- **New Research Initiatives to Engineering, Physics and Chemistry Departments for faculty and graduate students: Competitive NASA Research Announcements (NRA’s)**

- **More Fully Utilize the 52 Space Grant University Consortia, EPSCoR, and the University Space Research Association (USRA)**
Advanced Concept Analysis in Support of the Integrated Space Plan

Section 3.0

Requirements

November 2002
Requirements Flow-down from Rationale and Feedback from Design Process

- Space Act & NASA Strategic Plan
- Exploration/Science Rationale
- Science and Exploration Requirements
- Architectural Studies & Technology Trades
- Design Reference Missions and element concepts

Feedback:
- Phasing and deployment
- Optimize human enabled science
- Design enhancing or limiting elements
Requirements

Feedback: Optimize Human Enabled Science and Education

Science
- Missions
- Instruments
- Bandwidth
- Power
- Weight
- Destinations

Human Advantage
- Transportation
- Environmental
- Communication
- EVA/Robotics
- Bio-astronautics
- Power
- Weight
- Destinations
- Assembly
- Repair
- Upgrades
- Operation

Education
- Audio-video
- Tele-control
- Bandwidth
- Destinations
- Human Interaction
- In-situ Teaching & Reporting

Enabled capability

Rationale
Requirements
Operations
Requirement Definition Process

- Define mission requirements & constraints
- Derive System Requirements & constraints
- Design Subsystems
- Validation
<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 0</td>
<td>Space Policy</td>
<td>NASA Administrator</td>
</tr>
<tr>
<td></td>
<td><em>Example: Humans shall explore space, including the LEO, HEO, Libration points, Moon, Mars and beyond.</em></td>
<td></td>
</tr>
<tr>
<td>Level 1</td>
<td>Guiding Principles/Goals</td>
<td>Space Architect</td>
</tr>
<tr>
<td></td>
<td><em>Example: Spacecraft shall protect the crew from radiation hazards</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Example: Return vehicle shall safely return the crew to Earth</em></td>
<td></td>
</tr>
<tr>
<td>Level 2</td>
<td>Design Requirements</td>
<td>Design Team</td>
</tr>
<tr>
<td></td>
<td><em>Example: Transfer vehicle shall support 4-6 crew to ISS</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Example: To support telescope servicing, the vehicle shall support 6 EVAs</em></td>
<td></td>
</tr>
</tbody>
</table>
Requirements

Science: Level 1

- An optimal mix of human and robotic elements shall be employed to maximize the mission scientific return and the safety of the astronauts.
- Scientists shall be involved in every stage of exploration planning from conception to execution to ensure that quality science is accomplished.
- Astronauts with a high level of relevant scientific knowledge and experience shall be included in the missions and mission planning.
- Crew training and exploration planning shall be designed to take advantage of the human initiative, flexibility, adaptability, and inductive and deductive reasoning abilities.
- Space science missions shall be located at optimal destination for science return, consistent with taking advantage of the human enabled leverage.

(NRC/CHEX 1993)
Science: Level 1

Education: Level 1

Architecture: Level 1

- The Architecture shall support multiple science-driven destinations beyond Low Earth Orbit.
- The Architecture shall employ an evolutionary approach to fulfill scientific objectives.
- The Architecture shall support sustainable human presence beyond Low Earth Orbit.
- The Architecture shall provide for the crew arriving at the destination in optimal physical condition.
- Architecture systems and technologies shall be chosen for strategic, architecture-level goals.
- The Architecture shall employ the ISS as a test bed for human factors, life sciences, and critical technologies research

(JSC/EX)
Science: Level 1

Education: Level 1

Architecture: Level 1

- The architecture shall provide the capability to enable crewed support of science payloads located at Lagrange points.
- The architecture shall provide the capability to support L1 science missions and servicing.
- The architecture shall provide the capability to enable crewed science missions to the lunar surface.
- The architecture shall provide global lunar landing capability.
- The architecture shall provide the capability to return the crew from Lunar surface at anytime.

(JSC/EX)
Science: Level 1

Education: Level 1

Architecture: Level 1

- The Earth’s Neighborhood elements shall support future exploration beyond Earth’s Neighborhood.
- The architecture shall comply with NASA “Human Rating Document” (Latest revision)

(JSC/EX)
Requirements

Architecture: Level 1
Science: Level 1
Education: Level 1

To be supplied by Code N
Mission concepts to be supplied or reviewed by NASA HQ

Science Missions: (list in development)

Deep Space L1/L2 and beyond
- Large Space Telescope
- Earth Observing Platform
- Cosmic Background Radiation Polarimeter
- Near Earth Object-Asteroid Exploration

Lunar
- Lunar Astrobiology Laboratory
- Low Frequency Radio Telescope
- Lunar Planetary-Science Exploration
- Solar System Volatiles Search
- South Pole Aikten Basin Exploration

Mars
- Search for extant or fossil biospheres
- Search for Martian water
Example Science Missions: Flow-Down of Common Requirements

**NASA Vision and Mission:**
To improve life here.
To find life beyond.
To understand and protect our home planet.
To explore the universe and search for life.

**Fundamental Questions:**
How did the universe, galaxies, stars, and planets form and evolve, and what is their destiny?
Does life in any form, however simple or complex, carbon-based or other, exist elsewhere than on Earth?
How can we utilize the latest findings about the Sun, Earth, and other planetary bodies to develop accurate, predictive environmental, weather, climate, natural disaster, and natural resource models to help ensure sustainable development and improve the quality of life on Earth?

**Enterprise Strategic Goal:** [Space Science]
Chart the evolution of the universe, from origins to destiny, and understand its galaxies, stars, planets, and life.

**Theme Objectives:** [Enterprise Strategic Objectives (Space Science)]
Understand the structure of the universe, from its earliest beginnings to its ultimate fate.
Explore the ultimate limits of gravity and energy in the universe.
Learn how galaxies, stars, and planets form, interact, and evolve.
Understand the formation and evolution of the solar system and the Earth within it.
Probe the evolution of life on Earth, and determine if life exists elsewhere in the solar system.
Understand our changing Sun and its effects throughout the solar system.

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**Large Far Infrared Space Telescope – Concept A**
**Large Far Infrared Space Telescope – Concept B**
**Cosmic Microwave Background (CMB) Polarimeter**
**Near-Earth Object (NEO) Sample Return**
**Humans to Asteroids: Field Exploration Beyond LEO**
**Lunar South Pole-Aitken Basin Sample Return**
**Mars Precursor Lander**
**Mars Sample Return**
**Earth Science Missions**
Example Space Science Mission:  
Large Far Infrared Space Telescope – Concept A

<table>
<thead>
<tr>
<th>NASA Vision and Mission:</th>
</tr>
</thead>
<tbody>
<tr>
<td>To explore the universe and search for life.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fundamental Question:</th>
</tr>
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<tbody>
<tr>
<td>How did the universe, galaxies, stars, and planets form and evolve, and what is their destiny?</td>
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<thead>
<tr>
<th>Enterprise Strategic Goal (Space Science):</th>
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<tr>
<td>Chart the evolution of the universe, from origins to destiny, and understand its galaxies, stars, planets, and life.</td>
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<table>
<thead>
<tr>
<th>Theme Objectives:</th>
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<td>Understand the structure of the universe, from its earliest beginnings to its ultimate fate.</td>
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<td>Explore the ultimate limits of gravity and energy in the universe.</td>
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<tr>
<td>Learn how galaxies, stars, and planets form, interact, and evolve.</td>
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</table>

<table>
<thead>
<tr>
<th>Mission Objective:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Study interstellar gas and dust over a wide redshift range.</td>
</tr>
<tr>
<td>• What lies at the cores of star- and planet-forming regions?</td>
</tr>
<tr>
<td>• What properties do Kuiper Belt objects have?</td>
</tr>
<tr>
<td>• What is the principal power source for IR-bright galaxies?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mission Implementation:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assemble a 10 m telescope at Lunar L1, and operate it at Sun-Earth L2.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mission-Derived Architecture Requirements:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• High spatial and spectral resolution imaging in the 40-500 µm range.</td>
</tr>
<tr>
<td>• Membrane reflectors, actively cooled detectors, V-groove sunshade.</td>
</tr>
<tr>
<td>• EVAs over ~weeks to assemble and deploy truss at Earth-Moon L1.</td>
</tr>
<tr>
<td>• Infrastructure: crew transfer vehicles, robotic aids, EVA technology.</td>
</tr>
</tbody>
</table>

Rationale: FAIR-DART science objectives can be achieved only by a large-aperture, far-infrared and sub-millimeter, post-James Webb Space Telescope. Due to the size of the large reflectors, it would be impractical to launch it fully assembled.
Example Space Science Mission: 
Large Far Infrared Space Telescope – Concept B

**NASA Vision and Mission:**
To explore the universe and search for life.

**Fundamental Question:**
How did the universe, galaxies, stars, and planets form and evolve, and what is their destiny?

**Enterprise Strategic Goal (Space Science):**
Chart the evolution of the universe, from origins to destiny, and understand its galaxies, stars, planets, and life.

**Theme Objectives:**
Understand the structure of the universe, from its earliest beginnings to its ultimate fate. Explore the ultimate limits of gravity and energy in the universe. Learn how galaxies, stars, and planets form, interact, and evolve.

**Mission Objective:**
Take the next step to explore the far IR part of the sky.

- What is the history of star formation and element production?
- What prebiotic material is in the planet-forming environment?
- How do black holes and their host galaxies interact?

**Mission Implementation:**
Deploy an 8-10 m, cooled, far IR telescope at Sun-Earth L2.

**Mission-Derived Architecture Requirements:**
- Filled 8-10 m aperture, Sun-Earth L2, 0.1 K heterodyne detectors.
- Passive cooling to 4 K with V-groove radiators. Alternate concepts: membrane reflectors (FAIR-DART), and multiple fixed baselines.

**Rationale:**
Dust efficiently reprocesses radiation into the IR and submillimeter parts of the spectrum. The young distant universe is redshifted there from the visible and near IR. Large prebiotic molecules have strong, unique spectral features in this spectral region. Half the luminosity in the universe is observed to be in the far IR.
Example Space Science Mission: Cosmic Microwave Background (CMB) Polarimeter

**NASA Vision and Mission:**
To explore the universe and search for life.

**Fundamental Question:**
How did the universe, galaxies, stars, and planets form and evolve, and what is their destiny?

**Enterprise Strategic Goal (Space Science):**
Chart the evolution of the universe, from origins to destiny, and understand its galaxies, stars, planets, and life.

**Theme Objectives:**
Understand the structure of the universe, from its earliest beginnings to its ultimate fate.
Explore the ultimate limits of gravity and energy in the universe.
Learn how galaxies, stars, and planets form, interact, and evolve.

**Mission Objective:**
Reveal the large-scale structure of the universe.

• What do CMB polarization measurements reveal about the Big Bang, and about the physics of processes that occurred in the early universe at energies far above those accessible to Earth-bound accelerators?
• Is the current paradigm of inflationary cosmology correct?

**Mission Implementation:**
Deploy an ~6 m cooled long-wavelength telescope at Sun-Earth L2.

**Mission-Derived Architecture Requirements:**
• CMB polarization signals are about 10 times smaller than temperature anisotropy signals. To observe the entire sky at the same rate as current experiments would take 500,000 years.

*Rationale:* Minute fluctuations in the CMB are the seeds of all the structure we see today. Detailed CMB observations are fundamentally important to both astronomy and physics. MAP and Planck measure CMB temperature anisotropy.
Example Space Science Mission:  
Near-Earth Object (NEO) Sample Return

<table>
<thead>
<tr>
<th>NASA Vision and Mission:</th>
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<tbody>
<tr>
<td>To understand and protect our home planet. To explore the universe and search for life.</td>
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<tr>
<th>Fundamental Questions:</th>
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<tbody>
<tr>
<td>How did the universe, galaxies, stars, and planets form and evolve, and what is their destiny?</td>
</tr>
<tr>
<td>How can we utilize the latest findings about the Sun, Earth, and other planetary bodies to develop accurate, predictive environmental, weather, climate, natural disaster, and natural resource models to help ensure sustainable development and improve the quality of life on Earth?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Enterprise Strategic Goal (Space Science):</th>
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<tr>
<td>Chart the evolution of the universe, from origins to destiny, and understand its galaxies, stars, planets, and life.</td>
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<tr>
<th>Theme Objective:</th>
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<tr>
<td>Understand the formation and evolution of the solar system and the Earth within it.</td>
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</table>

<table>
<thead>
<tr>
<th>Mission Objective:</th>
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</thead>
<tbody>
<tr>
<td>Understand our origins and ensure our future.</td>
</tr>
<tr>
<td>To what extent did NEOs deliver carbon-based molecules and water?</td>
</tr>
<tr>
<td>What is the composition and structure of solar system building blocks?</td>
</tr>
<tr>
<td>How will we deal with a class of objects that threatens civilization?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mission Implementation:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensively study a NEO from orbit and in situ, and return samples.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mission-Derived Architecture Requirements:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Study structure: imaging, radar, spectroscopy, gravity, seismology.</td>
</tr>
<tr>
<td>Investigate anchoring methods: thrusters, solar sails, mass drivers.</td>
</tr>
<tr>
<td>Precisely track the NEO with transponders, make fuel out of ice.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rationale:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before technologies are developed to deflect NEOs, we need to understand them better. NEOs contain mineral, water, and fuel resources. NEOs are logical stepping stones to human Mars missions: Practice exploration techniques.</td>
</tr>
</tbody>
</table>
### NASA Vision and Mission:
To understand and protect our home planet. To explore the universe and search for life.

### Fundamental Questions:
How did the universe, galaxies, stars, and planets form and evolve, and what is their destiny? How can we utilize the latest findings about the Sun, Earth, and other planetary bodies to develop accurate, predictive environmental, weather, climate, natural disaster, and natural resource models to help ensure sustainable development and improve the quality of life on Earth?

### Enterprise Strategic Goal (Space Science):
Chart the evolution of the universe, from origins to destiny, and understand its galaxies, stars, planets, and life.

### Theme Objective:
Understand the formation and evolution of the solar system and the Earth within it.

### Mission Objective:
- What will NEOs reveal about the early solar system?
- How will NEOs help reduce the cost of future space exploration?
- What will we learn to help guard against the Earth impact threat?

### Mission Implementation:
Send humans to NEOs (Near-Earth Objects), explore, return samples.

### Mission-Derived Architecture Requirements:
- Milli-g fieldwork, surface EVAs, anchoring systems, dust challenge.
- Expand existing NEO search programs and precursor missions.
- Research on space hazards, NEO resources, propulsion technology.

**Rationale:** NEOs are easy to access, offer a rich store of knowledge about the early solar system, and have resources to reduce the cost of future exploration. NEO missions are a practical hedge against an impact threat, and serve as steps toward Mars.
Example Space Science Mission:
Lunar Astrobiology Laboratory

NASA Vision and Mission:
To find life beyond. To explore the universe and search for life.

Fundamental Question:
Does life in any form, however simple or complex, carbon-based or other, exist elsewhere than on Earth?

Enterprise Strategic Goal (Space Science):
Chart the evolution of the universe, from origins to destiny, and understand its galaxies, stars, planets, and life.

Theme Objective:
Probe the evolution of life on Earth, and determine if life exists elsewhere in the solar system.

Mission Objective:
Characterize an abiological environment.

Mission Implementation:
Establish a lunar astrobiology research station.

Mission-Derived Architecture Requirements:
- Short-range remote sensing: reflectance spectroscopy, fluorescence imaging/spectroscopy, gas chromatography/electronic nose.
- Contact instruments: Raman/IR spectroscopy, LIBS (laser induced breakdown spectroscopy), micro-CT (computed tomography).
- Analytical instruments: mass spectrometers, wet chemical probes.

Rationale: The Moon is an ideal negative control for in situ life detection, and is also an excellent environment for curating samples from Mars and elsewhere. Studying water ice will enhance the contrast of potential biosignatures against an abiological background, due to the chemical simplicity of ice compared to lithologic sediment.
Example Space Science Mission: Lunar Low Frequency Radio Telescope

**NASA Vision and Mission:**
To improve life here. To understand and protect our home planet. To explore the universe and search for life.

**Fundamental Questions:**
How did the universe, galaxies, stars, and planets form and evolve, and what is their destiny?
How can we utilize the latest findings about the Sun, Earth, and other planetary bodies to develop accurate, predictive environmental, weather, climate, natural disaster, and natural resource models to help ensure sustainable development and improve the quality of life on Earth?

**Enterprise Strategic Goal (Space Science):**
Chart the evolution of the universe, from origins to destiny, and understand its galaxies, stars, planets, and life.

**Theme Objectives:**
Understand the structure of the universe, from its earliest beginnings to its ultimate fate.
Understand the formation and evolution of the solar system and the Earth within it.
Understand our changing Sun and its effects throughout the solar system.

**Mission Objective:**
Open a new electromagnetic window on the universe.
- What radio emitters await discovery (e.g., extrasolar planets)?
- How can we complement current magnetospheric imagers?
- How do we predict space weather, enhancing astronaut safety?

**Mission Implementation:**
Deploy a low frequency radio telescope array on the lunar surface.

**Mission-Derived Architecture Requirements:**
- 19 easily deployed 20-kg stations, 6 km spacing, 150 kHz - 3 MHz.
- Incremental deployment, part of a larger program.

**Rationale:**
Observe galaxies, stars, pulsars, interstellar medium, and magnetospheric radio (300-700 kHz) emissions. Resolve density profiles of coronal mass ejections.
NASA Vision and Mission:
To understand and protect our home planet. To explore the universe and search for life.

Fundamental Question:
How did the universe, galaxies, stars, and planets form and evolve, and what is their destiny?

Enterprise Strategic Goal (Space Science):
Chart the evolution of the universe, from origins to destiny, and understand its galaxies, stars, planets, and life.

Theme Objective: [ Enterprise Strategic Objective (Space Science) ]
Understand the formation and evolution of the solar system and the Earth within it.

Mission Objective:
Address the first billion years of solar system history.

- What processes marked the initial stages of planet formation?
- How did the impactor flux decay in the solar system’s youth?
- How did this influence the emergence of life (on Earth, Mars)?

Mission Implementation:
Return samples from one of the solar system’s deepest basins.

Mission-Derived Architecture Requirements:
- Put a spacecraft in an area exposing lower crust and mantle rocks.
- Sample the surface rocks, and return them to Earth for analysis.
- Sieve to obtain rocks < 1 cm in size, enhancing sample diversity.

Rationale: The South Pole-Aitken Basin is the oldest and largest well-preserved basin on the Moon, and represents a key event during early heavy bombardment of the inner solar system. It exposes lower crust and possibly some upper mantle. A sample return mission will constrain the nature of the Moon’s crust and mantle, and the early impact history of the inner solar system, and will develop sample acquisition, handling, and return technologies applicable to Mars and other destinations.
Example HEDS Mission in Support of Space Science: Mars Precursor Lander

**NASA Vision and Mission:** [Mission flows from HEDS as well as Space Science strategic goals and objectives]
To extend life to there. To explore the universe and search for life.

**Fundamental Question:**
What is the fundamental role of gravity and cosmic radiation in vital biological, physical, and chemical systems in space, on other planetary bodies, and on Earth, and how do we apply this fundamental knowledge to foster a permanent human presence in space and to improve life on Earth?

**Enterprise Strategic Goal (Space Science):**
Use robotic science missions as forerunners to human exploration beyond Low-Earth Orbit.

**Theme Objective:** [Enterprise Strategic Objective (Space Science)]
Investigate the composition, evolution, and resources of Mars, the Moon, and small bodies.

**Mission Objective:**
Pave the way for safe future human Mars exploration.
- What data sets will reduce the risks to future human explorers?
- What technologies need to be demonstrated before being used for human missions?

**Mission Implementation:**
Collect Mars environmental data, and demonstrate key technologies.

**Mission-Derived Architecture Requirements:**
- Manifest instruments on Mars robotic missions.
- Utilize and test future human technologies on Mars robotic missions.
- Use a dedicated landed mission if the baseline Mars robotic program missions are oversubscribed, lack capability, or will not generate results by needed dates.

**Rationale:**
The existing Mars robotic program should be augmented whenever possible to acquire data sets and demonstrate future human mission technologies. If that is not feasible, a dedicated human precursor lander can carry all instruments and technology demonstration payloads.
Example Space Science Mission: Mars Sample Return

NASA Vision and Mission:
To find life beyond. To explore the universe and search for life.

Fundamental Question:
Does life in any form, however simple or complex, carbon-based or other, exist elsewhere than on Earth?

Enterprise Strategic Goal (Space Science): Chart the evolution of the universe, from origins to destiny, and understand its galaxies, stars, planets, and life.

Theme Objective:
Probe the evolution of life on Earth, and determine if life exists elsewhere in the solar system.

Mission Objective:
Determine whether Mars harbors fossil or extant life.
- Does Mars harbor extant or extinct life?
- How has the climate of Mars changed over time?
- What are the geological processes that have shaped the planet?

Mission Implementation:
Return samples from a well-characterized site, ideally near liquid water.

Mission-Derived Architecture Requirements:
- Return Martian soil, rock and atmospheric samples from a pre-selected landing site
- Protect the samples from forward contamination from Earth
- Protect the Earth from backward contamination from Mars

Rationale: The first returned samples from Mars will greatly increase our knowledge of Martian history, climate, geological processes, and astrobiology. The acquisition of rocks, in addition to soil and atmosphere samples, is considered scientifically essential. Planetary protection, both forward and backward, is critical for purity of the samples and protection of the Earth.
Example Space Science Mission: Template

<table>
<thead>
<tr>
<th>NASA Vision and Mission:</th>
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</thead>
<tbody>
<tr>
<td>Fundamental Question:</td>
</tr>
<tr>
<td>Enterprise Strategic Goal (Space Science):</td>
</tr>
</tbody>
</table>

| Theme Objective: [ Enterprise Strategic Objective ] |

| Mission Objective: |

| Mission Implementation: |

| Mission-Derived Architecture Requirements: |

| Rationale: |

| Reference: |
NASA HQ Codes and NASA Stakeholders shall provide high level (Level 0 and Level 1) requirements

NASA HQ Codes shall provide science mission examples/prototypes to drive Level 2 and higher architecture requirements

Requirements will be collected and captured in a database referencing origin, heritage, and rationale

Standard Form shall be provided to facilitate entry of requirements
Advanced Concept Analysis in Support of the Integrated Space Plan

Section 4.1

Exploration Architecture Analysis

Introduction

November 2002
Outline

- Introduction & Architecture Considerations
  - Trade Space & Decision Tree
- Earth’s Neighborhood
  - Requirements
  - Mission Modes
    - Mission Staging Points
    - Earth Entry Descent & Landing Mode
    - Utility of ISS
  - General Architecture Concept
  - Architecture Analysis
    - Architectures A & B
    - Element Design
- Mars
- Summary & Conclusions to Date
Requirements Flow-down from Rationale and Feedback from Design Process

- Space Act & NASA Strategic Plan
- Exploration/Science Rationale
- Science and Exploration Requirements
- Architectural Studies & Technology Trades
- Design Reference Missions and element concepts

Feedback: optimize human enabled science
Feedback: Design enhancing or limiting elements
Feedback: Phasing and deployment
Many possible program strategies (see next chart)

Strategy chosen will depend upon:
- Resulting funding profile
- Relative priorities
- Desired level of capabilities

Not all decisions must be made at outset
- XTV, HLLV appear to be constants required for any desired beyond-LEO capabilities
Examples of Possible Architecture Pathways

- Extended Mission
- Surface "Sorties"
- Orbital "Visit"
- Surface Outpost
- Surface "Sorties"
- L2 Science
- L1 Ops.
- Humans beyond LEO
- ISS CRV, Assured Acc.

Capabilities:

- Mars Hab
- L1 Infr.
- Science Instr.
- Lunar Hab
- LLV
- MTV
- HLLV
- XTV

Time:

- L2 Science Priority
- Lunar Science, Operations Priority
- Mars Exploration Priority

Elements and Milestones:

- Element IOC
- Milestone

Section 4.1 JSC/B. Drake

Nov. 2002
Exploration Route Map

- **Sun-Earth** L₁, L₂
- **Moon**
- **Earth’s Neighborhood**
- **Accessible Planetary Surfaces**

Legend:
- ☺️ Transfer
- ● Destination
- ○ Major Capability
- ⬤ Primary Route
- ⬤ Alternate Route

- **Earth**
- **Low Earth Orbit**
- **High Earth Orbit**
- **Earth-Moon** L₁, L₂
- **Mars**
Routes that Support Large Telescope Requirements

Direct Requirements (Customer Needs)
• Deliver and support large telescopes operating at Sun-Earth L₂

Derived Requirements (ways to do it)
• Complete assembly/perform maintenance at Low Earth Orbit, Earth-Moon L₁, L₂, or High Earth Orbit
• For Telescope construction: 6-8 2-person EVA sorties
• For Telescope maintenance: 4-6 2-person EVA sorties
• Support for telescope systems and structure
• Robotic/EVA support for construction, servicing, inspection
**Routes that Support Lunar Exploration**

**Direct Requirements (Customer Needs)**
- Transport crew in excellent condition with scientific equipment to the surface of the Moon
- Return the crew and scientific samples to Earth
- Sufficiently support the crew on the surface of the Moon to conduct scientific experiments
- Enable continued human research on the Lunar surface

**Derived Requirements (ways to do it)**
- 4 crewmembers to Lunar surface and return
- Nuclear Surface power to support life support, vehicle needs, science sorties
- Surface mobility to meet scientific requirements
- Shelter (radiation, etc.), Crew health (G in route, exercise, medical, etc.)
Architecture A Launch Synopsis:
Lunar Exploration Mission

LUNAR SURFACE

One Time  Recurring

Crew Transfer  Cargo Transfer

1) L1 Outpost to LEO
2) SEP Stage to LEO
3) L1 Outpost Outfitting in LEO

4) L1 Outpost with SEP Stage to L1
5) SEP Stage to LEO
6) Lunar Lander to LEO
7) Xenon and Thrusters for SEP Stage

8) Lunar Lander with SEP Stage to L1
9) SEP Stage to LEO

E) Crew and Lander to L1 Outpost
D) Crew and Lander to Surface
C) XTV and Crew to L1 Outpost
B) Crew and XTV to LEO
A) XTV Injection Stage to LEO
G) XTV and Crew Landing

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Architecture B Launch Synopsis:
Lunar Exploration Mission

LUNAR SURFACE

One Time ➔ Recurring

Crew Transfer
Cargo Transfer

L1

2) L1 Outpost to L1 using injection stage

4) Lunar Lander to L1 using injection stage

B) XTV and Crew to L1 Outpost

E) XTV and Crew aerocapture to LEO

D) Crew and Lander to L1 Outpost

C) Crew and Lander to Surface

L1

LEO

1) L1 Outpost & injection stage to LEO

3) Lunar Lander & injection stage to LEO

A) XTV & Injection Stage to LEO

F) XTV and Crew Landing

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Exploration Route Map

Routes that Support Mars Exploration

Direct Requirements (Customer Needs)
• Transport crew in excellent condition with scientific equipment to the surface of Mars
• Return the crew and scientific samples to Earth
• Sufficiently support the crew on the surface of Mars to conduct scientific experiments
• Enable continued human research on the surface of Mars

Derived Requirements (ways to do it)
4-6 crewmembers to surface of Mars and return
Nuclear Surface power to support life support, vehicle needs, science sorties
Surface mobility to meet scientific requirements
Shelter (radiation, etc.), Crew health (G in route, exercise, medical, etc.)
Increasing “Performance”
Decreasing vehicle wet mass, decreasing trip times, increasing payload, more challenging mission classes

Propulsion

- Chemical
- Nuclear Thermal
- Solar Electric / Chemical
- Solar Electric
- Nuclear Electric

Aerocapture?

- w/o AC
- w/ AC

Conjunction (long stay) vs. Opposition (short stay)

- Conj
- Opp

Split vs. All-up

- Split
- All Up

ISRU?

- w/o ISRU
- w/ ISRU

1988 “Mars Expedition”
1989 “Mars Evolution”
1990 “90-Day Study”
1991 “Synthesis Group”
1995 “DRM 1”
1997 “DRM 3”
1998 “DRM 4”
1999 “Dual Landers”
2000 SERT (SSP)
Current Studies

*Assumptions not necessarily consistent
Mars Architecture Mass History

Initial Mass in Low Earth Orbit (Metric Tonnes)

- 1988 Mars Expedition (Chem A/B)
- 1989 Mars Evolution (Chem A/B)
- 1990 90-Day Study (NTR)
- 1991 Synthesis Group (NTR)
- 1995 DRM 1 Long Stay (NTR)
- 1997 DRM 3 Refinement (NTR)
- 1998 DRM 4 Refinement (NTR or SEP)
- 1999 Dual Landers (SEP)
- 2000 DTP/NEXT (NTR or SEP)

ISS @ Assembly Complete (470 tons)
Mars Mission Trajectory Options

**Short-Stay Missions (Opposition Class)**
Variations of missions with short Mars surface stays and may include Venus swing-by

**Long-Stay Missions (Conjunction Class)**
Variations of missions with long Mars surface stays.
Mars Mission Delta-V Variations

**Short-Stay Missions (Opposition Class)**

**Long-Stay Missions (Conjunction Class)**

Minimum Total Propulsive DV (Km/Sec)

Earth Launch Date

Earth Departure Date

<table>
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Advanced Concept Work in Support of the Integrated Space Plan

Section 4.0
Exploration Architecture Analysis
Introduction Backup

November 2002
Human Expedition to Mars

**Objective**
- Establishment of early leadership in human exploration of the solar system

**Key Features**
- 3 human expeditions to Mars
- Chemical/aerobrake propulsion
- Split/sprint mission profile
- Aerocapture at earth return
- Vehicle assembly in low-earth orbit (SSF)
- 440-500 day round trip (20 days on Mars surface)
- Total Mission mass = 1628 mt

**Principal Results**
- Short-stay missions are energy intensive, thus requiring large transfer vehicles
- Advanced propulsion technologies (aerocapture and nuclear thermal rocket) can significantly reduce mass requirement (57-72%)
- On-orbit assembly, storage of cryogenic propellants, and vehicle checkout increase mission complexity
- Large mass in LEO requires a heavy-lift launch capability and potentially on-orbit assembly capability
Mars Evolution

Objective

• Emplace a permanent, largely self-sufficient outpost on the surface of Mars

Key Features

• First human flight in 2007 (4 growing to 7 crew)
• Vehicles assembled in LEO (free-flyer platform)
• Chemical/aerobraking propulsion
• Propellant production at Phobos
• Artificial-gravity spacecraft
• Surface stay initially 30-days growing to 500

Principal Results

• Heavy-Lift launch vehicle (140 t to LEO) required to support mass and flight rate requirements
• Even with HLLV, extensive on-orbit assembly and check-out required in low-earth orbit
• Use of nuclear thermal rocket, in addition to aerobraking, would increase payload capability and reduce flight times to and from Mars
• Advanced EVA systems are required to support the extensive surface operations required
• Significant research and development of in-situ resource utilization processes are required
• Architecture requires delivery of approximately 500t to low earth orbit per year
Objective
• To provide a database for the National Space Council to refer to as it considered strategic planning issues
• Agency-wide study commissioned by Admiral Truly after the President’s July 20, 1989 speech

Key Features
• Five reference approaches (generally similar)
• Robotic - Moon - Mars pathway
• Extensive use of:
  • Space Station Freedom for assembly and checkout operations
  • Reusable transportation vehicles (initially expendable)
  • In-Situ Resource Utilization (oxygen from the lunar regolith)
  • Chemical/aerobrake propulsion

Key Trades
• Launch Vehicle Size (80 - 140 mt)
• In-space assembly or direct to the surface
• Freedom, new spaceport, or direct assembly
• Chemical, electric, nuclear, or unconventional
• Aerobraking or all-propulsive
• Expendable or reusable spacecraft
• Propellant or tank transfer
• Open or closed life support
• Zero-gravity or artificial-gravity Mars vehicle
• In situ or Earth-supplied resources

Principal Results
• Premature discussion/disclosure of cost results can have unwanted effects, difficult to characterize long-term initiatives
• Use of local planetary resources can greatly enhance capabilities and reduce the cost of exploration
• Aerobraking reduces vehicle mass by as much as 50% as compared to all chemical systems
• Nuclear thermal propulsion provides a great deal of promise for Mars missions (40% mass reduction)
Charter

- Chartered by the National Space Council to develop several alternatives of exploration, future acquisition of scientific knowledge, and future space leadership.
- Chaired by Tom Stafford, Lieutenant General, U.S. Air Force (ret.)

Four Candidate Architectures

- Mars Exploration
- Science Emphasis for the Moon and Mars
- The Moon to Stay and Mars Exploration
- Space Resource Utilization

Principal Results

- Several supporting technologies identified as key for future exploration:
  - Heavy Lift Launch Vehicle (150-250 mt)
  - Nuclear Thermal Propulsion
  - Nuclear electric surface power
  - Extravehicular activity suit
  - Cryogenic transfer and long-term storage
  - Automated rendezvous and docking
  - Zero-g countermeasures
  - Telerobotics
  - Radiation effects and shielding
  - Closed loop life support systems
  - Human factors for long duration space missions
  - Lightweight structural materials and fabrication
  - Nuclear electric propulsion for follow-on cargo deliv.
  - In situ resource evaluation and processing
Objective

• Develop a “Reference Mission” based on previous studies and data.
• Reference Mission serves as a basis for comparing different approaches and criteria from future studies

Approach

• Limit the time that the crew is exposed to the harsh space environment by employing fast transits to and from Mars and abort to the surface strategy
• Utilize local resources to reduce mission mass
• Split Mission Strategy: Pre-deploy mission hardware to reduce mass and minimize risk to the crew of 6
• Examine three human missions to Mars beginning in 2009
• Utilize advanced space propulsion (Nuclear Thermal Propulsion) for in-space transportation
• Payloads sent directly to Mars using a large launch vehicle (200+ mt to LEO)
• Nuclear surface power for robust continuous power

Principal Results

• Total mission mass approximately 900 mt for the first crew (3 cargo vehicles, 1 piloted vehicle)
• Development of the large launch vehicle is a long-lead and expensive system. Approaches using smaller launch vehicles should be investigated.
Objective

- Refine DRM 1.0 to improve identified weaknesses
- Provide further refinement of systems design and concepts

Approach

- Refine launch strategy to eliminate the need for the large (200+ mt) launch vehicle. Dual launch (80 mt) strategy utilized.
- Repackage payload elements to reduce the physical size of the aerobrake used for Mars aerocapture and entry
- Investigate the need for the redundant surface habitat
- Incorporate emerging technologies and system concepts to reduce architectural mass

Principal Results

- Reduced system masses allowed for the elimination of redundant surface habitat, thus eliminating one Mars cargo vehicle
- Incorporation of TransHab concept in conjunction with other systems improvements (ECLSS, power, etc) resulted in a mass savings of ~30% at Mars entry.
- System mass improvements and revision of mission strategy resulted in over 50% payload mass savings
- Emerging systems concepts including Solar Electric Propulsion and Bi-Modal NTR shown to be viable alternative concepts
- Total mission mass estimates:
  - Nuclear Thermal Propulsion: 418 mt
  - Solar Electric Propulsion: 409 mt (early estimate)
Objective
• Refine DRM 3.0 to improve identified weaknesses
• Provide further refinement of systems design and concepts
• Improve risk abatement strategy

Approach
• Modify mission strategy to incorporate a round-trip crew transfer vehicle instead of pre-deploying the crew return habitat
• Place further emphasis on Solar Electric Propulsion concept (NTR and Chemical/Aerobrake investigated as options)
• Further refinement of In-situ resource utilization concept
• Shuttle derived launch vehicle (80 mt) used for LEO transportation

Principal Results
• Incorporation of a round-trip crew transfer vehicle reduces system reliability requirement from five to three years, but requires an additional rendezvous in Mars orbit
• End-to-end Solar Electric Propulsion vehicle mission concept is shown to be a viable concept, but vehicle packaging and size remain tall-poles
• Total mission mass estimates:
  • Solar Electric Propulsion: 467 mt
  • Nuclear Thermal Propulsion: 436 mt
  • Chemical/Aerobrake: 657 mt *

* similar but not same mission concept
Objective

- Refine Combo Lander approach to eliminate potential long-poles by separating the crew lander functions between two vehicles

Approach

- Long-duration stay mission with fast transits to and from Mars
- Aerobraking at Mars
- Descent/Ascent vehicle for crew transport from orbit, to surface, and back to Mars orbit
- Inflatable habitats for transit and surface vehicles
- CH₄/O₂ propellants brought with the crew of 6
- Solar surface power
- Solar Electric Propulsion used for interplanetary propulsion
- Magnum launch vehicle used for ETO transportation (100 mt to LEO)

Principal Results

- Six 100-mt launches required
- Significant improvement in aeroassist and parachute deployment conditions (as compared to Combo Lander II)
- Surface system reusability is enabled
- Greater improvement in Earth vicinity abort scenarios developed
- Total mission mass estimates:
  - Solar Electric Propulsion: 585 mt
Objective

- Develop a Mars mission approach embodying the philosophy:
  - Go Anywhere, anytime
  - Avoid political obstacles - No HLLV
  - Limit the total mission duration (goal of one-year)

Approach

- Include both short-stay and long-stay mission options
- Investigated both EELV-Exploration Class and 100-mt launch vehicles
- Solar Electric Propulsion and Nuclear Thermal Propulsion options
- Crew size of 6
- Understand trajectory sensitivities for all opportunities and various trip times

Principal Results

- Short-stay missions are very demanding missions
  - One-year round-trip missions occur infrequently (1 out of 7 opportunities)
  - Mission mass varies widely across launch opportunities (400-1600 mt)
  - Short-stay missions provide little time at Mars for contingencies
  - Round-trip mission times for short-stay missions range from 365 to 600 days
- Long-stay missions reduce mission complexity, but require longer overall mission
  - Mission mass constant across launch opportunities (30% variation)
  - Total mission times range from 892-945 days with surface stay times ranging from 501-596 days
- Utilizing EELV-Exploration Class launch vehicle impractical (excessive number of launches and complex orbital assembly and checkout)
- Estimated radiation exposure for long-stay missions is lower than short-stay missions
Advanced Concept Analysis in Support of the Integrated Space Plan

Section 4.1.1
Exploration Architecture Analysis
Earth’s Neighborhood

November 2002
Outline

• Introduction & Architecture Considerations
  – Trade Space & Decision Tree

• Earth’s Neighborhood
  – Requirements
  – Mission Modes
    • Mission Staging Points
    • Earth Entry Descent & Landing Mode
    • Utility of ISS
  – General Architecture Concept
  – Architecture Analysis
    • Architectures A & B
    • Element Design

• Mars

• Summary & Conclusions to Date
Key Architecture Requirements

Programmatic Requirements:

• Support multiple destinations
  – Lunar Surface
  – Sun-Earth L₂ (operational location for IR telescopes)
  – Mars
• Serve as a test bed for future exploration
  – Technologies
  – Operations
  – Systems
• 1st human mission no earlier than 2012
• Crew sizes of 4-6 persons

System Requirements:

• Use existing or “near-existing” launch vehicle systems
  – Shuttle
  – Evolved Expendable Launch Vehicle
  – Shuttle-Derived Launch Vehicle(s)
• Enable access to entire Lunar Surface
  – Expeditionary mission (3-day mission)
  – Extended duration mission (30-day mission)
• Assemble, checkout, and maintain astronomical observatories in space
Mission Approaches

Typical mission architectures are generally defined with each destination considered on its own basis and requiring its own infrastructure – an “expeditionary” mission architecture

- Examples: Mercury, Gemini, Apollo, Skylab, Columbus’ Voyage

An “evolutionary” mission architecture is one which emphasizes an ongoing mission and a mission on which other future missions can be built.

- Examples: ISS, Mars Orbiters as communications relay satellites
Utility of Libration Points

Environment:
- No orbital debris
- Nearly continuous solar energy
- Nearly continuous full-sky viewing
- True deep space environment
- Continuous view of Lunar nearside, Earth, terrestrial magnetosphere
- No atmospheric drag

Operations:
- Global anytime lunar access from L₁ for practically no additional energy
- Formation flying spacecraft mutually accessible with minimal delta-v, slow relative motion
- Excellent outpost/staging node for interplanetary missions
- Very low energy transfers available between libration points via Interplanetary Superhighway System
Lunar Mission Mode: Libration Point vs. Lunar Orbit Rendezvous

- **Operational Considerations**
  - **Lunar Orbit Rendezvous (LOR)**
    - Access to lunar poles would require polar orbit if LOR mission mode utilized
    - Lunar polar orbit provides infrequent opportunities for trans-Earth injection (once every 14 days)
      - Orbit orientation inertially fixed, aligns with efficient trans-Earth trajectory twice a month
    - Total $\Delta V = 8951$ m/s
  - **Libration Point Rendezvous (LPR)**
    - Continuous access from $L_1$ to lunar surface and return
      - Lunar rotation and libration point motion naturally synchronized
    - Continuous access to Earth - landing point partially controllable
    - Total $\Delta V = 10480$ m/s
  - Unique science opportunities at $L_1$
  - Deep-space human exploration analogs exist at $L_1$
  - Support for deep-space human exploration missions
L₁ Staging Profile
3-Day Lunar Surface Mission

- Launch from Earth establishes orbital geometry for L₁ departure
- Two direct-to-L₁ injection opportunities available each day
- Transit opportunities continuously available between L₁ and the lunar surface because of synchronized orbital geometry
  - All lunar landing sites available for practically no additional energy cost
- No wait at Lunar L₁ required for return opportunity orbital plane alignment at Earth
Lunar Orbit Staging Profile
3-Day Lunar Surface Mission (Polar)

- Lunar Lander pre-deployed to polar lunar orbit
  - Lunar Lander orbit around Moon establishes orbital geometry for Earth departure
- Lunar injection opportunities available every 14 days
- Transit opportunities between polar lunar orbit and the lunar surface available every 2 hours for polar landing sites, every 14 days for all other latitudes
- Trans-Earth injection opportunities available every 14 days
Landing Site Restrictions for LOR

In-plane lunar descent/ascent available every 2 hours

In-plane lunar descent/ascent available every 27 days

In-plane lunar descent/ascent available every 2 hours or 14 days depending on latitude of landing site
LOR Earth Return Opportunities:
100 km Polar Parking Orbit

Day 0:
Minimum-Energy Trans-Earth Injection is Available
TEI $\Delta V = 841$ m/s

Day 7:
Non-Regressing Polar Orbit is 90° from the desired TEI orientation
TEI $\Delta V = 2008$ m/s

Day 14:
Minimum-Energy Trans-Earth Injection is Available
TEI $\Delta V = 841$ m/s

Day 21:
Non-Regressing Polar Orbit is 90° from the desired TEI orientation
TEI $\Delta V = 2008$ m/s

Moon's Motion: ~13.2°/day

Polar Orbit Orientation
Lunar Mission $\Delta V$ Budget:
LOR vs. LPR

- LOR Total $\Delta V = 8,951$ m/s
- LPR Total $\Delta V = 10,480$ m/s
Other LPR Considerations:
Science Platform Servicing Missions

Interplanetary Superhighway System provides Low Energy Portals and Pathways (red/green tubes) generated by Libration points

- Efficient for cargo transfers between Earth-Moon and Sun-Earth Libration points

Building, Servicing Instruments & S/C at Lunar L1 Station

Low Energy Transfer Orbit to L1 Outpost
Lunar L₁ to Earth L₂ Transfers

- Assemble and deploy science platforms (advanced astronomical telescopes) at the Lunar L₁ Outpost
- Transfer platforms (14 m/s) from L₁ to a Earth L₂ halo orbit for operation
- Return platforms to Lunar L₁ for servicing and re-deploy
Lunar Mission Mode: Preliminary Conclusions

- Lunar Orbit Rendezvous (LOR) offers a lower overall mission ∆V cost with fewer critical maneuvers at the expense of anytime departure capability
  - Ascent/Descent opportunities at non-polar, non-equatorial sites separated by at least 14 days)

- Libration Point Rendezvous (LPR) is favorable because it enables global lunar surface access for no additional cost, continuous access to and anytime return from the lunar surface, and the potential for reusability and support for other exploration programs
  - Requires a higher total mission ∆V (17%)

- Current Earth’s Neighborhood architecture concepts incorporate LPR as a mission strategy for synergy with other exploration objectives
Earth Entry Descent & Landing
Mission Mode Trade

Trans-Earth Trajectory

- Propulsive Capture into LEO
  - Excessive Propellant Mass
- Aerocapture into LEO
  - RNDZ w/STS
  - RNDZ w/ISS
- Independent Deorbit & Entry
- Direct Entry
  - Vehicle, Crew returned in STS
  - 2001/02 Lunar Gateway Study
  - Apollo

Land Landing
- Runway Landing
- CRV/SAR Site
- Sea-Based Recovery Forces
- Land-Based Recovery Forces

Water Landing
- CRV/SAR Site
- Sea-Based Recovery Forces
- Land-Based Recovery Forces

Vehicle, Crew returned in STS

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Nov. 2002
Suggested Trade: Aerocapture vs. Direct Entry

Trans-Earth Trajectory

Aerocapture into LEO

Direct Entry

Propulsive Capture into LEO

RNDZ w/STS

RNDZ w/ISS

Independent Deorbit & Entry

Vehicle, Crew returned in STS

Land Landing

CRV/SAR Site

Runway Landing

Water Landing

Sea-Based Recovery Forces

Land-Based Recovery Forces

Runway Landing
### Suggested Trade: Aerocapture vs. Direct Entry

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<tr>
<th>Benefits</th>
<th>Challenges</th>
<th>Comments</th>
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</table>
| **Direct Entry**                                                         | • Simplest, fewest events  
  • Proven heritage  
  • Shortest mission duration | • Large number of worldwide landing sites required (Wx alt.)  
  • Earth landing lighting determined by lunar departure time  
  • Stage/module disposal constraints  
  • Higher peak heating | • Probably simplest entry configuration – no subsequent propulsive events |
| **Aerocapture**                                                          | • Control over landing site, lighting thru LEO phasing  
  • Stage/module disposal flexibility  
  • Lower peak heating | • Additional critical propulsive events required  
  • Potentially additional propulsion system  
  • Unproven maneuver (see comments)  
  • Additional mission duration  
  • Additional ∆V required (see comments) | • Candidate guidance strategies have existed for >20 years  
  • Additional propellant required may be offset by reduced coazimuth, disposal ∆V |

### Related Design and Operational Considerations

- Desired degree of vehicle reusability
  - Final entry mass
  - System packaging
  - Recovery system mass, applicable recovery system options
- Post-aerocapture entry crossrange requirements
  - Orbit loiter time vs. number of landing sites & opportunities
Three land landing zones are sufficient to allow any-time return from moon (or L₁): 15°-19°N, equatorial, and 15°-19°S, assuming:
- No weather alternate sites required
- No landing lighting constraints
- “Coazimuth” control (~120 m/s ΔV)
- ± 12 hrs TE flight time capability (longitude control)

Stage or module disposal
- 30 m/s ΔV at EI-15 to EI-60 provides 500 - 1300 km vacuum IP shift, -8° to -10° FPA (good for debris footprint control)
- Nominal vehicle landing will be >1000 km downrange of vacuum IP (0.3 L/D)
- Compatibility of landing zone will depend upon
  - Approach azimuth (controllable)
  - Debris footprint

Bottom Line: Land Landing Preferred over Water
  - Pros:
    - Crew Safety (emergency egress, water motion, vehicle sinking, etc.)
    - High proximity to SAR, Med facilities
    - Higher synergy with ACRV (shared support infrastructure)
    - LCC (recovery ops, vehicle refurbishment, etc.)
  - Cons:
    - Higher ΔV req. (coazimuth & stage disposal)
    - Potential stage/module disposal issues
Earth EDL Mission Mode: Preliminary Conclusions

• Land landing looks favorable for the same reasons concluded in Landing & Recovery Options study
• However, considerable accessibility constraints exist when combined with direct entry – aerocapture scenarios should be traded
• Effects of higher (L/D>0.3) ranging/crossranging capability have not been assessed and may be significant (direct)
• Vehicle degree of reusability and packaging trades may influence configuration & performance
Negative impacts on ISS operations:

- A full ISS crew (7) + exploration crew (4-6) exceeds planned ISS habitation capabilities
- Increased traffic interferes with ISS μ-g quiescent periods
- Dedicated infrastructure and mission support would be required to support exploration
  - Customized docking port(s)
  - Crew consumables and habitation support
  - Power and thermal heat rejection for docked vehicles

Negative impacts to exploration missions:

- Lengthens overall mission duration by requiring wait periods for orbit planes to align
  - Departure opportunities to and from $L_1$ only available once every 10 days
  - Departure opportunities to a fixed lunar orbit extremely rare
- Increases mission complexity by adding critical rendezvous & docking events to the mission sequence
- Launching payloads to higher-inclination orbits (such as ISS) penalizes launch vehicle lift capability
- ISS staging increases total mission $\Delta V$, reducing useful payload mass
Architecture Mission Modes

Summary

• Use **libration point rendezvous** for lunar mission staging and science platform assembly, deployment, and servicing missions

• The nominal Earth entry, descent, and landing mode will be either **LEO aerocapture + deorbit** or **direct entry** pending the results of further trade studies with **land landing** as the nominal landing mode

• The ISS **will not** be used for LEO mission staging
Architecture Functional Breakdown

- **L1 Gateway**
  - **Launch**
  - **Transfer to L1**
  - **L1 Science**
    - **Lunar Surface Science**
      - **Extended Surface Mission**
      - **Surface Mission**
    - **Telescope Assembly Mission**
    - **Science Missions (TBD)**
General Architecture Concept

Overview:

1. **Exploration Transfer Vehicle & High Energy Injection Stage**
   - Transports crew and cargo between LEO and Lunar L1.
   - Nominal aerocapture+entry with contingency direct Earth return.

2. **L1 Outpost**
   - "Gateway" to the Lunar surface.
   - Outpost for staging missions to Moon, Mars and telescope construction.

3. **Lunar Lander**
   - Transports crew between Outpost and Lunar Surface.
   - 9-day mission (3 days on Lunar surface).

4. **Solar Electric Propulsion Stage** [Architecture-Dependent]
   - High-efficiency SEP used to deliver cargo from LEO to a final destination.
   - SEP Stage returns to Earth for reuse.

5. **Lunar Habitat**
   - 30-day surface habitat placed at Lunar South Pole.

6. **Earth L2**

7. **Moon**

8. **Mars**

9. **Low-Energy Transfer** 
   - "Interplanetary Superhighway"
Architecture Analysis Overview

- Two reference architectures have been developed for comparison purposes.
- The first architecture (known henceforth as Architecture A) is distinguished by the use of the medium-lift Space Shuttles and augmented expendable launch vehicles for launch needs.
- Architecture B incorporates Shuttle-derived heavy-lift launchers for ETO launch.
Architecture A Overview

- Architecture A utilizes the Shuttle (24 mt to LEO) and augmented Evolved Expendable Launch Vehicles (40 mt to LEO) for Earth-to-orbit launch of architecture elements

- Architecture A will launch the transfer vehicle/crew and injection stage separately to a circular low-Earth orbit of 400 km x 28.5° with the transfer vehicle returning directly to Earth at the end of the mission
  - **Step 1:** Launch the Exploration Transfer Vehicle (XTV) injection stage to LEO on an EELV.
  - **Step 2:** Launch the entire XTV and exploration crew to LEO with the Shuttle or EELV. The XTV will rendezvous and dock with the injection stage, and depart to L₁.

- A low-thrust solar electric propulsion (SEP) stage will be used to deliver architecture cargo elements such as landers and habitats to Lunar L₁ and Low Lunar Orbit
Architecture B Overview

• Architecture B utilizes the Shuttle-derived Magnum launch vehicle for Earth-to-orbit launch of architecture elements (100 mt to LEO)

• Architecture B will launch the transfer vehicle, crew and injection stage in a single launch to a circular low-Earth orbit of 278 km x 28.5° with the transfer vehicle returning directly to Earth at the end of the mission

• The high-energy injection stage used for the Exploration Transfer Vehicle (XTV) will be used (scaled as necessary) to deliver architecture cargo elements to Lunar L1 and Low Lunar Orbit
Launch Vehicle Candidates & Payload Performance

Lift Capability to Low Earth Orbit (metric tons)

- Space Shuttle
- EELV-H
- Shuttle-Class
- Magnum
### Exploration Launch Comparison

#### Earth’s Neighborhood Missions

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<th>IMLEO 1</th>
<th>IMLEO 2</th>
<th>IMLEO 3</th>
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<tbody>
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<td><strong>Telescope Assembly</strong></td>
<td>150 mt *</td>
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<tr>
<td><strong>Lunar Expedition</strong></td>
<td>240 mt *</td>
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<tr>
<td><strong>Mars Mission</strong></td>
<td>450 mt *</td>
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#### Launch Comparison

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<th>Launches</th>
<th>Probability of Launch Success</th>
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<tr>
<td><strong>EELV-H</strong></td>
<td>9</td>
<td>80%</td>
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<td>(Payload to LEO = 23 mt)</td>
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<tr>
<td>Probability of Launch Failure = 1/40</td>
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<tr>
<td><strong>Shuttle-Class</strong></td>
<td>3</td>
<td>99%</td>
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<tr>
<td>(Payload to LEO (small shroud) = 71 mt)</td>
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<tr>
<td>(Payload to LEO (large shroud) = 60 mt)</td>
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<tr>
<td>[Assumes 4-segment SRMs]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probability of Launch Failure = 1/400</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Magnum</strong></td>
<td>2</td>
<td>99%</td>
</tr>
<tr>
<td>Probability of Launch Failure = 1/400</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note: A launch mass packaging efficiency of 75% is assumed for on-orbit assembly.*

---

*Telescope Assembly mission includes launches for infrastructure buildup*  
*Lunar Expedition includes launches for infrastructure buildup*
Architecture Elements

- Exploration Transfer Vehicle
  - Human transport from Earth to Lunar $L_1$ and return

- High-Energy Transportation Stage
  - Injection Stage
    - Provides initial boost for XTV
    - Delivers cargo to Lunar $L_1$ and Lunar Orbit [Arch. B]
  - Solar Electric Propulsion Stage [Arch. A only]

- $L_1$ Outpost

- Lunar Lander
  - Human transport from Lunar $L_1$ to surface and return

- Lunar Habitat
Architecture Transportation Elements

In-Space Transportation
- Deep-space propulsion for capture, orbital maintenance, and element return to Earth
- Key Technologies & Options:
  - Advanced Chemical (CH₄/O₂)
  - Long-term Cryo Storage

Earth-to-Orbit
- Transports cargo elements and crew from Earth to low-Earth orbit
- Options:
  - Shuttle-derived
  - Evolved EELV

High-Energy Injection
- Injects mission payloads from low-Earth orbit toward their intended destination
- Key Technologies & Options:
  - Advanced Chemical (H₂/O₂)
  - Solar Electric Propulsion
  - Long-term Cryo Storage

Descent / Ascent
- Deep-space propulsion for descent to and ascent from the lunar surface
- Key Technologies & Options:
  - Advanced Chemical (CH₄/O₂)
  - Long-term Cryo Storage

Earth Return
- High-energy aeroassist for orbital capture and entry of Earth’s atmosphere
- Key Technologies & Options:
  - Advanced Ablators
Architecture A Launch Synopsis:
Lunar Exploration Mission

**LUNAR SURFACE**

**One Time**

1) L1 Outpost to LEO
2) SEP Stage to LEO
3) L1 Outpost Outfitting in LEO
4) L1 Outpost with SEP Stage to L1
5) SEP Stage to LEO
6) Lunar Lander to LEO
7) Xenon and Thrusters for SEP Stage
8) Lunar Lander with SEP Stage to L1

**Recurring**

9) SEP Stage to LEO
10) L1 Outpost to LEO
11) SEP Stage to LEO
12) L1 Outpost with SEP Stage to L1

**E) Crew and Lander to L1 Outpost**

**D) Crew and Lander to Surface**

**C) XTV and Crew to L1 Outpost**

**F) XTV and Crew Aerocapture to LEO**

**G) XTV and Crew Landing**
Architecture B Launch Synopsis:
Lunar Exploration Mission

LUNAR SURFACE

One Time ➔ Recurring

Crew Transfer
Cargo Transfer

L1

- 2) L1 Outpost to L1 using injection stage
- 3) Lunar Lander & injection stage to LEO
- 4) Lunar Lander to L1 using injection stage

LEO

- 1) L1 Outpost & injection stage to LEO
- 3) Lunar Lander & injection stage to LEO
- A) XTV & Injection Stage to LEO
- E) XTV and Crew aerocapture to LEO
- B) XTV and Crew to L1 Outpost
- C) Crew and Lander to Surface
- D) Crew and Lander to L1 Outpost
- F) XTV and Crew Landing

*Human rated launch vehicle option

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Lunar Surface Expedition Mission Events

1A
- SEP Stage Launch on EELV
- Lunar Lander Launch on EELV

1B
- Lunar Lander Launch on Magnum

2A
- XTV Launch on EELV w/ crew
- Injection Stage launch on EELV
- Crew transfer to L1
- Lunar L1
- Lunar Surface Mission

2B
- XTV Launch on Magnum w/ crew
- Human rated launch vehicle option
- Return Crew to Earth

3
- Lander transfer to L1

4
## Mission Timeline Comparison:
### 3-Day Lunar Surface Mission

<table>
<thead>
<tr>
<th>Mission Phase</th>
<th>Phase Duration</th>
<th>Mission Elapsed Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A. Injection Stage to LEO [Architecture A]</td>
<td>0 days</td>
<td>-24 days</td>
</tr>
<tr>
<td>XTV w/ crew to LEO [Architecture A]</td>
<td>0 days</td>
<td>-3 days</td>
</tr>
<tr>
<td>XTV Rendezvous &amp; Dock w/ Injection Stage [Architecture A]</td>
<td>2.5 days</td>
<td>-0.5 days</td>
</tr>
<tr>
<td>1B. XTV w/crew &amp; Injection Stage Launch to LEO [Architecture B]</td>
<td>0 days</td>
<td>-0.5 days</td>
</tr>
<tr>
<td>2. XTV Checkout in LEO</td>
<td>0.5 days</td>
<td>+0.0 days</td>
</tr>
<tr>
<td>3. LEO to L1 Transit</td>
<td>3.5 days</td>
<td>+3.5 days</td>
</tr>
<tr>
<td>4. Outpost Prox-Ops &amp; Docking</td>
<td>1 day</td>
<td>+4.5 days</td>
</tr>
<tr>
<td>5. Lunar Mission Prep. / Lunar Lander Checkout</td>
<td>2 days</td>
<td>+6.5 days</td>
</tr>
<tr>
<td>6. L1 to Lunar Surface Transit</td>
<td>2.5 days</td>
<td>+9 days</td>
</tr>
<tr>
<td>7. Lunar Surface Mission (3-day mission)</td>
<td>3 days</td>
<td>+12 days</td>
</tr>
<tr>
<td>8. Lunar Surface to L1 Transit</td>
<td>2.5 days</td>
<td>+14.5 days</td>
</tr>
<tr>
<td>9. Outpost Prox-Ops &amp; Docking</td>
<td>1 day</td>
<td>+15.5 days</td>
</tr>
<tr>
<td>10. Outpost Ops and XTV Checkout</td>
<td>2 days</td>
<td>+17.5 days</td>
</tr>
<tr>
<td>11. L1 to LEO Transit &amp; Aerocapture</td>
<td>3.5 days</td>
<td>+21.0 days</td>
</tr>
<tr>
<td>12. Post-Aerocapture Ops to Landing</td>
<td>&lt;0.5 day</td>
<td>+21.5 days</td>
</tr>
</tbody>
</table>
Common Crew Vehicle Design Capture

Core Crew Vehicle
- Common crew element satisfying multiple mission capabilities
- Key Design Requirements:
  - Re-configurable for 4-7 crew
  - Independent one day mission duration
  - Autonomous / manual operations
  - Propulsive orbital maneuvering
  - Controlled aerodynamic flight

ISS Crew Return
- Provides safe and expeditious recovery of astronauts from low-Earth orbit
- Core Vehicle Configuration Changes:
  - Configured for 4 deconditioned crew
  - Medical emergency provisions
  - Emergency undock capability
  - ISS interfaces and six-month to two-year on-orbit stay
- Key Issues:
  - EELV launch compatibility including automated delivery to ISS
  - Degree of vehicle reusability

LEO Crew Transfer
- Crew transfer to low-Earth orbit and return
- Core Vehicle Configuration Changes:
  - Crew escape for aborts
  - Configured for 5 crew (3 ISS transfer)
  - 12 day mission duration for ISS support
  - Service Module for extended mission duration (propulsion, power, thermal control, life support consumables)
  - EVA systems for on-orbit satellite servicing and repair
- Key Issues:
  - EELV launch compatibility and human rating
  - Degree of vehicle reusability

Near-Earth Transfer
- Transport crew to lunar vicinity and return to Earth
- Core Vehicle Configuration Changes:
  - Configured for 4-6 crew (mission dependent)
  - Crew escape for aborts
  - 12+8 day mission
  - Deep-space environmental conditions
  - Service Module for extended mission duration (propulsion, power, thermal control, life support consumables)
  - EVA systems for servicing and repair as required
  - Injection stage for trans-lunar injection
- Key Issues:
  - Lunar return velocities
  - Large launch vehicle
  - Degree of vehicle reusability

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### XTV Capabilities Comparison

<table>
<thead>
<tr>
<th>Architecture A</th>
<th>Architecture B</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 crew</td>
<td>6 crew (Room for 7)</td>
</tr>
<tr>
<td>Crew time in XTV = 12 days</td>
<td>Crew time in XTV = 12.5 days</td>
</tr>
<tr>
<td>ISS not used for XTV staging</td>
<td>ISS not used for XTV staging</td>
</tr>
<tr>
<td>XTV launched in STS or EELV to 400 km circ., 28.5° inclination</td>
<td>XTV launched in Magnum to 278 km circ., 28.5° inclination</td>
</tr>
<tr>
<td>Injection stage launched on EELV</td>
<td>Combined Injection stage and XTV launch</td>
</tr>
<tr>
<td>EELV payload capability to staging orbit = 40,000 kg</td>
<td>Magnum payload capability to staging orbit = 100,000 kg</td>
</tr>
<tr>
<td>XTV pressurized volume = 8.25 m³/person</td>
<td>XTV pressurized volume = 8.25 m³/person</td>
</tr>
<tr>
<td>XTV cargo = 300 kg</td>
<td>XTV cargo = 300 kg</td>
</tr>
<tr>
<td>Aero shape is an ellipsled</td>
<td>Aero shape is TBD</td>
</tr>
</tbody>
</table>
Exploration Transfer Vehicle:  
Architecture A

• Requirements
  – Launch in Space Shuttle or EELV
  – Utilize space storable propellants
  – Crew of six
  – Total $\Delta V$ capability of 1955 m/s
  – Nominal return mode of aerocapture followed by Earth entry and land landing
  – 25% inert mass margin

• Current Concept
  – Integral LOX/CH$_4$ propulsion system
  – Slender-body, mid L/D shape for structural simplicity, good flying qualities, and lower stagnation point temperatures
  – PEM Fuel Cells for power generation
  – Parachute for descent and landing

• Launch Requirements for Mission to L1
  – XTV: 1 Shuttle/EELV
  – Injection Stage: 1 EELV

<table>
<thead>
<tr>
<th></th>
<th>XTV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Mass</td>
<td>9,971</td>
</tr>
<tr>
<td>Growth</td>
<td>2,493</td>
</tr>
<tr>
<td>Propellant</td>
<td>9,972</td>
</tr>
<tr>
<td>TOTAL</td>
<td>22,436</td>
</tr>
</tbody>
</table>

NOTE: All masses in kg
Exploration Transfer Vehicle: Architecture B

• Requirements
  – Launch on Magnum class vehicle
  – Utilize space storable propellants
  – Crew of six
  – Total ΔV capability of 1955 m/s
  – Nominal return mode of aerocapture followed by Earth entry and land landing
  – 25% inert mass margin

• Current Concept
  – Crew Escape for human-rated launch option
  – Integral LOX/CH₄ propulsion system
  – Slender-body, mid L/D shape for structural simplicity, good flying qualities, and lower stagnation point temperatures
  – Service module for consumables storage
  – PEM Fuel Cells/Batteries/PV Arrays for power generation

• Launch Requirements for Mission to L1
  – XTV & Injection Stage: 1 Magnum

<table>
<thead>
<tr>
<th>XTV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Mass</td>
<td>15,060</td>
</tr>
<tr>
<td>Growth</td>
<td>3,760</td>
</tr>
<tr>
<td>Propellant</td>
<td>11,830</td>
</tr>
<tr>
<td>TOTAL</td>
<td>30,650</td>
</tr>
</tbody>
</table>
Injection Stage:  
Architecture A

- **Requirements**
  - Launch on EELV (40 mt/launch)
  - Utilize high performance cryogenic propellants
  - Capability to loiter in LEO for 21 days
    - Rationale: Launch timing for Architecture A; missed departure opportunities for LEO staging
  - Total ΔV capability of 3120 m/s for trans-L1 injection from 400 km x 400 km LEO
  - 20% inert mass margin

- **Current Concept**
  - LOX/LH₂ propulsion system
  - Propellant storage via solar arrays and cryocoolers
  -Disposable blanket/MMOD shield

- **Launch Requirements for Mission to L1**
  - Injection Stage: 1 EELV
  - XTV: 1 STS/EELV
Injection Stage:
Architecture B

- **Requirements**
  - Launch on Magnum class vehicle
  - Launch with other Architecture B elements
  - Utilize high performance cryogenic propellants
  - Total ΔV capabilities:
    - Lunar Habitat: 4052 m/s for 100 km LLO insertion from 278 km x 278 km LEO
    - Lunar Lander: 3254 m/s for low-energy weak-stability boundary trajectory to L₁ from 278 km x 278 km LEO
  - 20% inert mass margin

- **Current Concept**
  - LOX/LH₂ propulsion system

- **Launch Requirements**
  - 1 Magnum class vehicle

---

<table>
<thead>
<tr>
<th>Payload</th>
<th>Resupply</th>
<th>XTV</th>
<th>Habitat</th>
<th>Lander</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔV (m/s)</td>
<td>TBD</td>
<td>3,120</td>
<td>4,052</td>
<td>3,254</td>
</tr>
<tr>
<td>Dry Mass</td>
<td>TBD</td>
<td>5,930</td>
<td>6,860</td>
<td>6,220</td>
</tr>
<tr>
<td>Growth</td>
<td>TBD</td>
<td>1,180</td>
<td>1,370</td>
<td>1,240</td>
</tr>
<tr>
<td>Propellant</td>
<td>TBD</td>
<td>40,100</td>
<td>57,460</td>
<td>49,180</td>
</tr>
<tr>
<td>TOTAL</td>
<td>TBD</td>
<td>47,210</td>
<td>65,690</td>
<td>56,640</td>
</tr>
</tbody>
</table>

**NOTE:** All masses in kg
## Injection Stage Trades:

### Architecture B

<table>
<thead>
<tr>
<th>Element</th>
<th>Direct Insertion</th>
<th>Weak Stability Boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>XTV</td>
<td>Lander</td>
</tr>
<tr>
<td>Departure Point</td>
<td>LEO 278 km circ</td>
<td>LEO 278 km circ</td>
</tr>
<tr>
<td>Destination</td>
<td>L1</td>
<td>L1</td>
</tr>
<tr>
<td></td>
<td>L1</td>
<td>LLO 100 km circ</td>
</tr>
<tr>
<td>ΔV (m/s)</td>
<td>3,120</td>
<td>3,905</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3,254</td>
</tr>
<tr>
<td>Payload Mass (kg)</td>
<td>30,653</td>
<td>35,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>35,000</td>
</tr>
<tr>
<td>Trip Time</td>
<td>82 hrs</td>
<td>82 hrs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90-180 days</td>
</tr>
<tr>
<td>Injection stage</td>
<td>47,210</td>
<td>77,340</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td></td>
<td>56,640</td>
</tr>
<tr>
<td>Propellant</td>
<td>40,100</td>
<td>67,910</td>
</tr>
<tr>
<td>Dry mass</td>
<td>5,930</td>
<td>7,860</td>
</tr>
<tr>
<td>Margin</td>
<td>1,180</td>
<td>1,570</td>
</tr>
<tr>
<td>Total Launch</td>
<td>77,860</td>
<td>112,340</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td></td>
<td>91,640</td>
</tr>
</tbody>
</table>
Solar Electric Propulsion Stage
[Architecture A Only]

**Mission:** High-efficiency solar electric propulsion (SEP) is used in the Earth’s Neighborhood architecture to deliver uncrewed elements from low-Earth orbit to a final destination. The SEP Stage subsequently returns to Earth for reuse.

- **Destination:** LEO/Lunar $L_1$
- **Element Design Lifetime:** 2-5 missions
- **Crew Size:** N/A
- **Mission Duration:** 170 days out/50 back
- **Element Mass:**
  - Stage: 35,000 kg
  - Payload: 30,000 kg
  - Post-outfitting: 65,000 kg (145,000 lb)
- **Element Volume:**
  - PV Array Area: 7,300 $m^2$
- **Power & Propulsion System:**
  - Average/Peak: 580 kWe
  - Power Generation: Photovoltaic Arrays
  - Energy Storage: Batteries
  - Propellant: Xenon
- **Support Missions:**
  - Propellant resupply: Every mission
  - Electric Thrusters: Every mission

Mission:
High-efficiency solar electric propulsion (SEP) is used in the Earth’s Neighborhood architecture to deliver uncrewed elements from low-Earth orbit to a final destination. The SEP Stage subsequently returns to Earth for reuse.
Lunar L1 Outpost
[Architectures A & B]

**Mission:** The Lunar L₁ Outpost is a mission staging and crew habitation platform stationed at the Lunar L₁ libration point for assembling and maintaining large astronomical observatories and conducting expeditions to the lunar surface.

- **Destination:** Lunar L₁
- **Element Design Lifetime:** 15 yrs
- **Crew Size:** 4 persons
- **Mission Duration:** 10-30 days
- **Element Mass:**
  - Launch: 22,800 kg
  - Outfitting: 600 kg
  - Post-outfitting: 23,400 kg (52,000 lb)
- **Element Volume:**
  - Launch: 145 m³
  - Inflated: 275 m³
- **Power & Propulsion System:**
  - Average/Peak: 12 kWe/15 kWe
  - Power Generation: Photovoltaic Arrays
  - Energy Storage: Li-ion Batteries
  - Propellant: O₂/CH₄
- **Support Missions:**
  - Outfitting at LEO: One mission/architecture
  - Life Support resupply: One mission/two years
Lunar Lander
[Architectures A & B]

**Mission:** The Lunar Lander is capable of delivering a crew of four to any site on the lunar surface and supporting that crew for three days on the surface. The Lander returns the crew to L1 at the end of the mission.

- **Destination:** Lunar L1/Lunar Surface
- **Element Design Lifetime:** 1 mission
- **Crew Size:** 4 persons
- **Mission Duration:** 8 days (3 on Moon)
- **Element Mass:**
  - Propellant: 26,900 kg
  - System Mass: 8,000 kg
  - Total: 34,900 kg (77,000 lb)
- **Element Volume:**
  - Pressurized: 21 m³
  - Habitable: 16 m³
- **Power & Propulsion System:**
  - Average: 1.3 kWe/3.1 kWe
  - Power Generation: PEM Fuel Cells
  - Propellant: O₂/CH₄
- **Support Missions:**
  - None (Disposable Vehicle)
Mission: Long-duration planetary surface missions are enabled in the Earth’s Neighborhood architecture through the use of a Lunar Habitat pre-deployed to the lunar polar regions. Mission crews are delivered to the Lunar Habitat and return to L1 via the Lunar Lander.

- **Destination:** Lunar Surface (North or South Pole)
- **Crew Size:** 4 persons
- **Mission Duration:** 30 days
- **Element Mass:**
  - Propellant: 14,300 kg
  - System Mass: 12,900 kg
  - Total: 27,200 kg (60,000 lb)
- **Element Volume:**
  - Pressurized: 240 m³
- **Power & Propulsion System:**
  - Average: 2.4 kWe/4.1 kWe
  - Power Generation: Photovoltaic Arrays
  - Energy Storage: Li-ion Batteries
  - Propellant: O₂/CH₄
- **Support Missions:**
  - Human Consumables: Every mission
## Mission Element Summary: Architecture A

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
<th>Number of Crew</th>
<th>Mission Duration</th>
<th>Launch Mass</th>
<th>Mission</th>
<th>Number of Launches for Element</th>
</tr>
</thead>
</table>
| **L1 Lunar Lander** | Number of crew: 4  
Mission duration: 8 days  
Launch mass: ~35,000 kg  
Mission: L1 to Moon to L1  
Number of launches: 1 EELV per lander | | | | | |
| **Exploration Transfer Vehicle** | Number of crew: 6  
Mission duration: 12 days  
Launch mass: 22,440 kg  
Mission: LEO to L1 to Earth  
Number of launches for element: 1 STS | | | | | |
| **L1 Outpost** | Number of crew: 6  
Mission duration: Indefinite  
Launch mass: 22,900 kg  
Mission: LEO to L1  
Number of launches: 1 EELV and 1 STS (for outfitting) | | | | | |
| **Lunar Habitat** | Number of crew: 4  
Mission duration: 30 days  
Launch mass: 27,200 kg  
Mission: LEO to Moon  
Number of launches: 1 EELV | | | | | |
| **Injection Stage** | Number of crew: N/A  
Mission duration: 14 days (loiter)  
Payload: Lunar Transfer Vehicle  
Launch mass: 37,000 kg  
Mission: LEO to L1  
Number of launches for element: 1 EELV | | | | | |
| **Solar Electric Propulsion Stage** | Number of crew: N/A  
Payload: Lander, Hab, Outpost  
Launch mass: ~35,000 kg  
Mission: LEO to L1 to LEO  
Number of launches: 1 EELV and 1 STS (recurring) | | | | | |
# Mission Element Summary: Architecture B

<table>
<thead>
<tr>
<th>L1 Lunar Lander</th>
<th>Exploration Transfer Vehicle</th>
<th>L1 Outpost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of crew: 4</td>
<td>Number of crew: 6</td>
<td>Number of crew: 6</td>
</tr>
<tr>
<td>Mission duration: 8 days</td>
<td>Mission duration: 12.5 days</td>
<td>Mission duration: Indefinite</td>
</tr>
<tr>
<td>Launch mass: ~35,000 kg</td>
<td>Launch mass: 30,650 kg</td>
<td>Launch mass: 22,900 kg</td>
</tr>
<tr>
<td>Mission: L1 to Moon to L1</td>
<td>Mission: LEO to L1 to Earth</td>
<td>Mission: LEO to L1</td>
</tr>
<tr>
<td>Number of launches: 1 Magnum launch per lander</td>
<td>Number of launches: 1 Magnum launch per mission</td>
<td>Number of launches: 1 Magnum launch</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lunar Habitat</th>
<th>Injection Stage</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of crew: 4</td>
<td>Number of crew: N/A</td>
<td></td>
</tr>
<tr>
<td>Mission duration: 30 days</td>
<td>Mission duration: 14 days (loiter)</td>
<td></td>
</tr>
<tr>
<td>Launch mass: 27,200 kg</td>
<td>Launch mass: 65,690 kg</td>
<td></td>
</tr>
<tr>
<td>Mission: LEO to Moon</td>
<td>Mission: LEO to L1</td>
<td></td>
</tr>
<tr>
<td>Number of launches: 1 Magnum launch</td>
<td>Number of launches: 1 Magnum launch</td>
<td></td>
</tr>
<tr>
<td>*Note: Injection stage sized for Lunar Habitat to LLO</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Advanced Concept Analysis in Support of the Integrated Space Plan

Section 4.1.2

Exploration Architecture Analysis
Mars

November 2002
Outline

• Introduction & Architecture Considerations
  – Trade Space & Decision Tree
• Earth’s Neighborhood
  – Requirements
  – Mission Modes
    • Mission Staging Points
    • Earth Entry Descent & Landing Mode
    • Utility of ISS
  – General Architecture Concept
  – Architecture Analysis
    • Architectures A & B
    • Element Design
• Mars
• Summary & Conclusions to Date
**Exploration of Mars**

**Objectives**

**Chart Our Destiny**
- Send explorers to the limits of technology
- Understand the solar system forces and processes that affect the future habitability of Earth
- Find extraterrestrial resources of human interest
- Assess suitability of selected planetary locales for future human exploration and commercialization
- Conduct in-depth scientific investigations

**Origin of Life and its Existence Beyond Earth**
- Understand the sources and reservoirs of water and organics ... the building blocks of life
- Determine the planetary conditions required for the emergence of life
- Search for evidence of past and present life elsewhere in the solar system

**Solar System Formation and Evolution**
- Understand the origin of the solar system and the forces that formed Earth and the other planets
- Determine the evolutionary processes that led to the diversity of solar system bodies and the uniqueness of the planet Earth
- Use the exotic worlds of our solar system as natural science laboratories
Mars Mission Goals and Objectives

**Goals and Objectives**
- Balance technical, programmatic, and safety risks
- Maximize scientific return
- Provide an operationally simple mission
- Develop a flexible implementation strategy
- Maximize human health and safety
- Low mission mass

**Groundrules and Assumptions**
- Examine multiple missions to Mars
- Programmatic assumption of first human mission in 2018, with cargo in 2016
- Insure that the systems are capable of operating in each injection opportunity through the 15-year synodic cycle
- Crew size should be minimized, but sufficient to meet science and operational needs
- Do not assume that crews return to the same site
Mission Design Considerations

Mission Class
- Short-Stay (opposition class)
- Long-Stay (conjunction class)

Crew Risk Exposure
- Zero-gravity
- Radiation
- Mission duration

Other Considerations
- Mission aborts
- Mission mass and launch strategy
- Pre-deployment (spilt mission) strategies
- Technology assumptions
- Departure and staging scenarios
Example Human Mars Mission Decision Tree
Increasing “Performance”
Decreasing vehicle wet mass, decreasing trip times, increasing payload, more challenging mission classes

Propulsion
- Chemical
- Nuclear Thermal
- Solar Electric / Chemical
- Solar Electric

Aerocapture?
- w/o AC
- w/ AC

Conjunction (long stay) vs. Opposition (short stay)
- Excessive Mass
- Conjunction (1952 Von Braun)
- Opp
- Conj

Split vs. All-up
- Split
- All Up

ISRU?
- w/o ISRU
- w/ ISRU

Mars Mission Trade Space

1988 “Mars Expedition”
1989 “Mars Evolution”
1990 “90-Day Study”
1991 “Synthesis Group”
1995 “DRM 1”
1997 “DRM 3”
1998 “DRM 4”
1999 “Dual Landers”
1989 Zubrin, et.al*
1994-99 Borowski, et.al
2000 SERT (SSP)
Current Studies

*Assumptions not necessarily consistent

Section 4.1.2 JSC/B. Drake
Nov. 2002
Mars Mission Planning

• Earth-Mars Mission Planning
  – Trips to Mars and back are, in effect, a double rendezvous problem
  – First rendezvous outbound (with Mars) must be developed considering influence of the rendezvous inbound (with Earth)
  – Practical considerations dictate favorable (and different) planetary alignments relative to the sun for both transfers

• Synodic Period
  – is the period of time necessary for the phase angle between Earth and Mars to repeat itself
  – Repetition rate for identical Earth-Mars phasing, and therefore launch opportunities for similar mission classes, is ~26 months
  – The eccentricity of Mars’ orbit causes significant variations in Earth-Mars relative distance and velocity from one opportunity to the next
  – The entire range of Earth-Mars geometry is encompassed by seven launch opportunities, or about 15 years
  – Before definitive claims of mission characteristics or propulsion system capabilities are made, analysis across the 15-year cycle should be performed
Earth-Mars Orbital Characteristics

**Opposition:** Minimum Earth-Mars distance varies from 60-100 million km. Round-trip communication time varies from 6-11 minutes.

**Conjunction:** Maximum Earth-Mars distance varies from 350-400 million km. Round-trip communication time varies from 40-45 minutes; also solar occultations (i.e., no communication) for approx. 2 weeks.

---

**Mars**
- Perihelion: 1.4 AU
- Aphelion: 1.6 AU
- Orbital period: 687 days
- Mean velocity: 24 km/sec
- Equatorial radius: 3398 km

**Earth**
- Perihelion: 1.0 AU
- Aphelion: 1.0 AU
- Orbital period: 365 days
- Mean velocity: 30 km/sec
- Equatorial radius: 6378 km

---

Section 4.1.2  JSC/B. Drake

Ref. Johnson Space Center

Nov. 2002
Mars Mission Trajectory Options

**Short-Stay Missions**  
*(Opposition Class)*

Variations of missions with short Mars surface stays and may include Venus swing-by

**Long-Stay Missions**  
*(Conjunction Class)*

Variations of missions with long Mars surface stays.
Short-Stay Mission Implications

• Significant variation of propulsion requirements for the Short-Stay mission across synodic cycle (100%) dictates need for advanced propulsion technology
  – Nuclear Thermal Propulsion
  – High-Power Electric Propulsion

• Short stay in the vicinity of Mars can compromise mission return and crew safety
  – Limited time for gravity-acclimation
  – Limited time for contingencies or dust storms
  – Majority of time spent in deep space (zero-gravity & deep space radiation)

• Total mission duration for the Short-Stay Mission on the order of 12-22 months
  – System reliability still critical to mission success and crew safety
  – Short (one-year) missions are possible, but limited to single opportunities over the 15-year synodic cycle

• Venus swing-by’s can reduce propulsive requirement (and thus mission mass)
  – Pass within 0.72 AU of the sun (increases radiation and thermal load)
Long-Stay Mission Implications

- **Small variation (10%) of propulsion requirement for the Long-Stay mission across the 15-year synodic cycle**
  - Can go any opportunity
  - Vehicles and systems common between opportunities

- **Long-Stay mission trip times can be reduced for minimal impacts, thus reducing life science concerns of deep space travel (radiation and zero-gravity exposure)**

- **Long stay in the vicinity of Mars increases mission return**
  - Sufficient time for gravity-acclimation
  - Sufficient time for dust storms or other contingency situations
  - Majority of time spent on Mars (improved gravity and radiation environment)

- **Total mission duration on the order of 30 months**
  - System reliability still critical to mission success and crew safety
Delta-V Variations

Short-Stay Missions
(Opposition Class)

Long-Stay Missions
(Conjunction Class)
Total Mission $\Delta V$ vs Earth Departure Date
Low-Earth Orbit Departure

ASSUMPTIONS
Aeroentry @ Mars/Earth
Parking Orbits:
Earth Departure = 407 X 407 km
Mars Aeroentry
Mars Departure = 500 X 500 km
Earth Aeroentry

Mission $\Delta V$ (m/s)

Earth Departure Date

Ref. Johnson Space Center
ASSUMPTIONS
Aeroentry @ Mars/Earth
Parking Orbits:
Earth Departure = 407 X 407 km
Mars Aeroentry
Mars Departure = 33,793 X 250 km
Earth Aeroentry

One-Year Round Trip
Short-Stay No Venus Swingby
Short-Stay with Venus Swingby
Long-Stay Minimum Energy
Long-Stay Fast Transits
Minimum Solar Distance vs. Mission Opportunity
Short-Stay Mars Missions

Radiation doses during solar fly-by can increase 2-8 times

Assumptions:
- All propulsive mission
- Earth parking orbit = 407 km
- Mars parking orbit = 500 km
- 40 day Mars stay
- Figure of merit = Total $\Delta V$ (all legs)
- All minimum solar distances are due to inbound leg(s) unless accompanied by an "O" indicating minimum solar distance due to the outbound leg

Earth Departure Date

Min. Solar Distance vs. Mission Opportunity

G. Condon/JSC/EG

Ref. Johnson Space Center

Nov. 2002
# Mission Characteristic Comparisons

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Short-Stay Mission</th>
<th>Long-Stay Mission</th>
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</thead>
<tbody>
<tr>
<td>Mission Duration (days)</td>
<td>365-661</td>
<td>892-945</td>
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<tr>
<td>Surface Stay</td>
<td>30</td>
<td>501-596</td>
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<tr>
<td>One-Way Transits</td>
<td>104-357</td>
<td>134-210</td>
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<tr>
<td>Total Transit Time</td>
<td>335-631</td>
<td>296-413</td>
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<tr>
<td>Trajectory Characteristics</td>
<td>Venus Swing-by</td>
<td>No Venus Swing-by</td>
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<tr>
<td>Closest Approach to Sun</td>
<td>0.35 – 0.72 AU</td>
<td>1.0 AU</td>
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<tr>
<td>Total Mission Mass (mt)</td>
<td>500-1200</td>
<td>400-700</td>
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<tr>
<td>% Vehicles</td>
<td>21%</td>
<td>31%</td>
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<tr>
<td>% Propellant</td>
<td>74%</td>
<td>47%</td>
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<tr>
<td>% Surface Systems</td>
<td>5%</td>
<td>22%</td>
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1 Assuming Nuclear Thermal Propulsion (Isp 925 sec)
2 First Piloted Flight - 90 Day Study
3 First Piloted Flight - Mars Design Reference Mission
# Technology and Mission Implications

<table>
<thead>
<tr>
<th></th>
<th><strong>Short-Stay</strong></th>
<th><strong>Long-Stay</strong></th>
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</thead>
<tbody>
<tr>
<td><strong>Transportation</strong></td>
<td>• Advanced propulsion <strong>required</strong> for reasonable mass</td>
<td>• Advanced propulsion enhances missions (lower mass or shorter transits)</td>
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<tr>
<td><strong>Earth-to-Orbit</strong></td>
<td>• Large mission mass necessitates high launch rate and/or larger launcher</td>
<td>• Lower mission mass relieves launch requirement and launch rate</td>
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<tr>
<td><strong>Human Health</strong></td>
<td>• Certification process of long zero-g space missions unknown</td>
<td>• Mission transits within US zero-g spaceflight experience</td>
</tr>
<tr>
<td></td>
<td>• Crew exposure to surface environment minimized</td>
<td>• Extended exposure of crew to surface environment</td>
</tr>
<tr>
<td><strong>System Reliability</strong></td>
<td>• Similar (12-22 months)</td>
<td>• Similar (30 months)</td>
</tr>
<tr>
<td><strong>Mission Focus</strong></td>
<td>• Transportation and propulsion</td>
<td>• Surface and mission return</td>
</tr>
</tbody>
</table>

Ref. Johnson Space Center

Nov. 2002
Mars Architecture Key Attributes

- Crew of 4-6
- Short (30-day) initial visits for focused local science evolving to long (500-day) stays for extensive regional exploration
- Total mission durations range from 365 to 950 days.
- Capability to go to Mars any opportunity
- Maximum use of capabilities developed for Earth’s Neighborhood
- Ability to introduce new technologies as they are developed
- Advanced transportation and enhanced launch capacity required to reduce risk and architecture cost
Mars Exploration Transportation Elements

**Earth-to-Orbit**
- Transports cargo elements and crew from Earth to low-Earth orbit
- Options:
  - Shuttle-derived
  - Clean-sheet approach

**In-Space Transportation**
- Deep-space propulsion for element delivery and return to Earth
- Key Technologies & Options:
  - Nuclear Electric Propulsion
  - Solar Electric Propulsion
  - Advanced Chemical

**Aeroassist**
- Utilization of Mars atmosphere for capture, entry, and descent
- Key Technologies & Options:
  - Advanced Ablators
  - Integrated Launch Shroud / Aeroshell

**Descent / Ascent**
- Deep-space propulsion for descent to, and ascent from, the martian surface
- Key Technologies & Options:
  - Advanced Chemical (CH₄/O₂)
  - Long-term Cyro Storage

**Earth Return**
- High-energy aeroassist for orbital capture and entry of Earth’s atmosphere
- Key Technologies & Options:
  - Advanced Ablators
Mars Mission Launches Required and Associated Reliability

TOTAL LAUNCH MASS - 450 Metric Tonnes

Number of Launches Required

Payload per Launch (Metric Tonnes)

Cumulative Launch Reliability

Launch Reliability = 99.7% (STS Reliability)

97% (EELV Reliability Req.)

94% (World-wide Reliability)

LOSS OF COMMONALITY WITH STS INFRASTRUCTURE

- INTEGRAL AEROBRAKES LOST
- INTEGRAL INJECTION STAGES LOST
- PACKAGING INEFFICIENCIES INCREASE
- ONORBIT INTEGRATION COMPLEXITY INCREASEs

NO AERO-CAPTURE

ISS-SCALE PACKAGING EFFICIENCIES

IDEAL PACKAGING EFFICIENCY

Launch Reliability = 99.7%

Ideal Packaging Efficiency

97% (EELV Reliability Req.)

94% (World-wide Reliability)

TOTAL LAUNCH MASS - 450 Metric Tonnes

NO AERO-CAPTURE

ISS-SCALE PACKAGING EFFICIENCIES

IDEAL PACKAGING EFFICIENCY

Launch Reliability = 99.7%

Ideal Packaging Efficiency

97% (EELV Reliability Req.)

94% (World-wide Reliability)
The Forward Deployment Strategy

**Cargo Missions**

**Crew Mission**

*Forward Deployment Provides the Crew Dual Abort Paths*

Architectural/Functional Backup

Architectural Backup for Crew #1

Outbound | Prior to Crew Arrival | Crew Arrival

Depart Earth | Arrive Mars | Depart Mars | Arrive Earth
## Forward Deployment Sequence

### Short-Stay Mission Sequence

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<tr>
<td>2 Crew</td>
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<td>3 Cargo</td>
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</table>

- **Crew Transits**
- **Surface Mission**
- **Cargo Outbound**
- **Overlapping Resources**
- **Unoccupied Wait**

### Long-Stay Mission Sequence

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<tr>
<td>3 Cargo</td>
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</tr>
</tbody>
</table>

- **Crew Transits**
- **Surface Mission**
- **Cargo Outbound**
- **Overlapping Resources**
- **Unoccupied Wait**

**NO Overlapping of mission resources**
Mars Long-Stay Mission Overview Option
(Solar Electric Propulsion Option)


2. Surface Habitat and exploration gear aerocaptures into Mars orbit
   - Descent/Ascent Vehicle aerocaptures and remains in Mars orbit for the crew

3. Crew rendezvous with Descent/Ascent Vehicle in Mars Orbit then lands in vicinity of Habitat Lander

4. Crew travels to Mars in “fast transit” 180-206 day transfer. Aerocaptures into Mars orbit

5. Transit Habitat vehicle delivered to LEO. SEP spirals Transit Habitat to High Earth Orbit. Crew delivered to vehicle via crew taxi. (Option: SEP spirals back to LEO for reuse).

6. Habitat remains in Mars orbit
   - In-depth regional exploration (500-600 days). Crew ascends and rendezvous with waiting Transit Habitat

7. Crew lands on surface. 30 days provided to satisfy “long-stay” criteria.

8. Crew returns to Earth on “fast transit” 180-206 day transfer.

9. Direct capsule entry at Earth

Total mission duration: 892-945 days
Time on Mars surface: 500-600 days
Surface Architecture

**Outpost Missions (Bite Size Chunks)**
- Full Mission and augmented systems
  - Rovers
  - Power (nuke)
  - Science (drills)
  - etc.

**Basic Survivability (30 Days)**
- Short-stay capability (30 days)
  - Ascent vehicle and propellant (abort-to-orbit)
  - Contingency science
  - Common lander design

**Full Mission Capability (18 Months)**
- Full surface mission support systems
  - Power
  - Life Support
  - Maintenance
  - Thermal
  - Crew accommodations
  - Science
  - Common lander design
Mission Sequence
High Earth Orbit Boost Phase

**UNPILOTED VEHICLES**

- "Shuttle Class" 2 SEP launched to low Earth orbit
- "Shuttle Class" 3 SEP launched to low Earth orbit
- "Shuttle Class" 4 SEP vehicle boosts Transit Habitat to High Earth Orbit
- STS 4 / Taxi Servicing mission in High Earth Orbit

**PILOTED VEHICLES**

- "Shuttle Class" 1 Transit Habitat launched to low Earth orbit
- STS 1 & 2 Transit Habitat outfitting missions
- "Shuttle Class" 5 SEP vehicle launched to low Earth orbit
- "Shuttle Class" 6 SEP vehicle boosts Transit Habitat to High Earth Orbit
- STS 3 / Taxi Transit Habitat servicing mission in High Earth Orbit
Mission Sequence
Trans-Mars Injection / Mars Arrival Phase

Unpiloted Vehicles injected toward Mars on near minimum energy transfers

Unpiloted vehicles aerocapture into Mars orbit prior to the crew

Crew transfers to Descent/Ascent Vehicle

Transit Habitat performs rendezvous with Descent/Ascent vehicle in Low Mars Orbit.

STS 5 / Taxi Flight Crew Delivery to Transit Habitat

Transit Habitat Trans-Mars Injection (180-206 day transfers)

Transit habitat aerocaptures into Mars orbit

Surface Habitat performs deorbit, entry, descent, and precision landing on Mars
Mission Sequence
Surface Mission / Mars Ascent / Return Phases

- **Initial Operations**: 30 days for systems checkout and crew acclimation. Contingency abort-to-orbit capability.
- **Initial Habitat Operations**: Safe vehicle, habitat inflation, power system deployment, habitat outfitting and systems checkout.
- **Surface Exploration**: Concentrates on the search for life, drilling, geology, and microbiology investigations (up to 18 months long).
- **Ascent & Rendezvous**: Ascent from Mars surface and rendezvous with Transit Habitat in low-Mars orbit.
- **Low-Mars Orbit Wait**: Transit Habitat remains in low-Mars Orbit during surface mission (unmanned).
- **Earth Return**: Direct Earth entry at end of mission.
- **Crew performs**: deorbit, entry, descent, and precision landing on Mars in Descent / Ascent Vehicle.
**Mars Transit Vehicle**
- Supports mission crew of six for up to 200-day transits to and from Mars
- Return propulsion stage integrated with transit system
- Provides return-to Earth abort capability for up to 30 hours post-TMI
- Total Vehicle Mass in High-Earth Orbit = 188 mt

**Mars Surface Habitat**
- Vehicle supports mission crew of six for up to 18 months on the surface of Mars
- Provides robust exploration and science capabilities
- Descent vehicle capable of landing 36,000 kg
- Total Vehicle Mass in High-Earth Orbit = 99 mt

**Descent/Ascent Vehicle**
- Transports six crew from Mars orbit to the surface and back to orbit
- Provides contingency abort-to-orbit capability
- Supports six crew for 30-days
- Vehicle capable of utilizing locally produced propellants
- Total Vehicle Mass in High-Earth Orbit = 103 mt

Section 4.1.2  JSC/B. Drake
Low-Earth Orbit Rendezvous and Docking

- Utilizing a large volume, large mass launch vehicle requires only automated rendezvous and docking

- Both Earth surface and LEO based navigation and control infrastructure utilized to enable LEO operations

- Dual launch sequence:
  - Mars payload launched first to LEO
  - Injection stage launched second
  - Mars payload acts as primary control vehicle during rendezvous and docking maneuver

- Vehicles remotely checked out in LEO prior to initiating Trans-Mars Injection maneuver
Solar Electric Vehicle Transportation Concept

2016

Cargo Boost
SEP-1 vehicle boosts cargo vehicles to high Earth departure orbit

2018

Piloted/Cargo Boost
Both cargo and piloted vehicles are boosted to high Earth departure orbit

2020

Return
SEP-2 vehicle returns to LEO for new propulsion module and mission payload

Return
SEP-1 vehicle returns to LEO for new propulsion module and mission payload
Mars Transit Habitat

- Supports mission crew of six for up to 200-day transits to and from Mars
- Provides zero-g countermeasures and deep-space radiation protection
- Return propulsion stage integrated with transit system
- Provides return-to Earth abort capability for up to 30 hours post-TMI

### Mars Transit Habitat

<table>
<thead>
<tr>
<th>TRANSIT HABITAT</th>
<th>Mass (kg)</th>
<th>Stowed Vol. (M3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 Power System</td>
<td>5834.6</td>
<td>0.000</td>
</tr>
<tr>
<td>2.0 Avionics</td>
<td>287.0</td>
<td>0.140</td>
</tr>
<tr>
<td>3.0 Environmental Control &amp; Life Support</td>
<td>3948.9</td>
<td>19.133</td>
</tr>
<tr>
<td>4.0 Thermal Management System</td>
<td>1257.3</td>
<td>5.260</td>
</tr>
<tr>
<td>5.0 Crew Accommodations</td>
<td>4309.9</td>
<td>30.719</td>
</tr>
<tr>
<td>6.0 EVA Systems</td>
<td>886.7</td>
<td>2.922</td>
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<tr>
<td>7.0 Structure</td>
<td>896.9</td>
<td>0.000</td>
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<tr>
<td>Crew Margin (15%)</td>
<td>2475.9</td>
<td>8.726</td>
</tr>
<tr>
<td>Food (Return Trip)</td>
<td>2436.0</td>
<td>8.473</td>
</tr>
<tr>
<td>Food (Outbound Trip)</td>
<td>2436.0</td>
<td>8.473</td>
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<tr>
<td>Food (Contingency)</td>
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<td>25.461</td>
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</table>

**Total Transit Habitat Mass: 32629.1 kg 109.306 M3**

**Crew Taxi/Earth Return Capsule**: 3246.5 kg 0.000 M3

**Circ Stage**: 14770.6 kg 0.000 M3
- Stage: 567.7 kg 0.000 M3
- Propulsion: 1301.6 kg 0.000 M3
- Propellants: 12901.3 kg 0.000 M3

**Aerobrake**: 4848.5 kg 0.000 M3

**TEI Stage**: 51429.8 kg 0.000 M3
- Stage: 1286.0 kg 0.000 M3
- Propulsion: 2363.1 kg 0.000 M3
- Propellants: 47780.7 kg 0.000 M3

**TMI Stage**: 66583.9 kg 0.000 M3
- Stage: 1455.1 kg 0.000 M3
- Propulsion: 2518.5 kg 0.000 M3
- Propellants: 62610.3 kg 0.000 M3

**INITIAL MASS IN HIGH EARTH ORBIT**: 173508.4 kg
Mars Habitat Lander

- Vehicle supports mission crew of six for up to 18 months on the surface of Mars
- Provides robust exploration and science capabilities
- Descent vehicle capable of landing 36,000 kg

### Payloads and Systems

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<tr>
<th>Mass (kg)</th>
<th>Stowed Vol. (M$^3$)</th>
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<tr>
<td>30325.2</td>
<td>99.996</td>
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<tr>
<td>1.0 Power System</td>
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<td>3.0 Environmental Control &amp; Life Support</td>
<td>3948.9</td>
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<td>4.0 Thermal Management System</td>
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<td>5.0 Crew Accommodations</td>
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<td>6.0 EVA Systems</td>
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<td>7.0 In-Situ Resource Utilization</td>
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<td>8.0 Mobility</td>
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<td>9.0 Science</td>
<td>829.9</td>
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<tr>
<td>10.0 Margin (15%)</td>
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<tr>
<td>Food</td>
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### Ascent Stage

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<td>Propulsion</td>
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<td>Propellants</td>
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### Descent Stage

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<tr>
<td>(Payload Down)</td>
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<tr>
<td>Propulsion</td>
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### Aerobrake

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<tr>
<th>Mass (kg)</th>
<th>Stowed Vol. (M$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4656.2</td>
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</table>

### Circ/Deorbit Stage

<table>
<thead>
<tr>
<th>Mass (kg)</th>
<th>Stowed Vol. (M$^3$)</th>
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</thead>
<tbody>
<tr>
<td>9494.0</td>
<td>0.000</td>
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<tr>
<td>Stage</td>
<td>365.0</td>
</tr>
<tr>
<td>Propulsion</td>
<td>1339.5</td>
</tr>
<tr>
<td>Propellants</td>
<td>7789.5</td>
</tr>
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</table>

### TMI Stage

<table>
<thead>
<tr>
<th>Mass (kg)</th>
<th>Stowed Vol. (M$^3$)</th>
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</thead>
<tbody>
<tr>
<td>24357.3</td>
<td>0.000</td>
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<tr>
<td>(TMI Payload)</td>
<td>57254.8</td>
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<tr>
<td>Stage</td>
<td>686.4</td>
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<tr>
<td>Propulsion</td>
<td>2045.9</td>
</tr>
<tr>
<td>Propellants</td>
<td>21625.1</td>
</tr>
</tbody>
</table>

### INITIAL MASS IN HIGH EARTH ORBIT

<table>
<thead>
<tr>
<th>Mass (kg)</th>
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</thead>
<tbody>
<tr>
<td>81712.1</td>
</tr>
</tbody>
</table>

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Mars Descent / Ascent Vehicle

- Transports six crew from Mars orbit to the surface and return to Mars orbit
- Provides contingency abort-to-orbit capability
- Vehicle supports crew for 30-days
- Vehicle capable of utilizing locally produced propellants

<table>
<thead>
<tr>
<th>Payloads and Systems</th>
<th>Mass (kg)</th>
<th>Stowed Vol. (M³)</th>
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</thead>
<tbody>
<tr>
<td>1.0 Power System</td>
<td>4762.0</td>
<td>0.000</td>
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<tr>
<td>2.0 Avionics</td>
<td>153.0</td>
<td>0.279</td>
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<tr>
<td>3.0 Environmental Control &amp; Life Support</td>
<td>1037.6</td>
<td>3.983</td>
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<tr>
<td>4.0 Thermal Management System</td>
<td>527.4</td>
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<td>5.0 Crew Accommodations</td>
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<td>5.776</td>
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<td>6.0 EVA Systems</td>
<td>1085.0</td>
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<tr>
<td>7.0 In-Situ Resource Utilization</td>
<td>0.0</td>
<td>0.000</td>
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<tr>
<td>8.0 Mobility</td>
<td>1200.4</td>
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<td>9.0 Science</td>
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<td>1.600</td>
</tr>
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<td>10.0 Structure</td>
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<td></td>
<td>1415.1</td>
<td>3.599</td>
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<tr>
<td></td>
<td>360.0</td>
<td>1.252</td>
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<tr>
<td></td>
<td>558.0</td>
<td>-</td>
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</table>

| Ascent Stage         | 17779.2   | 1.000            |
| Crew Module          | 1617.5    | 1.000            |
| Stage                | 471.3     | 0.000            |
| Propulsion           | 2121.1    | 0.000            |
| Propellants          | 13569.3   | 0.000            |

| Descent Stage        | 12876.5   | 0.000            |
| (Payload Down)       | 31246.3   | -                |
| Stage                | 1242.3    | 0.000            |
| Propulsion           | 3436.0    | 0.000            |
| Propellants          | 8198.2    | 0.000            |

| Aerobrake            | 4656.2    | 0.000            |

| Circ/Deorbit Stage   | 9494.0    | 0.000            |
| Stage                | 365.0     | 0.000            |
| Propulsion           | 1339.5    | 0.000            |
| Propellants          | 7789.5    | 0.000            |

| TMI Stage            | 24357.3   | 0.000            |
| (TMI Payload)        | 58273.1   | -                |
| Stage                | 686.4     | 0.000            |
| Propulsion           | 2045.9    | 0.000            |
| Propellants          | 21625.1   | 0.000            |

INITIAL MASS IN HIGH EARTH ORBIT 82630.4
Solar Electric Propulsion Vehicle

Photovoltaic Array Blanket

Articulated Thruster Boom

Inflatable Ribs

Kapton Webbing

Mars Payload

SETV Bus Module

SEP Transfer Vehicle

<table>
<thead>
<tr>
<th>Component</th>
<th>Total Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reusable SEP Power Module</td>
<td>27,935</td>
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<tr>
<td>Central Bus</td>
<td>3,770</td>
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<tr>
<td>Power System</td>
<td>12,370</td>
</tr>
<tr>
<td>Manipulator Arm</td>
<td>11,795</td>
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<tr>
<td>SEP Propulsion Module</td>
<td>7,730</td>
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<tr>
<td>Propulsion Platform</td>
<td>3,900</td>
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<tr>
<td>Propellant Feed System</td>
<td>3,830</td>
</tr>
<tr>
<td>Maximum Propellant Load</td>
<td>64,335</td>
</tr>
</tbody>
</table>

Ref. Glenn Research Center

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Example Power System Redundancy

First Human Mission Elements

Primary Power
- Nuclear
- Spare Engine
- Spare Radiator

Emergency Backup
- Solar/Regenerative Fuel Cell

Emergency Backup
- ISRU Fuel Cell Reactants

Emergency Backup
- Surface Mobile Power Systems

Abort to Orbit

Second Human Mission Elements

Primary Power
- Nuclear
- Spare Engine
- Spare Radiator

Emergency Backup
- Solar/Regenerative Fuel Cell

Emergency Backup
- Surface Mobile Power Systems
First Human Mission Elements

- Life Support System
  - Bioregenerative

- Emergency Backup
  - Physical/Chemical

- Long-Term Backup
  - ISRU Water/ O₂ Cache

Abort to Orbit

Second Human Mission Elements

- Life Support System
  - Bioregenerative

- Emergency Backup
  - Physical/Chemical

- Long-Term Backup
  - ISRU Water/ O₂ Cache

Abort to Orbit
Mars Vicinity Abort Options

**System Pre-Deployment**
- Surface habitat pre-deployed prior to crew landing.
- Initial habitat safing, checkout, and verification
- Risk to crew is reduced since crew does not commit to the landing phase until all habitat systems are operational.

**Initial Operations (30 days)**
- Crew lands in separate vehicle
- 30-day initial operations for crew acclimation, initial science
- Once acclimated, crew performs habitat system initialization, checkout and verification.
- Contingency abort-to-orbit capability provided

**Full Surface Mission (600 days)**
- Crew transition to surface habitat complete
- Long-stay criteria met
- Ascent Vehicle placed in stand-by mode
- Contingency abort-to-orbit in Ascent Vehicle if required. Must wait in Mars orbit until Trans-Earth Injection window opens.
The Value of Technology Investments
Mars Mission Example

NOTES:
- Results are cumulative and thus trends will be different for different technology combinations/sequences
- The change between points shows the relative mass savings for that particular technology
- 2018 One-Year Round-Trip Mission, Crew of 4, Lander pre-deployed

Mass Savings Normalized to ISS Mass

Today

All Propulsive Chemical
Advanced Propulsion
Closed Loop Life Support
Advanced Materials
Maintenance & Spares
Advanced Avionics
Aerocapture
Architecture Unique Technology Needs
Long-Stay Mars Mission

• **Human Support**
  – Advanced health care systems for long periods away from Earth (30 months)
  – Advanced surface mobility and EVA: suitable for robust surface exploration (dexterity, mobility, maintainability)

• **Advanced Space Transportation**
  – Advanced interplanetary propulsion: Primary options include:
    • Nuclear Electric Propulsion (30005 sec Isp, 6 MWe)
    • Solar Electric Propulsion / Chemical / Aerobrake (1.7 Mwe, 18% efficiency thin film solar)
  – Large volume / large mass Earth-to-Orbit transportation
  – Aeroassist technologies for Mars aerocapture and Earth return
  – In-situ consumable production for EVA system breathing oxygen and ECLSS backup
  – Automated rendezvous and docking of exploration payloads (2) in Earth orbit

• **Advanced Space Power**
  – Nuclear power reactor 30 kWe for crew support and science investigations

• **Miscellaneous**
  – Integrated vehicle health maintenance for vehicles unattended for long periods (22-42 months)
  – Advanced reliability for long vehicle operations (up to 32-51 months)
Example “Assumed” Technology Advancements

• **Human Support**
  – **Closed-loop Life Support**: capable of operating for long periods (up to 3 years)
  – **Advanced Habitation**: Advanced habitat concepts that provide large volume with low mass
  – **Radiation Protection**: Adequate radiation protection for prolonged exposure to deep-space radiation (both galactic cosmic rays and solar proton events)
  – **Advanced Health Care**: Advanced health countermeasure systems and protocols to mitigate the long duration exposure to the deep-space environment (zero and partial gravity)
  – **Medical Care**: Advanced medical care and environmental health monitoring
  – **Advanced Surface Mobility and EVA**: suitable for robust surface exploration (dexterity, mobility, maintainability)

• **Advanced Space Transportation**
  – **Advanced Interplanetary Propulsion**: Concepts which reduce mission mass and risk: Options include Nuclear Thermal, Nuclear Electric, Solar Electric, and Advanced Chemical
  – **Aeroassist**: High energy aerocapture for orbital insertion, guided entry, precision landing and hazard detection/avoidance on planetary bodies
  – **In-situ Consumable Production**: Concepts to produce useful products (breathing oxygen, power system reactants, propellants) out of planetary resources
  – **Low-Cost Launch**: Low-cost transportation of exploration payloads
  – **Automated Rendezvous and Docking**: of exploration payloads in Earth orbit
  – **Cryogenic Fluid Management**: Long-term storage and maintenance of cryogenic propellants both in space and on planetary surfaces. Cryogenic propellant options include hydrogen, oxygen, methane, xenon, krypton
Example “Assumed” Technology Advancements

- **Advanced Space Power**
  - **Power Generation**: Advanced lightweight, highly reliable power systems for both stationary and mobile systems. Options include both solar and nuclear systems.
  - **Photovoltaic**: Advanced lightweight thin film solar photovoltaic power generation.
  - **Energy Storage**: High capacity regenerative fuel cell and lightweight batteries for long-term energy storage
  - **Dust Mitigation**: Advanced dust mitigation (95%) efficiency for Mars surface solar photovoltaic applications
  - **PMAD**: Lightweight, high efficiency power management and distribution systems

- **Information and Automation**
  - **Autonomy**: Advanced vehicle and systems health management and autonomous operations
  - **Communication**: Robust, high bandwidth communications at exploration destinations (the space internet)
  - **Operations**: Autonomous systems operation, independent of direct-earth based control, at remote exploration destinations

- **Sensors and Instruments**
  - **Wireless**: Wireless instruments and vehicle systems
  - **Sensors**: Advanced system, medical, and health monitoring
Earth-to-Orbit Launch

Application: Affordable delivery of cargo elements and crew from Earth to LEO.

Needs: 80-100 mt with payload volumes up to 10 m x 30 m.

Key Options: Shuttle derived or clean sheet approaches

Advanced Chemical Propulsion

Application: High energy injection stages for transportation of elements in near-Earth space. Advanced chemical engines for descent and ascent at planetary destinations.

Needs: 5-6 klbf throttleable engines which are compatible with utilization of local resources.

Key Options: O2/Methane, O2/Hydrogen

Electric Propulsion

Application: High-efficiency propulsion for delivery of cargo and crew elements from Earth vicinity to planetary destinations and return.

Key Options: 6-20 MWe nuclear electric. 1-3 MWe solar electric (combined with chemical injection stages and aeroassist at Mars).
Key In-Space Transportation Technology Options & Needs

**Aeroassist**

Application: Utilization of planetary atmospheres (Mars and Earth return) for orbital capture, entry, descent, and landing.

Needs: Arrival speeds of 7.4 km/s (Mars) and 11.0 – 13.5 km/s (Earth return).

Key Options: Advanced ablators. Integrated aeroshell/payload shroud concepts.

**Cryogenic Fluid Management**

Application: Long-term storage of cryogenic fluids in space and on planetary surfaces.

Needs: Storage of cryogenic fluids (H₂, O₂, CH₄) for up to 1200 days.

Key Options: Combination of passive and active systems.
An Emerging Architecture

Artificial-Gravity Nuclear Electric Propulsion Option
New Approach
Mars Lagrange Point Staging Location

• Low energy transfers between Earth-moon \( L_1 \) and Mars \( L_{1-2} \)
• Move Mars tele-operation from Earth to High Mars Orbit
  – Deploy and operate micro-missions
  – Short light time (<7 sec. Round-trip)
• Reduce mass and cost
  – Stay out of Mars gravity well -aerocapture for transit vehicle not needed
  – Enables reuse of transit vehicles
• Fuel depots at Moon and Mars gateways:
  – Potential fuel sources: Earth, Moon, Mars
• Safe locations to operate nuclear electric propulsion if needed
• Equivalent access to all of Mars surface
• Use existing or planned launch vehicles??
• Stepping stone for humans to Mars with incremental investments
New Options

Low Energy Transfer
Earth-Moon L1 to Sun- Mars L1

High Mars Orbit or
Sun – Mars L1

≤ 20 min.
3.6 sec

One way communication time
Potential Mars System Human Destinations

**Martian Surface**
- Automated / teleoperated robots
- Direct Human Exploration
- Access to Mars Resources
  - Propellant
  - Life Support Consumables

**Phobos/Deimos**
- Accelerated and amplified robotic surface exploration through telepresence
- Round-trip light time delay <0.2 second

**High Mars Orbit / Lagrange Point**
- Accelerated and amplified robotic surface exploration through telepresence
- Round-trip light time delay <7 seconds
- Reduction of cost and risk associated with human landing
- Vehicle(s) never enter gravity “well” (reduced propellant requirements)

**Teleoperation**

**Mars “Sphere of Influence”**
Artificial Gravity Concept

- **Crew Module**
  - Inflatable Pressure Shell
  - Radiation Shielding
  - Micrometeoroid Protection
  - Life Support
  - EVA Support
  - Auxiliary Power
  - Rotational RCS (chemical/arcjet)
  - Body-Mounted Radiator

- **Guy Cables**
  - Rotational acceleration/deceleration loads

- **Main Radiators**

- **Main Power**
  - Redundant Reactors
  - Redundant Power Conversion
  - Reactor Radiation Shielding

- **Propulsion Modules**
  - Propellant Tankage
  - Electric Propulsion

- **Main Masts**
  - Deployable
  - Vehicle tension loading
  - Torsion Loads
  - Element zero-g positional control

AG Rotation

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Mars Architecture Analysis

Backup
High Earth Orbit Staging Mission Scenarios

- Space Station Orbit (LEO)
- Elliptical Parking Orbit (EPO)
- Mars Aerocapture
- Chemical Injection Burn
- EP Transfer
- Crew Transfer via Crew Taxi
- Libration Points
- Near Earth Asteroids

Earth
Mars
Earth Vicinity Abort Scenarios
(SEP Architecture)

**Post-Trans-Mars Injection Aborts:** Trans-Earth Injection stage can be used to return the crew from an off-nominal TMI burn

**Post-Trans-Mars Injection Abort Options**

1. **Long Return Option (within 8 hrs of TMI)**
   - Crew lives in Transit Habitat after abort declaration
   - Crew returned to Earth in the Earth Return Vehicle up to 30 days later

2. **Quick Return Option (within 30 hrs of TMI)**
   - Crew returned in the Earth Return Vehicle
   - Return transit time 1-2 days

3. **Heliocentric Aborts (1-2 months after TMI)**
   - Return transit times range from 360-570 days
   - Crew lives in the Transit Habitat during return - direct Earth entry via Earth Return Vehicle
   - Can perform this abort only for some (3 of 7) opportunities (2014, 2016, 2018) with the current TEI size (33% increase to cover all opportunities)
Total Mission $\Delta V$ vs Earth Departure Date
Short-Stay Mars Missions

**Assumptions**
- All propulsive mission
- Earth parking orbit = 407 km
- Mars parking orbit = 500 km
- 40 day Mars stay
- Figure of merit = Total $\Delta V$ (all legs)

**Mission $\Delta V$ (m/s)**
- 365 Day Mission
- No Venus Swby
- Inbound Venus Swingby
- Local Min $\Delta V$ No Venus
- Local Min $\Delta V$ Venus Swby (Return Leg)
- One Way Cargo

**Earth Departure Date**
- 275 day
- 205
- 206
- 347
- 332
- 312
- 300
- 27-Dec-32

**Total Mission $\Delta V$ vs Earth Departure Date**
- 365 Day Mission
- No Venus Swby
- Inbound Venus Swingby
- Local Min $\Delta V$ No Venus
- Local Min $\Delta V$ Venus Swby (Return Leg)
- One Way Cargo

**Notes**

- Assumptions
- Missions
- Departure Dates
- Missions vs Departure Dates

Section 4.1.2 JSC/B. Drake
Minimum Solar Distance vs. Mission Opportunity
Short-Stay Mars Missions

Radiation doses during solar fly-by can increase 2-8 times

Earth Departure Date

Minimum Solar Distance (AU)

Earth
Venus
Mercury

Assumptions
- All propulsive mission
- Earth parking orbit = 407 km
- Mars parking orbit = 500 km
- 40 day Mars stay
- Figure of merit = Total $\Delta V$ (all legs)
- All minimum solar distances are due to inbound leg(s) unless accompanied by an "O" indicating minimum solar distance due to the outbound leg

Global Min $\Delta V$

365 Day Mission
No Venus Swby (unless indicated)

Long-Stay Mission with Fast Transits to/from Mars

Local Min $\Delta V$
No Venus Swby

Local Min $\Delta V$
Venus Swby (Return Leg Only)

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Objective

- Establishment of early leadership in human exploration of the solar system

Key Features

- 3 human expeditions to Mars
- Chemical/aerobrake propulsion
- Split/sprint mission profile
- Aerocapture at earth return
- Vehicle assembly in low-earth orbit (SSF)
- 440-500 day round trip (20 days on Mars surface)
- Total Mission mass = 1628 mt

Principal Results

- Short-stay missions are energy intensive, thus requiring large transfer vehicles
- Advanced propulsion technologies (aerocapture and nuclear thermal rocket) can significantly reduce mass requirement (57-72%)
- On-orbit assembly, storage of cryogenic propellants, and vehicle checkout increase mission complexity
- Large mass in LEO requires a heavy-lift launch capability and potentially on-orbit assembly capability
Mars Evolution

Objective

- Emplace a permanent, largely self-sufficient outpost on the surface of Mars

Key Features

- First human flight in 2007 (4 growing to 7 crew)
- Vehicles assembled in LEO (free-flyer platform)
- Chemical/aerobraking propulsion
- Propellant production at Phobos
- Artificial-gravity spacecraft
- Surface stay initially 30-days growing to 500

Principal Results

- Heavy-Lift launch vehicle (140 t to LEO) required to support mass and flight rate requirements
- Even with HLLV, extensive on-orbit assembly and check-out required in low-earth orbit
- Use of nuclear thermal rocket, in addition to aerobraking, would increase payload capability and reduce flight times to and from Mars
- Advanced EVA systems are required to support the extensive surface operations required
- Significant research and development of in-situ resource utilization processes are required
- Architecture requires delivery of approximately 500t to low earth orbit per year
NASA 90-Day Study

Objective
- To provide a database for the National Space Council to refer to as it considered strategic planning issues
- Agency-wide study commissioned by Admiral Truly after the President’s July 20, 1989 speech

Key Features
- Five reference approaches (generally similar)
- Robotic - Moon - Mars pathway
- Extensive use of:
  - Space Station Freedom for assembly and checkout operations
  - Reusable transportation vehicles (initially expendable)
  - In-Situ Resource Utilization (oxygen from the lunar regolith)
  - Chemical/aerobrake propulsion

Key Trades
- Launch Vehicle Size (80 - 140 mt)
- In-space assembly or direct to the surface
- Freedom, new spaceport, or direct assembly
- Chemical, electric, nuclear, or unconventional
- Aerobraking or all-propulsive
- Expendable or reusable spacecraft
- Propellant or tank transfer
- Open or closed life support
- Zero-gravity or artificial-gravity Mars vehicle
- In situ or Earth-supplied resources

Principal Results
- Premature discussion/disclosure of cost results can have unwanted effects, difficult to characterize long-term initiatives
- Use of local planetary resources can greatly enhance capabilities and reduce the cost of exploration
- Aerobraking reduces vehicle mass by as much as 50% as compared to all chemical systems
- Nuclear thermal propulsion provides a great deal of promise for Mars missions (40% mass reduction)
Charter

- Chartered by the National Space Council to develop several alternatives of exploration, future acquisition of scientific knowledge, and future space leadership.
- Chaired by Tom Stafford, Lieutenant General, U.S. Air Force (ret.)

Four Candidate Architectures

- Mars Exploration
- Science Emphasis for the Moon and Mars
- The Moon to Stay and Mars Exploration
- Space Resource Utilization

Principal Results

- Several supporting technologies identified as key for future exploration:
  - Heavy Lift Launch Vehicle (150-250 mt)
  - Nuclear Thermal Propulsion
  - Nuclear electric surface power
  - Extravehicular activity suit
  - Cryogenic transfer and long-term storage
  - Automated rendezvous and docking
  - Zero-g countermeasures
  - Telerobotics
  - Radiation effects and shielding
  - Closed loop life support systems
  - Human factors for long duration space missions
  - Lightweight structural materials and fabrication
  - Nuclear electric propulsion for follow-on cargo deliv.
  - In situ resource evaluation and processing
Mars Exploration Mission Studies
Design Reference Mission 1.0

**Objective**
- Develop a “Reference Mission” based on previous studies and data.
- Reference Mission serves as a basis for comparing different approaches and criteria from future studies

**Approach**
- Limit the time that the crew is exposed to the harsh space environment by employing fast transits to and from Mars and abort to the surface strategy
- Utilize local resources to reduce mission mass
- Split Mission Strategy: Pre-deploy mission hardware to reduce mass and minimize risk to the crew of 6
- Examine three human missions to Mars beginning in 2009
- Utilize advanced space propulsion (Nuclear Thermal Propulsion) for in-space transportation
- Payloads sent directly to Mars using a large launch vehicle (200+ mt to LEO)
- Nuclear surface power for robust continuous power

**Principal Results**
- Total mission mass approximately 900 mt for the first crew (3 cargo vehicles, 1 piloted vehicle)
- Development of the large launch vehicle is a long-lead and expensive system. Approaches using smaller launch vehicles should be investigated.
Mars Exploration Mission Studies
Design Reference Mission 3.0

Objective

- Refine DRM 1.0 to improve identified weaknesses
- Provide further refinement of systems design and concepts

Approach

- Refine launch strategy to eliminate the need for the large (200+ mt) launch vehicle. Dual launch (80 mt) strategy utilized.
- Repackage payload elements to reduce the physical size of the aerobrake used for Mars aerocapture and entry
- Investigate the need for the redundant surface habitat
- Incorporate emerging technologies and system concepts to reduce architectural mass

Principal Results

- Reduced system masses allowed for the elimination of redundant surface habitat, thus eliminating one Mars cargo vehicle
- Incorporation of TransHab concept in conjunction with other systems improvements (ECLSS, power, etc) resulted in a mass savings of ~30% at Mars entry.
- System mass improvements and revision of mission strategy resulted in over 50% payload mass savings
- Emerging systems concepts including Solar Electric Propulsion and Bi-Modal NTR shown to be viable alternative concepts
- Total mission mass estimates:
  - Nuclear Thermal Propulsion: 418 mt
  - Solar Electric Propulsion: 409 mt (early estimate)
Mars Exploration Mission Studies
Design Reference Mission 4.0

Objective
• Refine DRM 3.0 to improve identified weaknesses
• Provide further refinement of systems design and concepts
• Improve risk abatement strategy

Approach
• Modify mission strategy to incorporate a round-trip crew transfer vehicle instead of pre-deploying the crew return habitat
• Place further emphasis on Solar Electric Propulsion concept (NTR and Chemical/Aerobrake investigated as options)
• Further refinement of In-situ resource utilization concept
• Shuttle derived launch vehicle (80 mt) used for LEO transportation

Principal Results
• Incorporation of a round-trip crew transfer vehicle reduces system reliability requirement from five to three years, but requires an additional rendezvous in Mars orbit
• End-to-end Solar Electric Propulsion vehicle mission concept is shown to be a viable concept, but vehicle packaging and size remain tall-poles
• Total mission mass estimates:
  • Solar Electric Propulsion: 467 mt
  • Nuclear Thermal Propulsion: 436 mt
  • Chemical/Aerobrake: 657 mt *

* similar but not same mission concept

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**Objective**

- Refine Combo Lander approach to eliminate potential long-poles by separating the crew lander functions between two vehicles

**Approach**

- Long-duration stay mission with fast transits to and from Mars
- Aerobraking at Mars
- Descent/Ascent vehicle for crew transport from orbit, to surface, and back to Mars orbit
- Inflatable habitats for transit and surface vehicles
- CH₄/O₂ propellants brought with the crew of 6
- Solar surface power
- Solar Electric Propulsion used for interplanetary propulsion
- Magnum launch vehicle used for ETO transportation (100 mt to LEO)

**Principal Results**

- Six 100-mt launches required
- Significant improvement in aeroassist and parachute deployment conditions (as compared to Combo Lander II)
- Surface system reusability is enabled
- Greater improvement in Earth vicinity abort scenarios developed
- Total mission mass estimates:
  - Solar Electric Propulsion: 585 mt
Objective

- Develop a Mars mission approach embodying the philosophy:
  - Go Anywhere, anytime
  - Avoid political obstacles - No HLLV
  - Limit the total mission duration (goal of one-year)

Approach

- Include both short-stay and long-stay mission options
- Investigated both EELV-Exploration Class and 100-mt launch vehicles
- Solar Electric Propulsion and Nuclear Thermal Propulsion options
- Crew size of 6
- Understand trajectory sensitivities for all opportunities and various trip times

Principal Results

- Short-stay missions are very demanding missions
  - One-year round-trip missions occur infrequently (1 out of 7 opportunities)
  - Mission mass varies widely across launch opportunities (400-1600 mt)
  - Short-stay missions provide little time at Mars for contingencies
  - Round-trip mission times for short-stay missions range from 365 to 600 days
- Long-stay missions reduce mission complexity, but require longer overall mission
  - Mission mass constant across launch opportunities (30% variation)
  - Total mission times range from 892-945 days with surface stay times ranging from 501-596 days
- Utilizing EELV-Exploration Class launch vehicle impractical (excessive number of launches and complex orbital assembly and checkout)
- Estimated radiation exposure for long-stay missions is lower than short-stay missions
Mars Surface Science Objectives

• To explore Mars and learn how Mars is similar to, and how it is different from, our home planet
  – whether life evolved on Mars and, if so, whether and how such life may have become extinct
  – whether Mars is still a geologically live planet
  – how the early history of Mars and the history of volatiles on Mars may illuminate the history of Earth

• Strategy Components
  – Fossil-Life Search
  – Atmospheric Evolution and Climate History
  – Geoscience and Geologic History
Science Functions

- Exploring in person
  - Cleaving rocks
  - Auguring holes
  - Trenching
  - Raking and sieving
  - Drilling
  - Documenting
  - Observing (human eye)

- Exploring via Telepresence
  - As above through remote control

- Surveying

- Sounding

- Deploying Instruments

- Planning
- Documenting
- Preparing Samples for Analysis
- Sample Curation
- Laboratory Analysis, Synthesis, and Computer Modeling
- Consulting Colleagues on Earth
Science Tools and Equipment

For EVA Exploration
- Drills
- Geologists field tool kit
- Portable chem/mineral analysis
- Cameras / imaging
- Portable workstation
- Navigation aids and communications
- Electronic field notebook
- Life detection

Laboratory Analysis
- Elemental analyzer
- Mineralogical analyzer
- Stable isotope analyzer
- Petrographic Microscope
- Life detection and characterization equipment

Science Collaboration
- High quality voice and imagery communications for collaboration with colleagues on Earth

Telepresence Exploration
- Predeployed rovers
- High bandwidth telecommunications
- Displays
- Controls
- Imaging and remote manipulation
- Virtual environment graphics
- Geological, chemical, and biological sensors

Library
- Mission critical information on-board in digital form
- Remote access to information on Earth

<table>
<thead>
<tr>
<th>Payloads and Systems</th>
<th>HABITAT LANDER System Mass (kg)</th>
<th>DESCENT / ASCENT LANDER System Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.0 Science</td>
<td>829.9</td>
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<td>Field Geology Package</td>
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<td>Exobiology Laboratory</td>
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<td>Geophysical/Meteorology Inst.</td>
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<td>Teleoperated Science Rovers</td>
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<td>Traverse Geophysical Inst.</td>
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<td>Drill Equipment</td>
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<tr>
<td>Meterology Balloons</td>
<td>200.0</td>
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</tr>
</tbody>
</table>
Exploration Field Work

- Field work is a primary objective
- The landing site is probably not the most interesting site

- A “field camp” could be used to minimize commuting time
Mobility is Key for Exploring the Surface

- EVA suits
  - 4 - 8 hour duration
- Unpressurized rovers
  - similar duration as EVA suit
- Pressurized rovers
  - several days duration
Rover Teleoperations

- Explore beyond the range of EVAs
- Early reconnaissance
- Follow-up visits
- Maintenance
Habitat Laboratory

- Search for life
- Test hypotheses
- High-grade samples
Medical Facilities

- Monitor crew health
- Available for emergencies
Wardroom

- Community meals
- Meeting room
- Social area
- “Information Wall”
Crew Quarters

- Privacy
- Buddy system
- Personal space
Automation and Information

- **Robots to assist crew**
  - autonomous
  - supervised
  - teleoperated

- **Local navigation aids**
  - space-based
  - surface-based

- **Information storage and retrieval**
External Maintenance and Repair

- Emphasize reliability to minimize spares and maintenance activities

- Repairable systems EVA and robotic compatible
• Capability to repair at the piece-part level
• Manufacture simple parts
• Common parts/modules to minimize the number of spares
Advanced Concept Analysis in Support of the Integrated Space Plan

Section 4.1.3

Exploration Architecture Analysis
Human Missions to the Sun-Earth Libration Point (L2)

November 2002
Human Missions to Sun-Earth Libration Points
Primary Objectives

• Can provide an inexpensive and early validation of:
  – Core exploration capabilities and technologies
    • Transit Habitat (subscale)
    • High Performance Chemical Propulsion Stage (trans-Mars injection stage)
    • Aeroassist (at Earth return)
    • Advanced space power systems
    • Launch vehicle
  – Development and demonstration of interplanetary cruise hardware
  – Deep-space operational experience
    • Begin to bridge the operational experience gap between LEO missions and long-duration deep space missions

• Does not make sense to use Sun-Earth libration points as a staging location for Mars missions
  – Requires more energy (~700 m/s)
  – Adds more trip time (~2 months)
High Earth Orbit Staging Mission Scenarios

- Elliptical Parking Orbit (EPO)
- Earth Space Station Orbit (LEO)
- Mars Aerocapture
- Chemical Injection Burn
- EP Transfer
- Crew Transfer via Crew Taxi
- Rendezvous
- Near Earth Asteroids
- Libration Points
Earth-Sun Libration Point Trajectories

L2 Sun-Earth: Propulsive Energy vs. Flight Time from LEO
Initial Earth Circular Parking Orbit: 407 km

ΔV budget for Mars Transit Habitat

Flight Time (days)

Delta-V (mps)

Earth Departure

Total

Arrival
Earth-Sun Libration Point Vehicle Configuration
HEO Departure

Mass Statement for round-trip Earth-Sun (L2) mission

<table>
<thead>
<tr>
<th>Sun-Earth L₂ Mission Mass Breakdown</th>
<th>Mass (kg)</th>
<th>Stowed Vol. (M³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 Power System</td>
<td>3339</td>
<td>0.000</td>
</tr>
<tr>
<td>2.0 Avionics</td>
<td>287</td>
<td>0.140</td>
</tr>
<tr>
<td>3.0 Environmental Control &amp; Life Support</td>
<td>2797</td>
<td>19.133</td>
</tr>
<tr>
<td>4.0 Thermal Management System</td>
<td>1163</td>
<td>5.260</td>
</tr>
<tr>
<td>5.0 Crew Accommodations</td>
<td>2153</td>
<td>15.685</td>
</tr>
<tr>
<td>6.0 EVA Systems</td>
<td>738</td>
<td>1.782</td>
</tr>
<tr>
<td>7.0 Structure</td>
<td>822</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Margin (15%)</td>
<td>1695</td>
</tr>
<tr>
<td></td>
<td>Crew</td>
<td>372</td>
</tr>
<tr>
<td></td>
<td>Food (Return Trip)</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Food (Stay time)</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>Food (Outbound Trip)</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Food (Contingency)</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total Transit Habitat Mass</strong></td>
<td>14540</td>
<td>50.525</td>
</tr>
<tr>
<td><strong>Earth Return Vehicle</strong></td>
<td>4271</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Total Transit Habitat Mass plus ERV</strong></td>
<td>18810</td>
<td></td>
</tr>
<tr>
<td><strong>Aerobrake</strong></td>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Primary Structure</td>
<td>3184.0</td>
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<tr>
<td></td>
<td>Thermal Protection System</td>
<td>3012.0</td>
</tr>
<tr>
<td></td>
<td>Margin</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Total Transit Habitat plus Aerobrake</strong></td>
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<td></td>
</tr>
<tr>
<td><strong>Propulsion Stage</strong></td>
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<tr>
<td></td>
<td>Stage</td>
<td>1149</td>
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<tr>
<td></td>
<td>Propulsion</td>
<td>1792</td>
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<tr>
<td></td>
<td>Propellants</td>
<td>11223</td>
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<tr>
<td><strong>Total with Stage</strong></td>
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<tr>
<td><strong>SEP Vehicle</strong></td>
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<tr>
<td></td>
<td>Power System</td>
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<td>Propulsion System</td>
<td>3142</td>
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<td></td>
<td>Propellant</td>
<td>20149</td>
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<tr>
<td><strong>INITIAL MASS IN LOW EARTH ORBIT</strong></td>
<td>65975</td>
<td></td>
</tr>
</tbody>
</table>

- “Mini-TransHab” design based on current TransHab approach
- Supports mission crew of 4 for up to 100-day round-trip mission
- 400 kWe SEP spirals vehicle to HEO (7 months), crew taxi used to deliver flight crew to HEO
- Return propulsion stage integrated with transit system
- Earth Return Vehicle for crew return
### Human Libration Point Missions
#### Common Capabilities

<table>
<thead>
<tr>
<th>Earth to Orbit Transportation</th>
<th>Interplanetary Habitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost effective delivery of large exploration payloads to low-Earth orbit</td>
<td>Long duration (100 days) support of multiple mission crews</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High Performance Chemical Propulsion Stage</th>
<th>Solar Electric Propulsion Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performs all major propulsive maneuvers including injection, capture, and return</td>
<td>Transports mission payloads from low-Earth orbit to high-Earth staging orbits</td>
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</table>

<table>
<thead>
<tr>
<th>Crew Taxi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transports mission crew from low-Earth orbit to high-Earth staging orbits</td>
</tr>
</tbody>
</table>
Backup
• “100-day” Class Mission
• 25-day transits to and from libration point
• 50-days in libration point halo orbit
Sun-Earth Libration Point
LEO Departure Options

Option A

- Magnum used for delivery of hardware, STS delivers crew
- Stage A performs departure burn. Stage B performs all other burns.
- Aerobraking at Earth return - habitat reused.

Option B

- Delta-IV H and STS used for delivery to LEO
- Stage A performs partial departure burn. Stage B finishes departure burn and performs all other maneuvers.
- Direct entry at Earth return - no reuse
Earth-Sun Libration Point Vehicle Configuration
LEO Departure Option A

Mass Statement for round-trip Earth-Sun (L2) mission

- “Mini-TransHab” design based on current TransHab approach
- Supports mission crew of 4 for up to 100-day round-trip mission
- Provides zero-g and deep-space radiation protection
- Return propulsion stage integrated with transit system
- Habitation system returned to Low-Earth Orbit for reuse

<table>
<thead>
<tr>
<th>Sun-Earth L₂ Mission Mass Breakdown</th>
<th>Mass (kg)</th>
<th>Stowed Vol. (M³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 Power System</td>
<td>3339</td>
<td>0.000</td>
</tr>
<tr>
<td>2.0 Avionics</td>
<td>287</td>
<td>0.140</td>
</tr>
<tr>
<td>3.0 Environmental Control &amp; Life Support</td>
<td>2797</td>
<td>19.133</td>
</tr>
<tr>
<td>4.0 Thermal Management System</td>
<td>1163</td>
<td>5.260</td>
</tr>
<tr>
<td>5.0 Crew Accommodations</td>
<td>2153</td>
<td>15.685</td>
</tr>
<tr>
<td>6.0 EVA Systems</td>
<td>738</td>
<td>1.782</td>
</tr>
<tr>
<td>7.0 Structure</td>
<td>822</td>
<td>0.000</td>
</tr>
<tr>
<td>Margin (15%)</td>
<td>1695</td>
<td>6.300</td>
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<tr>
<td>Crew</td>
<td>372</td>
<td>-</td>
</tr>
<tr>
<td>Food (Return Trip)</td>
<td>200</td>
<td>0.696</td>
</tr>
<tr>
<td>Food (Stay time)</td>
<td>400</td>
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<tr>
<td>Food (Outbound Trip)</td>
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<td>0.696</td>
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<td>Food (Contingency)</td>
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<td>0.000</td>
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<tr>
<td><strong>Total Transit Habitat Mass</strong></td>
<td><strong>14540</strong></td>
<td><strong>50.525</strong></td>
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</table>

<table>
<thead>
<tr>
<th>Aerobrake</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Primary Structure</td>
<td>3184</td>
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</tr>
<tr>
<td>Thermal Protection System</td>
<td>3012</td>
<td>-</td>
</tr>
<tr>
<td>Margin</td>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Total Transit Habitat plus Aerobrake</strong></td>
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</table>

<table>
<thead>
<tr>
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<tr>
<td>Propellants</td>
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<tr>
<td><strong>Total with Stage A</strong></td>
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<table>
<thead>
<tr>
<th>Stage B</th>
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<td>Stage</td>
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<td>Propellants</td>
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<td><strong>INITIAL MASS IN LOW EARTH ORBIT</strong></td>
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</table>
### Earth-Sun Libration Point Vehicle Configuration

**LEO Departure Option B**

Mass Statement for round-trip Earth-Sun (L2) mission

<table>
<thead>
<tr>
<th>Sun-Earth L₂ Mission Mass Breakdown</th>
<th>Mass (kg)</th>
<th>Stowed Vol. (M³)</th>
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</thead>
<tbody>
<tr>
<td>1.0 Power System</td>
<td>3339</td>
<td>0.000</td>
</tr>
<tr>
<td>2.0 Avionics</td>
<td>287</td>
<td>0.140</td>
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<td>2797</td>
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<td>7.0 Structure</td>
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</tr>
<tr>
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<td>6.300</td>
</tr>
<tr>
<td>Crew</td>
<td>372</td>
<td>-</td>
</tr>
<tr>
<td>Food (Return Trip)</td>
<td>200</td>
<td>0.696</td>
</tr>
<tr>
<td>Food (Stay time)</td>
<td>400</td>
<td>0.835</td>
</tr>
<tr>
<td>Food (Outbound Trip)</td>
<td>200</td>
<td>0.696</td>
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<tr>
<td>Food (Contingency)</td>
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<td><strong>Total Transit Habitat Mass</strong></td>
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<td>50.525</td>
</tr>
<tr>
<td><strong>Earth Return Vehicle</strong></td>
<td>4271</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Total Transit Habitat Mass plus ERV</strong></td>
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</table>

#### Stage A

<table>
<thead>
<tr>
<th></th>
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<th>Stowed Vol. (M³)</th>
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<tr>
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<td>Propulsion</td>
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<td><strong>Total with Stage A</strong></td>
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#### Stage B

<table>
<thead>
<tr>
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<th>Mass (kg)</th>
<th>Stowed Vol. (M³)</th>
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<tbody>
<tr>
<td>Stage</td>
<td>2392</td>
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<td>Propulsion</td>
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<tr>
<td>Propellants</td>
<td>29909</td>
<td>0.000</td>
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</table>

**INITIAL MASS IN LOW EARTH ORBIT** 85029

- “Mini-TransHab” design based on current TransHab approach
- Supports mission crew of 4 for up to 100-day round-trip mission
- Provides zero-g and deep-space radiation protection
- Return propulsion stage integrated with transit system
- Earth Return Vehicle for crew return; Transit Habitat abandoned.
Human Libration Point Missions
Common Capabilities

Earth to Orbit Transportation

Functions
• Cost effective delivery of large exploration payloads to low-Earth orbit

Technologies
• Lightweight composites for fuel tanks and payload shrouds
• Automated rendezvous and docking
• Low-cost engine concepts
• Advanced light-weight sensors

Destination Commonality
• Moon
• Asteroids
• Libration Points
• Mars

Sizing Parameters

<table>
<thead>
<tr>
<th>Payload Capability:</th>
<th>80-90 mt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit Altitude:</td>
<td>407 x 407 km</td>
</tr>
<tr>
<td>Orbit Inclination:</td>
<td>28.5-51.6 deg</td>
</tr>
<tr>
<td>Payload Length:</td>
<td>15 m</td>
</tr>
<tr>
<td>Payload Diameter:</td>
<td>7.5-8 m</td>
</tr>
</tbody>
</table>
**Interplanetary Habitation**

(Identical habitation system as Lunar scenario)

**Functions**

- Provides habitation for *four* crew for up to 100 days in deep space

**Technologies**

- High volume-to-weight structures
- Deep-space radiation protection
- Advanced life support system closure (100% air and water)
- Zero/low-gravity research and countermeasures

**Destination Commonality**

- Moon
- Asteroids
- Libration Points
- Mars

**Sizing Parameters**

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
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<tbody>
<tr>
<td>Power</td>
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<tr>
<td>Avionics</td>
<td>290</td>
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<tr>
<td>Life Support System</td>
<td>2,800</td>
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<tr>
<td>Thermal Management</td>
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<tr>
<td>Crew Accommodations</td>
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<td>Structure</td>
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<tr>
<td>Margin</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>12,290</strong></td>
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* No crew consumables
Human Exploration of Mars  
Common Capabilities

Solar Electric Propulsion Vehicle

Functions
• Transports mission payloads from low-Earth orbit to high-Earth staging orbits

Sizing Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Specific Impulse:</td>
<td>2,500 sec</td>
</tr>
<tr>
<td>Propellant:</td>
<td>$X_e$ or $K_t$</td>
</tr>
<tr>
<td>Power Module Mass:</td>
<td>28,000 kg</td>
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<tr>
<td>Propulsion Module Mass:</td>
<td>7,730 kg</td>
</tr>
<tr>
<td>Max Propellant Load:</td>
<td>64,270 kg</td>
</tr>
<tr>
<td>Spiral Time:</td>
<td>&lt; 360 days</td>
</tr>
<tr>
<td>Payload Mass:</td>
<td>180-200 mt</td>
</tr>
<tr>
<td>Final Orbit</td>
<td>800 x 120,550 km</td>
</tr>
</tbody>
</table>

Technologies
• Advanced light-weight inflatable structures  
• Advance high-performance thin film CuInS$_2$ solar cells  
• High-power (100 kWe) electric thrusters (option include Hall, VASIMR, Ion)  
• Radiation hardened electronic systems

Destination Commonality
• Moon  
• Asteroids  
• Libration Points  
• Mars
Human Exploration of Mars
Common Capabilities

Crew Taxi

Functions
• Transports mission crew from low-Earth orbit to high-earth staging orbits

Technologies
• Advanced thermal protection
• Lightweight structures, systems, sensors and avionics
• High energy aerocapture and thermal protection
• Automated rendezvous and docking

Destination Commonality
• Moon
• Asteroids
• Libration Points
• Mars

Sizing Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Crew size</td>
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<tr>
<td>Dry Mass</td>
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<tr>
<td>Propellant</td>
<td>11,810 kg</td>
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<tr>
<td>ASE</td>
<td>1,627 kg</td>
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<tr>
<td>Mission Duration</td>
<td>2.7 days</td>
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<tr>
<td>Final orbit</td>
<td>120,550 x 800 km</td>
</tr>
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</table>
**Human Libration Point Missions**

**Common Capabilities**

---

**High Performance Chemical Transfer Stage**

(Identical to the Trans-Mars Injection stage)

**Technologies**

- Advanced, high performance, space engine
  - Multi-start, space start
  - LO$_2$/CH$_4$ for ISRU compatibility
  - 20,000 lb$_f$ thrust
  - Highly reliable and operationally simple
- Long-term cryogenic fluid management and storage

**Destination Commonality**

- Asteroids
- Libration Points
- Mars
- Moon

**Functions**

- Injects mission payloads from High-Earth orbit toward the Sun-Earth Libration Point

**Sizing Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Specific Impulse</td>
<td>379 sec</td>
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<tr>
<td>Propellant</td>
<td>LO$_2$/CH$_4$</td>
</tr>
<tr>
<td>Total Thrust</td>
<td>120 klbf</td>
</tr>
<tr>
<td># Engine out capability</td>
<td>1</td>
</tr>
<tr>
<td>Dry Mass</td>
<td>3,821 kg</td>
</tr>
<tr>
<td>Max Propellant Load</td>
<td>62,610 kg</td>
</tr>
</tbody>
</table>
Sun-Earth Libration Point Geometry

Sun-Earth L₁
L₄
L₅
L₃
L₂
L₁
Moon

Earth

To Sun

1.5 Million km

1.5 Million km
Advanced Concept Analysis in Support of the Integrated Space Plan

Section 4.1.4

Human Exploration of Mars
Opposition Class (Short-Stay)/Conjunction Class (Long-Stay) Mission Comparison

November 2002
Earth-Mars Mission Planning

- Trips to Mars and back are, in effect, a double rendezvous problem
- First rendezvous outbound must be developed considering influence of the rendezvous inbound
- Practical considerations dictate favorable (and different) planetary alignments relative to the sun for both transfers

Synodic Period

- Is the period of time necessary for the phase angle between Earth and Mars to repeat itself
- Repetition rate for identical Earth-Mars phasing, and therefore launch opportunities for similar mission classes, is ~26 months
- The eccentricity of Mars’ orbit causes significant variations in Earth-Mars relative distance and velocity from one opportunity to the next
- The entire range of Earth-Mars geometry is encompassed by seven launch opportunities, or about 15 years
- Before definitive claims of mission characteristics or propulsion system capabilities are made, analysis across the 15-year cycle should be performed
Earth-Mars Orbital Characteristics

Conjunction: Maximum Earth-Mars distance varies from 350-400 million km. Round-trip communication time varies from 40-45 minutes; also solar occultations (i.e., no communication) for approx. 2 weeks.

Opposition: Minimum Earth-Mars distance varies from 60-100 million km. Round-trip communication time varies from 6-11 minutes.

Mars
- Perihelion: 1.4 AU
- Aphelion: 1.6 AU
- Orbital period: 687 days
- Mean velocity: 24 km/sec
- Equatorial radius: 3398 km

Earth
- Perihelion: 1.0 AU
- Aphelion: 1.0 AU
- Orbital period: 365 days
- Mean velocity: 30 km/sec
- Equatorial radius: 6378 km
Mars Trajectory Classes

**Long-Stay Missions**
- Variations about the minimum energy mission
- Often referred to as Conjunction Class missions

**Short-Stay Missions**
- Variations of missions with short Mars surface stays and may include Venus swing-by
- Often referred to as Opposition Class missions

**MISSION TIMES**

<table>
<thead>
<tr>
<th></th>
<th>OUTBOUND</th>
<th>STAY</th>
<th>RETURN</th>
<th>TOTAL MISSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outbound 1</td>
<td>224 days</td>
<td>458 days</td>
<td>237 days</td>
<td>919 days</td>
</tr>
<tr>
<td>Outbound 2</td>
<td>286 days</td>
<td>30 days</td>
<td>318 days</td>
<td>634 days</td>
</tr>
</tbody>
</table>

Diagram with Earth, Mars, and Venus trajectories.
Either an outbound or inbound transfer which passes in the vicinity of Venus can have the same result as a deep-space maneuver

- More propulsively efficient than the three-impulse strategy
- Requires that Venus be in a specific relative geometry with Earth and Mars
Delta-V Variations

Short-Stay Missions (Opposition Class)

Long-Stay Missions (Conjunction Class)
Short-Stay Mission Implications

- Significant variation of propulsion requirements for the Short-Stay mission across synodic cycle (100%) dictates need for advanced propulsion technology
  - Nuclear Thermal Propulsion
  - High-Power Electric Propulsion

- Short stay in the vicinity of Mars compromises mission return and crew safety
  - Limited time for gravity-acclimation
  - Limited time for contingencies or dust storms
  - Majority of time spent in deep space (zero-gravity & deep space radiation)

- Total mission duration for the Short-Stay Mission on the order of 15-25 months
  - System reliability still critical to success
  - Life support system reliability
  - Short (one-year) missions are possible, but limited to single opportunities over the 15-year synodic cycle

- Venus swing-by’s can reduce propulsive requirement (and thus mission mass)
  - Pass within 0.72 AU of the sun (increases radiation and thermal load)
Long-Stay Mission Implications

- Small variation (10%) of propulsion requirement for the Long-Stay mission across the 15-year synodic cycle
  - Can go any opportunity
  - Vehicles and systems common between opportunities

- Long-Stay mission trip times can be reduced for minimal impacts, thus reducing life science concerns of deep space travel (radiation and zero-gravity exposure)

- Long stay in the vicinity of Mars increases mission return and crew safety
  - Sufficient time for gravity-acclimation
  - Sufficient time for dust storms or other contingency situations
  - Majority of time spent on Mars (improved gravity and radiation environment)

- Total mission duration on the order of 30 months
  - System reliability still critical to success
  - Life support system reliability

- Surface of Mars is the “Second” safest place in the solar system
  - Planetary surface and atmosphere for increased radiation protection
  - Hypogravity environment (3/8th -g)
  - Stable environment (things don’t happen fast on the surface)
Mars Mission Duration Comparison

Mission Duration, Days

- Long-Stay Mission (180-Day Transits)
- Short-Stay Mission (Minimum Energy)
- Vasco Da Gamma (1497)
- Amerigo Vespucci (1501)

- Return Transit
- Time at Destination
- Outbound Transit

Example Lift Capability Needed* (Magnum-Class)

* Assuming NTP=925 sec Propulsion
## Mission Characteristic Comparisons

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Short-Stay Mission</th>
<th>Long-Stay Mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission Duration (days)</td>
<td>590-740</td>
<td>850-950</td>
</tr>
<tr>
<td>Surface Stay</td>
<td>30-90</td>
<td>490-640</td>
</tr>
<tr>
<td>One-Way Transits</td>
<td>190-370</td>
<td>120-200</td>
</tr>
<tr>
<td>Total Transit Time</td>
<td>540-700</td>
<td>240-400</td>
</tr>
<tr>
<td>Trajectory Characteristics</td>
<td>Venus Swing-by</td>
<td>No Venus Swing-by</td>
</tr>
<tr>
<td>Total Mission Mass (mt)</td>
<td>500-1200</td>
<td>400-700</td>
</tr>
<tr>
<td>% Vehicles</td>
<td>21%</td>
<td>31%</td>
</tr>
<tr>
<td>% Propellant</td>
<td>74%</td>
<td>47%</td>
</tr>
<tr>
<td>% Surface Systems</td>
<td>5%</td>
<td>22%</td>
</tr>
</tbody>
</table>

1 Assuming Nuclear Thermal Propulsion (Isp 925 sec)
2 First Piloted Flight - 90 Day Study
3 First Piloted Flight - Mars Design Reference Mission
# Technology and Mission Implications

## Short-Stay

<table>
<thead>
<tr>
<th>Category</th>
<th>Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation</td>
<td>Advanced propulsion <strong>required</strong> for reasonable mass</td>
</tr>
<tr>
<td>Earth-to-Orbit</td>
<td>Large mission mass necessitates high flight rate and/or larger launcher</td>
</tr>
<tr>
<td>Human Health</td>
<td>Certification process of long zero-g space missions unknown</td>
</tr>
<tr>
<td>System Reliability</td>
<td>Similar (15-25 months)</td>
</tr>
<tr>
<td>Mission Focus</td>
<td>Transportation and propulsion</td>
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</table>

## Long-Stay

<table>
<thead>
<tr>
<th>Category</th>
<th>Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation</td>
<td>Advanced propulsion enhances missions (lower mass or shorter transits)</td>
</tr>
<tr>
<td>Earth-to-Orbit</td>
<td>Lower mission mass relieves launch requirement and launch rate</td>
</tr>
<tr>
<td>Human Health</td>
<td>Mission transits within US zero-g spaceflight experience on MIR</td>
</tr>
<tr>
<td>System Reliability</td>
<td>Similar (30 months)</td>
</tr>
<tr>
<td>Mission Focus</td>
<td>Surface and mission return</td>
</tr>
</tbody>
</table>
Backup Data
Repetitive Phasing

- Repetition rate for identical phasing = \( \frac{360 \text{ degrees}}{0.9856 \text{ deg/day} - 0.5242 \text{ deg/day}} \) = 780 days ~ 26 months

- Number of opportunities for full progression around sun = \( \frac{360 \text{ degrees}}{49 \text{ deg per opportunity}} \) ~ 7 opportunities

First Opportunity

Second Opportunity
### Example Earth-Mars Long-Stay Missions

**Minimum Energy**

<table>
<thead>
<tr>
<th>Launch Date</th>
<th>$\Delta V_{(1)}$ TMI</th>
<th>Outbound (Days)</th>
<th>$\Delta V_{(2)}$ MOI</th>
<th>Mars Stay-Time (Days)</th>
<th>$\Delta V_{(2)}$ TEI</th>
<th>Inbound (Days)</th>
<th>Total Mission Duration (Days)</th>
<th>$\Delta V_{(3)}$ Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/03/01</td>
<td>3639</td>
<td>200</td>
<td>2532</td>
<td>545</td>
<td>2108</td>
<td>205</td>
<td>950</td>
<td>8278</td>
</tr>
<tr>
<td>6/08/03</td>
<td>3574</td>
<td>204</td>
<td>2095</td>
<td>547</td>
<td>2647</td>
<td>192</td>
<td>943</td>
<td>8316</td>
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<tr>
<td>8/20/05</td>
<td>3963</td>
<td>217</td>
<td>2038</td>
<td>492</td>
<td>2703</td>
<td>214</td>
<td>923</td>
<td>8704</td>
</tr>
<tr>
<td>10/06/07</td>
<td>4199</td>
<td>248</td>
<td>2032</td>
<td>437</td>
<td>2278</td>
<td>262</td>
<td>947</td>
<td>8509</td>
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<tr>
<td>11/08/09</td>
<td>4035</td>
<td>278</td>
<td>1988</td>
<td>374</td>
<td>2064</td>
<td>270</td>
<td>922</td>
<td>8087</td>
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<tr>
<td>11/28/11</td>
<td>3672</td>
<td>252</td>
<td>2532</td>
<td>418</td>
<td>1989</td>
<td>259</td>
<td>929</td>
<td>8193</td>
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<tr>
<td>1/17/14</td>
<td>3832</td>
<td>224</td>
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<td>1941</td>
<td>237</td>
<td>919</td>
<td>8567</td>
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<tr>
<td>3/11/16</td>
<td>3739</td>
<td>204</td>
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<td>529</td>
<td>1983</td>
<td>212</td>
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<td>8399</td>
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<td>5/11/18</td>
<td>3530</td>
<td>204</td>
<td>2230</td>
<td>553</td>
<td>2466</td>
<td>190</td>
<td>946</td>
<td>8227</td>
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<tr>
<td>7/27/20</td>
<td>3807</td>
<td>207</td>
<td>2031</td>
<td>517</td>
<td>2746</td>
<td>203</td>
<td>927</td>
<td>8584</td>
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</table>

(1) Launch from ISS altitude orbit (407 km)
(2) 500 km circular orbit at Mars
(3) Assumes direct entry upon Earth return

All velocities in meters/second
### Example Earth-Mars Short-Stay Missions
(with Venus Swingby)

<table>
<thead>
<tr>
<th>Launch Date</th>
<th>Venus Swingby</th>
<th>$\Delta V_{(1)}$</th>
<th>Outbound (Days)</th>
<th>$\Delta V_{(2)}$</th>
<th>Mars Stay-Time (Days)</th>
<th>$\Delta V_{(2)}$</th>
<th>Inbound (Days)</th>
<th>Total Mission Duration (Days)</th>
<th>$\Delta V_{(3)}$ Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/01/01</td>
<td>Inbound</td>
<td>3635</td>
<td>201</td>
<td>2538</td>
<td>40</td>
<td>4248</td>
<td>345</td>
<td>586</td>
<td>10422</td>
</tr>
<tr>
<td>8/22/02</td>
<td>Outbound</td>
<td>3820</td>
<td>302</td>
<td>4744</td>
<td>40</td>
<td>3134</td>
<td>261</td>
<td>603</td>
<td>11704</td>
</tr>
<tr>
<td>3/09/04</td>
<td>Outbound</td>
<td>4131</td>
<td>344</td>
<td>4429</td>
<td>40</td>
<td>2639</td>
<td>271</td>
<td>655</td>
<td>11198</td>
</tr>
<tr>
<td>8/27/07</td>
<td>Inbound</td>
<td>4600</td>
<td>188</td>
<td>4341</td>
<td>40</td>
<td>4030</td>
<td>340</td>
<td>568</td>
<td>12972</td>
</tr>
<tr>
<td>1/17/09</td>
<td>In &amp; Out</td>
<td>4208</td>
<td>330</td>
<td>3339</td>
<td>40</td>
<td>3367</td>
<td>367</td>
<td>737</td>
<td>11342</td>
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<td>11/28/10</td>
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<td>4426</td>
<td>330</td>
<td>3502</td>
<td>40</td>
<td>2494</td>
<td>303</td>
<td>673</td>
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<tr>
<td>11/21/13</td>
<td>Inbound</td>
<td>3692</td>
<td>281</td>
<td>2464</td>
<td>40</td>
<td>4419</td>
<td>311</td>
<td>632</td>
<td>10575</td>
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<tr>
<td>10/26/15</td>
<td>Inbound</td>
<td>4865</td>
<td>279</td>
<td>3136</td>
<td>40</td>
<td>4810</td>
<td>261</td>
<td>580</td>
<td>12811</td>
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<tr>
<td>4/06/17</td>
<td>Outbound</td>
<td>4181</td>
<td>359</td>
<td>3780</td>
<td>40</td>
<td>2531</td>
<td>245</td>
<td>645</td>
<td>10502</td>
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<td>6/09/20</td>
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<td>4164</td>
<td>190</td>
<td>2707</td>
<td>40</td>
<td>3961</td>
<td>364</td>
<td>594</td>
<td>10832</td>
</tr>
</tbody>
</table>

(1) Launch from ISS altitude orbit (407 km)
(2) 500 km circular orbit at Mars
(3) Assumes direct entry upon Earth return
All velocities in meters/second

TMI Trans-Mars Injection
MOI Mars Orbit Capture
TEI Trans-Earth Injection
Trip times to and from Mars can be shortened depending on:

- Class of mission (conjunction or opposition)
- Propulsion technology employed
- Entry velocities at either Earth or Mars (if using aeroassist)
Total Mission $\Delta V$ vs Earth Departure Date

**Short-Stay Mars Missions**

### Assumptions
- All propulsive mission
- Earth parking orbit = 407 km
- Mars parking orbit = 500 km
- 40 day Mars stay
- Figure of merit = Total $\Delta V$ (all legs)

### Missions

<table>
<thead>
<tr>
<th>Mission Type</th>
<th>$\Delta V$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>365 Day Mission</td>
<td></td>
</tr>
<tr>
<td>No Venus Swby</td>
<td>583</td>
</tr>
<tr>
<td>Local Min $\Delta V$</td>
<td>453</td>
</tr>
<tr>
<td>Venus Swby (Inbound)</td>
<td>446</td>
</tr>
<tr>
<td>Venus Swby (Outbound)</td>
<td>519</td>
</tr>
<tr>
<td>One Way Cargo</td>
<td>585</td>
</tr>
<tr>
<td>No Inbound Venus Swby</td>
<td></td>
</tr>
<tr>
<td>Local Min $\Delta V$</td>
<td></td>
</tr>
<tr>
<td>Venus Swby (Return)</td>
<td>497</td>
</tr>
<tr>
<td>No Inbound Venus Swby</td>
<td>494</td>
</tr>
<tr>
<td>Local Min $\Delta V$</td>
<td></td>
</tr>
<tr>
<td>Venus Swby (Return)</td>
<td>468</td>
</tr>
<tr>
<td>No Inbound Venus Swby</td>
<td>461</td>
</tr>
<tr>
<td>Local Min $\Delta V$</td>
<td></td>
</tr>
<tr>
<td>Venus Swby (Return)</td>
<td>527</td>
</tr>
<tr>
<td>No Inbound Venus Swby</td>
<td>545</td>
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<tr>
<td>Local Min $\Delta V$</td>
<td></td>
</tr>
<tr>
<td>Venus Swby (Return)</td>
<td>619</td>
</tr>
<tr>
<td>No Inbound Venus Swby</td>
<td>661</td>
</tr>
</tbody>
</table>

### Earth Departure Date

- 01-Jan-15
- 31-Dec-16
- 31-Dec-18
- 30-Dec-20
- 30-Dec-22
- 29-Dec-24
- 29-Dec-26
- 28-Dec-28
- 28-Dec-30
- 27-Dec-32

- **Local Min $\Delta V$ One Way Cargo**
- **365 Day Mission No Venus Swby**
- **Local Min $\Delta V$ No Venus**
- **Local Min $\Delta V$ Venus Swby (Return Leg)**
Minimum Solar Distance vs. Mission Opportunity
Short-Stay Mars Missions

Radiation doses during solar fly-by can increase 2-8 times

Earth

Venus

Mercury

Minimum Solar Distance (AU)

Earth Departure Date

Assumptions
- All propulsive mission
- Earth parking orbit = 407 km
- Mars parking orbit = 500 km
- 40 day Mars stay
- Figure of merit = Total \( \Delta V \) (all legs)
- All minimum solar distances are due to inbound leg(s) unless accompanied by an "O" indicating minimum solar distance due to the outbound leg

Long-Stay Mission with Fast Transits to-from Mars

365 Day Mission No Venus Swby (unless indicated)

Local Min \( \Delta V \) No Venus Swby

Local Min \( \Delta V \) Venus Swby (Return Leg Only)

G. Condon/JSC/EG

Section 4.1.3 JSC/B. Drake

Nov. 2002
**Trip Time Sensitivity: Long-Stay Missions**

Mars Long Duration Stay Missions with Equal Transfer Times
(Outbound and Inbound)
All-up Mission

* Total mission durations range from 830-960 days

Mass estimates derived from vehicle scaling equations and are not based on detailed point designs

Section 4.1.3 JSC/B. Drake
Trip Time Sensitivity: Long-Stay Missions

Mars Long Duration Stay Missions with Equal Transfer Times
(Outbound and Inbound)
All-up Mission

Piloted Vehicle Mass in LEO (t)

All Chemical Propulsion (Isp=475s)

Launch Date, Year

* Total mission durations range from 830-960 days

Mass estimates derived from vehicle scaling equations
and are not based on detailed point designs
Trip Time Sensitivity: Short-Stay Missions

Mars Short Duration Stay Mission
Nuclear Thermal Propulsion (Isp=925s)
Short Outbound Leg

* Includes 30-day surface stay

Mass estimates derived from vehicle scaling equations and are not based on detailed point designs
Mars Mission Duration Comparison
2018 Opportunity

Representative Good Opportunity

- Long-Stay (Minimum Energy)
- Long-Stay (120-Day Transits)
- Short-Stay (Minimum Energy)
- Short-Stay (440-Day Total Mission)
- Vasco Da Gamma (1497)

Example Lift Capability Needed* (Magnum-Class)

Mission Duration, Days

Return Transit
Time at Destination
Outbound Transit

* Assuming NTP=925 sec Propulsion

Section 4.1.3 JSC/B. Drake

Nov. 2002 299
Representative Intermediate Opportunity

- Long-Stay (Minimum Energy)
- Long-Stay (120-Day Transits)
- Short-Stay (Minimum Energy)
- Short-Stay (440-Day Total Mission)
- Amerigo Vespucci (1501)

Mission Duration, Days

- Return Transit
- Time at Destination
- Outbound Transit

* Assuming NTP=925 sec Propulsion

Section 4.1.3  JSC/B. Drake
Mars Mission Duration Comparison
2009 Opportunity

Representative Bad Opportunity

Long-Stay (Minimum Energy)

Long-Stay (120-Day Transits)

Short-Stay (Minimum Energy)

Short-Stay (440-Day Total Mission)

James Cook (1768)

Mission Duration, Days

Example Lift Capability Needed* (Magnum-Class)

Return Transit
Time at Destination
Outbound Transit

* Assuming NTP=925 sec Propulsion

Section 4.1.3  JSC/B. Drake

Nov. 2002
Advanced Concept Analysis in Support of the Integrated Space Plan

Section 4.2

Exploration Architecture Analysis
Launch Vehicle Definition

November 2002
### Preliminary Concepts for Exploration Blueprint Launch Vehicle

<table>
<thead>
<tr>
<th>Concept Configuration</th>
<th>Concept Description</th>
<th>Performance (Destination)</th>
<th>GLOW</th>
<th>2 Stage In-line</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shuttle Class</strong></td>
<td>• 1.5 Stage Vehicle • Sidemount Payload Carrier - 15’x 82’ Pld envelope • ET - LOX/LH2 Core • 3 SSME Boattail on Carrier • 2 - Four Segment SRBs</td>
<td>• 1.5 Stage Vehicle • Sidemount Payload Carrier - 25’x 90’ Pld envelope • ET LOX/LH2 Core - 5 ft. stretch LH2 tank • 3 SSME Engines on Carrier • 2 - Five Segment SRBs</td>
<td>4.52 Mlb</td>
<td>4.70 Mlb w/ J2S(4)</td>
</tr>
<tr>
<td><strong>Shuttle Class Evolved</strong></td>
<td>• 2.5 Stage Vehicle • Inline Payload Shroud - 31’x 90’ Pld for Mars - 25’x 90’ Pld for Near Earth • ET Derived, LOX/LH2 Core • 3 RS-68 Engines • 2 - Five Segment SRBs • Large LOX/LH2 Upper Stage - 2 J-2S Engines or - 1 SSME</td>
<td>• 2.5 Stage Vehicle • Inline Payload Shroud - 31’x 90’ Pld for Mars - 25’x 90’ Pld for Near Earth • ET Derived, LOX/LH2 Core • 3 RS-68 Engines • 2 - Five Segment SRBs • Large LOX/LH2 Upper Stage - 2 J-2S Engines or - 1 SSME</td>
<td>6.33 Mlb w/ J2S(2) 6.34 Mlb w/ SSME(1)</td>
<td>4.39 Mlb w/ SSME(2)</td>
</tr>
<tr>
<td><strong>In-line HLLV</strong></td>
<td>• 2 Stage Vehicle • Inline Payload Shroud - 31’x 90’ Pld for Mars - 25’x 90’ Pld for Near Earth • LOX/RP First Stage • 8 RD-180 Engines • LOX/LH2 Second Stage - 4 J-2S Engines or - 2 SSME</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>2 Stage In-line</strong></td>
<td>• 2 Stage Vehicle • Inline Payload Shroud - 31’x 90’ Pld for Mars - 25’x 90’ Pld for Near Earth • LOX/RP First Stage • 8 RD-180 Engines • LOX/LH2 Second Stage - 4 J-2S Engines or - 2 SSME</td>
<td></td>
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</table>
## Preliminary Concepts for Exploration Blueprint Launch Vehicle

<table>
<thead>
<tr>
<th>Concept Configuration</th>
<th>Shuttle Class</th>
<th>Shuttle Class Evolved</th>
<th>In-line HLLV</th>
<th>2 Stage In-line</th>
</tr>
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<tbody>
<tr>
<td><strong>Pros</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>• Uses ET Design Heritage/Facilities</td>
<td>• Uses ET Design Heritage/Facilities</td>
<td>• ET Evolved Design/Facilities</td>
<td>• Saturn V Heritage</td>
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<tr>
<td>• Uses Existing 4-Segment SRB</td>
<td>• Uses Existing Engines</td>
<td>• Inline Config Better for cg Track</td>
<td>• Inline Config Better for cg Track</td>
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<td>• Uses Existing Engines</td>
<td>• Larger Payload Carrier</td>
<td>• Shroud Jettisoned Prior to Orbit</td>
<td>• Shroud Jettisoned Prior to Orbit</td>
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<td>• Production Status at Termination</td>
<td>• Moderate Cost</td>
<td>• Growth Potential</td>
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<td>• Shortest Development Time</td>
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<td>• Least Facility Impact</td>
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<td>• Least Development Risk</td>
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<td>• Lower Cost</td>
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<tr>
<td><strong>Cons</strong></td>
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<tr>
<td>• Less Aerodynamic configuration</td>
<td>• Less Aerodynamic configuration</td>
<td>• Significant Pad/Facility Mods</td>
<td>• 8 Engines on Booster</td>
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<tr>
<td>• cg Tracking Issues w/ Side Mount</td>
<td>• cg Tracking Issues w/ Side Mount</td>
<td>• SSME Air Start Program</td>
<td>• J-2S Production Restart or</td>
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<td>• SSME Expended</td>
<td>• SSME Expended</td>
<td>• J-2S Production Restart</td>
<td>SSME Air Start Program</td>
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<td>• Does not Meet 100 mt Payload Req.</td>
<td>• Does not Meet 100 mt Payload Req.</td>
<td>• VAB Height Concerns</td>
<td>• SSME Expended</td>
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<td>• 15 ft. Dia. Payload Volume Constraint</td>
<td>• Ground Processing Concerns w/ Solids</td>
<td>• SSME Expended</td>
<td>• Significant Pad/Facility Mods</td>
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<td>• Ground Processing Concerns w/ Solids</td>
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<td>• Longest Development Time</td>
<td>• Higher Cost</td>
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<td></td>
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<td>• Higher Cost</td>
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</table>

### In-line HLLV

- **1.5 Stage Vehicle**
  - Sidemount Payload Carrier
  - ET - LOX/LH2 Core
  - 3 SSME Boattail on Carrier
  - 2 - Four Segment SRBs

- **2.5 Stage Vehicle**
  - Inline Payload Shroud
  - 31’x 90’ Pld for Mars
  - 25’x 90’ Pld for Near Earth
  - ET Derived, LOX/LH2 Core
  - 3 RS-68 Engines
  - 2 - Five Segment SRBs
  - Large LOX/LH2 Upper Stage
  - 2 J-2S Engines
  - or - 1 SSME

### 2 Stage In-line

- **2 Stage Vehicle**
  - Inline Payload Shroud
  - 31’x 90’ Pld for Mars
  - 25’x 90’ Pld for Near Earth
  - LOX/RP First Stage
  - 8 RD-180 Engines
  - LOX/LH2 Second Stage
  - 4 J-2S Engines
  - or - 2 SSME
### Development Schedule

#### Engineering Design Features/Technologies Per Vehicle Family

<table>
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<tr>
<th>Stage</th>
<th>Task Name</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
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<th>2011</th>
<th>2012</th>
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<td>Recovery System for 5 Segment SRB</td>
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<td>A B</td>
<td>New Engine Development for RS-83</td>
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<td>New Large Upper Stage</td>
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<tr>
<td>C D</td>
<td>Air Start Capability for SSME</td>
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<td></td>
<td>Restart J-2S Production</td>
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</tbody>
</table>

#### Preliminary

- **A**: 1.5 Stage w/4 SRB
- **B**: 1.5 Stage w/4 SRB
- **C**: 2.5 Stage w/SSME
- **D**: 2.5 Stage w/J-2S
- **E**: 2 Stage w/SSME
- **F**: 2 Stage w/J-2S (25 ft)
- **G**: 1.5 Stage w/2 SRB (25 ft)
## Engineering Design Features/Technologies Per Vehicle Family

<table>
<thead>
<tr>
<th></th>
<th>1.5 Stage w / 4 SRB</th>
<th>1.5 Stage w / 4 SRB</th>
<th>2.5 Stage w / SSME</th>
<th>2.5 Stage w / J-2S</th>
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<th>2 Stage w / J-2S</th>
<th>1.5 Stage w / 2 SRB</th>
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<td>¥</td>
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<td>- Advanced Composite Fabrication Processes and Facilities</td>
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<tr>
<td><strong>Recovery System for 5 Segment SRB</strong></td>
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<td>- Higher Apogee Altitude May Require Recovery System Redesign</td>
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<td>¥</td>
<td>¥</td>
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<td></td>
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<tr>
<td>- Minimal DDT&amp;E (Inherit from STS)</td>
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<td>- Increased Performance Over 4 Segment SRB</td>
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<td><strong>New Engine Development for RS-83</strong></td>
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<td><strong>New Large Upper Stage</strong></td>
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<td>- Air Start Capability for SSME</td>
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<tr>
<td>- Restart J-2S Production</td>
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</table>
## Shuttle Class Evolved

### Vehicle Characteristics

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tr>
<td>Payload (30 x 150 nmi)</td>
<td>93.5 mt</td>
</tr>
<tr>
<td>Gross liftoff mass</td>
<td>5.4 mlb</td>
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<tr>
<td>T/W @ liftoff</td>
<td>1.40</td>
</tr>
<tr>
<td>Max Q</td>
<td>646 psf</td>
</tr>
<tr>
<td>Max accel</td>
<td>3.8 g</td>
</tr>
<tr>
<td>Shroud mass</td>
<td>N/A klb</td>
</tr>
</tbody>
</table>

### Booster (5-segment):

| Propellants                 | HTPB        |
| Ascent propellant mass      | 2.9 mlb     |
| Burnout mass                | 430 klb     |
| Separation conditions       | Mach= 4.8, Q= 17.0 psf, alt= 177 kft |
| Vacuum Level thrust         | 3.92 mlb each|
| SL Isp                      | 265 sec     |

### External Tank (SLWT w/ 5 ft stretch):

| Propellants                 | LO2/LH2     |
| Ascent propellant mass      | 1.68 mlb    |
| Burnout mass                | 104.0 klb   |
| Engines                     | 3 SSME Engines (104%) |
| Vacuum thrust               | 492 klb each|
| SL Isp                      | 453 sec     |
| Sea Level thrust            | 397 klb each|
| SL Isp                      | 365 sec     |
Shuttle Class Evolved Configuration

NOTE:
DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
REUSABLE FIVE SEGMENT SOLID ROCKET BOOSTER (21)
Shuttle Class Evolved Side-Mount Combined Ascent Loads - Compression, Moment, & Shear

Exploration Blueprint - Shuttle C-25

Station Number


11-14-2002
Two Stage In-Line Vehicle w/ SSME

Vehicle Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
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<tbody>
<tr>
<td>Payload (30 x 150 nmi)</td>
<td>102.0 mt</td>
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<tr>
<td>Gross liftoff mass</td>
<td>4.4 mlb</td>
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<tr>
<td>T/W @ liftoff</td>
<td>1.30</td>
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<tr>
<td>Max Q</td>
<td>700 psf</td>
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<tr>
<td>Max accel</td>
<td>5.0 g</td>
</tr>
<tr>
<td>Shroud mass</td>
<td>40.5 klb</td>
</tr>
</tbody>
</table>

First Stage:

- Propellants: LOX/RP
- Ascent propellant mass: 2855 klb
- Burnout mass: 290 klb
- Separation conditions: Mach= 7.6, Q= 37.2 psf, alt= 181 kft
- Engines (each): 8 RD-180 Engines
  - Vacuum thrust: 951 klb each
  - SL Isp: 338 sec
- Sea Level thrust: 874 klb each
  - SL Isp: 311 sec

Second Stage:

- Propellants: LO2/LH2
- Ascent propellant mass: 809 klb
- Burnout mass: 112 klb
- Engines: 2 SSME Engines
  - Vacuum thrust: 471 klb each
  - SL Isp: 453 sec
Two Stage In-Line w/ SSME Configuration

NOTES:
DIMENSIONS IN INCHES
UNLESS OTHERWISE NOTED

TWO STAGE IN-LINE VEHICLE
WITH 8 RD180 ENGINES FIRST STAGE
AND 2 SSME ENGINES IN SEC. STAGE

PAYLOAD SHROUD

LH2 TANK
LOX TANK
SEC STAGE SSME ENG. (2)

LH2 TANK
LOX TANK
FIRST STAGE RD180 ENG. (8)
Two Stage In-Line Vehicle w/ SSME Side View

Saturn Class for Exploration Blueprint - 04 (2x SSME) Upper Stage

Programmed by Alan D. Philips, et al.  11-07-2002
Two Stage In-Line w/ SSME Combined Ascent Loads - Compression, Moment, & Shear
Two Stage In-Line Vehicle w/ J-2S

Vehicle Characteristics

Payload (30 x 150 nmi)  102.0 mt
Gross liftoff mass        4.912 mlb
T/W @ liftoff            1.30
Max Q                    600 psf
Max accel                4.81 g
Shroud mass              32.2 klb

First Stage:

Propellants        LOX/RP
Ascent propellant mass 3333 klb
Burnout mass        313 klb
Separation conditions Mach= 7.89, Q= 28.5 psf, alt= 190 kft
Engines (each)      8 RD–180 Engines
                      Vacuum thrust= 951 klb each  vac Isp= 338 sec
                      Sea Level thrust= 874 klb each  SL Isp= 311 sec

Second Stage:

Propellants        LO2/LH2
Ascent propellant mass 878 klb
Burnout mass        129 klb
Engines             4 J-2S Engines
                      Vacuum thrust= 265 klb each  vac Isp= 435 sec
                      Sea Level thrust= 201 klb each  SL Isp= 330 sec
Two Stage In-Line w/ J-2S Configuration

NOTES:
DIMENSIONS IN INCHES
UNLESS OTHERWISE NOTED

TWO STAGE IN-LINE VEHICLE
WITH 8 RD180 ENGINES FIRST STAGE
AND 4 J-2S ENGINES IN SEC. STAGE

PAYLOAD SHROUD

1606.30
420.00
330.00
4363.30 (363.61 FT) 4277.20
1434.00
317.61

1080.00 (300 FT)
372.00 (13 FT)

LH2 TANK
LOX TANK

1236.90
668.20

SEC. STAGE
J-2S ENG. (4)

LH2 TANK
LOX TANK

278.01
781.80

FIRST, STAGE
RD 180 ENG. (8)
Two Stage In-Line Vehicle w/ J-2S Side View

Saturn Class for Exploration Blueprint - 03 (4x J-2S) Upper Stage

Programmed by Alan D. Philips, et al.

11-07-2002
Two Stage In-Line w/ J-2S Combined Ascent Loads - Compression, Moment, & Shear
**In-line HLLV w/ 2 J-2S, 30 x 150 nmi Elliptical**

**Vehicle Characteristics**
- Gross liftoff mass: 6.324 Mlb
- T/W @ liftoff: 1.37
- Max Q: 600 psf
- Max accel: 2.4 g
- P/L container mass: 17997 lb

**Booster:** Five Segment SRB
- Number of Boosters: 2 SRBs
- Propellants: Solid Prop
- Ascent propellant mass: 1428 klb, each
- Burnout mass: 217 klb, each
- Separation conditions:
  - Engines (each): 1 Five segment Shuttle SRB
    - SL thrust: 3334 klb each
    - SL Isp: 265 sec

**First Stage:** EB - HLV
- Propellants: LO2/LH2
- Ascent propellant mass: 2043 klb
- Burnout mass: 220 klb
- Engines: 3 RS-68 Engines
  - Vacuum thrust: 751 klb each
  - Vac Isp: 409 sec
  - SL thrust: 656 klb each
  - SL Isp: 357 sec

**Second Stage:** EB - HLV
- Propellants: LO2/LH2
- Ascent propellant mass: 417 klb
- Burnout mass: 81 klb
- Engines: 2 J-2S
  - Vacuum thrust: 265 klb each
  - Vac Isp: 436 sec
  - SL thrust: 0 klb each
  - SL Isp: 0 sec

**Target Payload:**
- 100.0 mton to 30nmi x 150nmi @ 28.5 (DRM)
- 108.5 mton to 30nmi x 150nmi @ 28.5 (DRM)
In-line HLLV w/ J-2S Configuration
In-Line HLLV w/ J-2S Combined Ascent Loads - Compression, Moment, & Shear

LVA Graphical Output

Magnum for Exploration Blueprint - 09 (2x J-2S) Upper Stage

- Compression (x10^6 lbs)
- Moment (x10^6 in-lbs)
- Shear (x10^6 lbs)

Station Number

100 250 500 750 1000 1250 1500 1750 2000 2250 2500 2750 3000 3250 3500 3750 4000 4250 4500 4750

-375.0 -350.0 -325.0 -300.0 -275.0 -250.0 -225.0 -200.0 -175.0 -150.0 -125.0 -100.0 -75.0 -50.0 -25.0 0.0

11-07-2002

LVA v4.7.1 Programmed by Mark D. Phillips, et al.
**In-line HLLV w/ 1 SSME, 30 x 150 nmi Elliptical**

### Vehicle Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Gross liftoff mass</td>
<td>6.326 Mlb</td>
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<tr>
<td>T/W @ liftoff</td>
<td>1.37</td>
</tr>
<tr>
<td>Max Q</td>
<td>600 psf</td>
</tr>
<tr>
<td>Max accel</td>
<td>2.5 g</td>
</tr>
<tr>
<td>P/L container mass</td>
<td>17997 lb</td>
</tr>
</tbody>
</table>

**Booster:** Five Segment SRB
- Number of Boosters: 2 SRBs
- Propellants: Solid Prop
- Ascent propellant mass: 1428 klb, each
- Burnout mass: 217 klb, each
- Separation conditions: 1 Five segment Shuttle SRB
  - SL thrust: 3334 klb each
  - SL Isp: 265 sec

**First Stage:** EB - HLV
- Propellants: LO2/LH2
- Ascent propellant mass: 2066 klb
- Burnout mass: 218 klb
- Engines: 3 RS-68 Engines
  - Vacuum thrust: 751 klb each
  - vac Isp: 409 sec
  - SL thrust: 656 klb each
  - SL Isp: 357 sec

**Second Stage:** EB - HLV
- Propellants: LO2/LH2
- Ascent propellant mass: 407 klb
- Burnout mass: 70 klb
- Engines: 1 SSME
  - Vacuum thrust: 471 klb each
  - vac Isp: 453 sec
  - SL thrust: 380 klb each
  - SL Isp: 365 sec

**Target Payload:**
- 100.0 mton to 30nmi x 150nmi @ 28.5 (DRM)
- Payload: 113.5 mton to 30nmi x 150nmi @ 28.5 (DRM)
In-line HLLV w/ 1 SSME, 150 nmi Circular

Vehicle Characteristics
- Gross liftoff mass: 6.137 Mlb
- T/W @ liftoff: 1.41
- Max Q: 700 psf
- Max accel: 2.8 g
- P/L container mass: 40,126 lb

Booster:
- Five Segment SRB
- Number of Boosters: 2 SRBs
- Propellants: Solid Prop
- Ascent propellant mass: 14,280 klb, each
- Burnout mass: 217 klb, each
- Engines (each): 1 Five segment Shuttle SRB
  - SL thrust: 3334 klb each
  - SL Isp: 265 sec

First Stage:
- EB - HLV
- Propellants: LO2/LH2
- Ascent propellant mass: 1974 klb
- Burnout mass: 216 klb
- Engines: 3 RS-68 Engines
  - Vacuum thrust: 751 klb each
  - Isp: 409 sec
  - SL thrust: 656 klb each
  - Isp: 357 sec

Second Stage:
- EB - HLV
- Propellants: LO2/LH2
- Ascent propellant mass: 307 klb
- Burnout mass: 65 klb
- Engines: 1 SSME
  - Vacuum thrust: 471 klb each
  - Isp: 453 sec
  - SL thrust: 380 klb each
  - Isp: 365 sec

Kick Stage:
- Circularize @ 150 nmi
- Jettison mass: 8350 lb
- Target Payload: 100.0 mton to 150nmi circ @ 28.5 (DRM)
- Payload: 103.6 mton to 150nmi circ @ 28.5 (DRM)
In-line HLLV w/ 1 SSME Configuration

NOTES:
DIMENSIONS IN INCHES UNLESS OTHERWISE INDICATED

100 METRIC TONS 2 STAGE MAGNUM VEHICLE WITH KICK UPPER STAGE

MAGNUM S-POD

192.90

Ø 372.00

UPPER STAGE

250.92

LH2 TANK

660.20

LOX TANK

186.50

SEC. STAGE SSME ENGINE

575.52

LOX TANK

1420.32

LS2 TANK

RS 68 ENGINE (3)

REUSABLE 5 SEGMENT SOLID ROCKET BOOSTER (2)
In-line HLLV w/ SSME Combined Ascent Loads - Compression, Moment, & Shear
**In-line HLLV w/ 2 SSME, 150 nmi Circular**

### Vehicle Characteristics
- **Gross liftoff mass**: 6.210 Mlb
- **T/W @ liftoff** : 1.39
- **Max Q**: 700 psf
- **Max accel**: 2.4 g
- **P/L container mass**: 40129 lb

**Booster**: Five Segment SRB
- **Number of Boosters**: 2 SRBs
- **Propellants**: Solid Prop
- **Ascent propellant mass**: 1428 klb, each
- **Burnout mass**: 217 klb, each

**Separation conditions**
- **Engines (each)**: 1 Five segment Shuttle SRB
  - **SL thrust**: 3334 klb each
  - **Isp**: 265 sec

**First Stage**: EB - HLV
- **Propellants**: LO2/LH2
- **Ascent propellant mass**: 1916 klb
- **Burnout mass**: 215 klb
- **Engines**: 3 RS-68 Engines
  - **Vacuum thrust**: 751 klb each
  - **Isp**: 409 sec
  - **SL thrust**: 656 klb each
  - **Isp**: 357 sec

**Second Stage**: EB - HLV
- **Propellants**: LO2/LH2
- **Ascent propellant mass**: 413 klb
- **Burnout mass**: 91 klb
- **Engines**: 2 SSME
  - **Vacuum thrust**: 471 klb each
  - **Isp**: 453 sec
  - **SL thrust**: 380 klb each
  - **Isp**: 365 sec

**Kick Stage**: Circularize @ 150 nmi
- **Jettison mass**: 8350 lb
- **Target Payload**: 100.0 mton to 150nmi circ @ 28.5 (DRM)
- **Payload**: 104.8 mton to 150nmi circ @ 28.5 (DRM)
In-line HLLV w/ 2 SSME Configuration
In-line HLLV Dual Engine 2nd Stage Side View

Programmed by Alan D. Philips, et al.
10-22-2002
In-line HLLV Dual Engine 2nd Stage Combined Ascent Loads - Compression, Moment, & Shear
Magnum Derived Launch Vehicle w/ 4 SRBs

**Vehicle Characteristics**
- **Gross liftoff mass**: 8.785 mlb
- **T/W @ liftoff**: 1.52
- **Max Q**: 700 psf
- **Max accel**: 3.30 g
- **Shroud mass**: 41.4 klb

**Booster:**
- **Number of Boosters**: 4 SRBs
- **Propellants**: Solid Prop
- **Ascent propellant mass**: 1428 klb, each
- **Burnout mass**: 217 klb, each
- **Separation conditions**: Mach= 5.74, Q= 8.1 psf, alt= 205 kft
- **Engines (each)**: Five segment Shuttle SRB
  - Vacuum thrust= 3334 klb each
  - Sea Level thrust= 3088 klb each
  - **Vacuum ISP**: 265 sec
  - **Sea Level ISP**: 245 sec

**Core:**
- **Propellants**: LO2/LH2
- **Ascent propellant mass**: 1673 klb
- **Burnout mass**: 231 klb
- **Engines**: 2 RS-83 Engines
  - Vacuum thrust= 757 klb each
  - Sea Level thrust= 640 klb each
  - **Vacuum ISP**: 449 sec
  - **Sea Level ISP**: 379 sec

**Kick Stage:**
- **Circularize @ 150 nmi
- Jettison mass**: 8.4 klb

**Target Payload**: 100 MT to 150 nmi circ @ 28.5 (DRM)
**Actual Payload**: 106.6 MT to 150 nmi circ @ 28.5
Magnum Derived Launch Vehicle w/ 4 SRBs
Magnum In-Line Combined Ascent Loads - Compression, Moment, & Shear
Shuttle-CX Launch Vehicle w/ 4 SRBs

**Vehicle Characteristics**

- Gross liftoff mass: 8.739 mlb
- T/W @ liftoff: 1.56
- Max Q: 694 psf
- Max accel: 3.00 g

**Booster:**
- Five Segment SRB
- Number of Boosters: 4 SRBs
- Propellants: Solid Prop
- Ascent propellant mass: 1428 klb, each
- Burnout mass: 217 klb, each
- Booster separation conditions: Velocity= 5709 ft/s, Q= 7.2 psf, alt= 206 kft, time= 132.4 sec.
- Engines (each): 1 Five segment Shuttle SRB
  - Vacuum thrust= 3334 klb each, vac Isp= 265 sec
  - Sea Level thrust= 3088 klb each, SL Isp= 245 sec

**Payload Container**
- Shuttle-CX
- Propellants: LO2/LH2
- Ascent propellant mass: 1674 klb
- Shroud separation conditions: Velocity= 6902 ft/s, Q= 0.0 psf, alt= 400 kft, time= 220.6 sec.
- Burnout mass w/o payload: 141 lb
- External Tank Dry Mass: 64 lb
- Engines: 2 RS-83 Engines
  - Vacuum thrust= 757 klb each, vac Isp= 449 sec
  - Sea Level thrust= 640 klb each, SL Isp= 379 sec
  - Shuttle OMS

**Kick Stage:**
- n/a

**Target Payload:** 100 MT to 150nm circ @ 28.5 (DRM)
**Actual Payload:** 102.9 MT to 150nm circ @ 28.5
Shuttle-CX Launch Vehicle w/ 4 SRBs
Shuttle-CX Side-Mount Combined Ascent Loads - Compression, Moment, & Shear

[Graphical Output Diagram Showing Load Parameters]
Five-Segment SRB

<table>
<thead>
<tr>
<th>Performance Comparison</th>
<th>Four-Segment RSRB</th>
<th>Five-Segment SRB</th>
<th>Five-Segment (+96&quot;) SRB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Burn Rate (in/sec)</td>
<td>0.368</td>
<td>0.351</td>
<td>0.338</td>
</tr>
<tr>
<td>Nozzle Throat Dia. (in)</td>
<td>53.9</td>
<td>59.6</td>
<td>59.6</td>
</tr>
<tr>
<td>Maximum Operation Pressure (psia)</td>
<td>906.8</td>
<td>980</td>
<td>966.2</td>
</tr>
<tr>
<td>Maximum Thrust (M lbf)</td>
<td>3.145</td>
<td>3.921</td>
<td>3.943</td>
</tr>
<tr>
<td>Specific Impulse (sea level) (lbf·sec/lbm)</td>
<td>268.4</td>
<td>264.7</td>
<td>264.7</td>
</tr>
<tr>
<td>Action Time (sec)</td>
<td>123.5</td>
<td>128.9</td>
<td>133.0</td>
</tr>
<tr>
<td>Action Time Total Impulse (M lbf·sec)</td>
<td>296.9</td>
<td>368.28</td>
<td>388.73</td>
</tr>
</tbody>
</table>

FSB Performance Comparison

- 5-Seg SRB
- 4-Seg RSRB
- 5-Seg +96 SRB

Section 4.2 MSFC/V. Houston

Nov. 2002  340
## RS-83 Engine

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust, Sea Level:</td>
<td>640 Klbf</td>
</tr>
<tr>
<td>Thrust, Vacuum:</td>
<td>757 Klbf</td>
</tr>
<tr>
<td>Specific Impulse:</td>
<td>448.7 sec vac</td>
</tr>
<tr>
<td>Chamber Pressure:</td>
<td>2,800 psia</td>
</tr>
<tr>
<td>Mixture Ratio:</td>
<td>6.9 S.L. / 6.0 Alt</td>
</tr>
<tr>
<td>Engine T/W</td>
<td>55 S.L.</td>
</tr>
<tr>
<td>Area Ratio:</td>
<td>55:1</td>
</tr>
<tr>
<td>Throttling:</td>
<td>50 - 100% thrust</td>
</tr>
</tbody>
</table>
Magnum Circularization and De-orbit Stage

Main Thruster: OMS derived, AeroJet AJ10-190 class, pressure-fed 6,000 lbf bipropellant thruster
- \( P_c = 125 \) psia
- Mixture Ratio = 1.65
- \( I_{sp \text{ vac}} = 313 \) sec
- Mass = 260 lbm (120 kg)

Reaction Control Thruster:
Marquardt R-4D class, bipropellant 110 lbf thruster
- \( P_c = 100-400 \) psia
- Mixture Ratio = 1.65
- \( I_{sp \text{ vac (ss)}} = 311 \) sec
- Mass = 8.3 lbm (3.8 kg)

Stage Mass Breakdown

<table>
<thead>
<tr>
<th>Component</th>
<th>lbm</th>
<th>kg</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structures</td>
<td>1540.6</td>
<td>700</td>
<td>including pressurant tanks</td>
</tr>
<tr>
<td>Thermal*</td>
<td>140</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>Electrical*</td>
<td>443</td>
<td>201</td>
<td></td>
</tr>
<tr>
<td>GN&amp;C*</td>
<td>118</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>C&amp;DH*</td>
<td>49</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>Propulsion*</td>
<td>105</td>
<td>48</td>
<td>with integrated RCS</td>
</tr>
<tr>
<td>design contingency</td>
<td>359</td>
<td>163</td>
<td></td>
</tr>
<tr>
<td>Dry Mass Subtotal (15%)</td>
<td>2755</td>
<td>1252</td>
<td></td>
</tr>
<tr>
<td>Propellant Mass</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NTO</td>
<td>3485</td>
<td>1584</td>
<td></td>
</tr>
<tr>
<td>MMH</td>
<td>2112</td>
<td>960</td>
<td></td>
</tr>
<tr>
<td>Pressurant</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Total Stage Mass</td>
<td>8354</td>
<td>3797</td>
<td></td>
</tr>
</tbody>
</table>

* Masses derived from 2000 High Energy Upper Stage Study

Overall Length: 174.3 in. (442.7 cm)
Maximum Diameter: 110.2 in. (279.9 cm)
Mission Profile for Magnum Type 100 MT
Launch Vehicle w/ 1 SSME Upper Stage

**Payload**

**Liftoff**
T = +1 sec
T/W = 1.50

**Shroud Separation**
T = +300 sec
Alt = 400 Kft
Vel = 10.5 Kft/sec

**Core Stage Separation**
T = +358 sec
Alt = 449 Kft
Vel = 24.3 Kft/sec

**5 Segment SRB Separation**
T = +132 sec
Alt = 162 Kft
Vel = 4.4 Kft/sec

**Upper Stage Separation**
T = +642 sec
Alt = 470 Kft
Vel = 14.3 Kft/sec

**Payload Capability**
103.6 MT

**Large Payload Shroud**
35 ft Outside Diameter
31 ft x 90 ft cyl. payload envelope

**Lox/LH2 Upper Stage**
1 - SSME Engine
307 Klb Propellant

**Two, 5 Segment SRBs**

**Lox/LH2 Core**
3 - RS 68 Engines
1.97 Mlb Propellant
27.6 ft Diameter

**Kick Stage Circ**
T ~ +4800 sec
Alt = 911 Kft (150 nmi)
Vel = Orbital

**Preliminary**
Mission Profile for Magnum Type 100 MT Launch Vehicle w/ 2 SSME Upper Stage

**Payload Capability**
104.8 MT

**Large Payload Shroud**
- 35 ft Outside Diameter
- 31 ft x 90 ft cyl. payload envelope

**Lox/LH2 Upper Stage**
- 2 - SSME Engine
- 413 Klb Propellant

**Two, 5 Segment SRBs**
- Lox/LH2 Core
  - 3 - RS 68 Engines
  - 1.92 Mlb Propellant
  - 27.6 ft Diameter

**Core Stage Separation**
- T = +348 sec
- Alt = 435 Kft
- Vel = 12.8 Kft/sec

**Shroud Separation**
- T = +300 sec
- Alt = 400 Kft
- Vel = 9.8 Kft/sec

**5 Segment SRB Separation**
- T = +132 sec
- Alt = 160 Kft
- Vel = 4.2 Kft/sec

**Liftoff**
- T = +1 sec
- T/W = 1.48

**Upper Stage Separation**
- T = +539 sec
- Alt = 471 Kft
- Vel = 24.3 Kft/sec

**Kick Stage Circ**
- T ~ +4700 sec
- Alt = 911 Kft (150 nmi)
- Vel = Orbital

**Preliminary**
SSME Altitude Start Conclusions

from Alternate Propulsion Subsystem Concepts
NAS8-39210, DCN 1-1-PP-02147, March 1993

• Altitude sub-orbital start of SSME is feasible

• Preburner valve sequenced to higher positions and modified timings to accommodate lower inlet pressure

• Modify basic timing of the open loop and closed loop control modes

• Initial bootstrap rate reduced from current start time

• Time to reach main stage not affected

• Minimum propellant inlet pressures required, LOX – 40 psi, LH2 – 32 psi

A recent top-level look at air-starting an SSME for a two-stage RLV would require a Class A certification program with a ROM cost of approximately 100 million in 2003 dollars.
J-2S Restart Study Production Summary

Alternative Propulsion Subsystem Concepts
NAS8-39210, DCN 1-1-PP-02147, April 1993

Could be produced to existing drawings:
- Only engine electronics absolutely require replacement
- No material changes
- All processes are still possible

Desirable changes identified:
- 24 production changes (no change in form/fit/function)
- 20 changes in fabrication technique (ie, castings, die forgings, etc.)
- 12 material substitutions
- 11 reliability & operational enhancements

245 million 1992 dollars* production restart:
- Assumes a 6 year production restart schedule
- Assumes one engine certification program
- Assumes certification results are a “one-for-one” match with historical data
- Unit cost of 10 million 1992 dollars* for a 10 lot buy

* 1992 to 2002 inflation index ~ 1.3
Magnum Five-Segment SRB Recovery Issue

- The recovery issues related to the five-segment SRB with separation trajectory apogee in excess of 300k ft is valid for the four five-segment SRB Magnum configuration.

- With the two five-segment SRB Magnum configuration booster separation trajectory apogee is less than 260k ft, well under the five-segment SRB design requirement ceiling of 280k ft.
Structures Guidelines & Assumptions

- Gr/Ep IM7/8552 construction with Aluminum cryotanks
- Weights provided are best effort / preliminary
- Weights do not include any additional factors (weight growth, etc.)
- Ascent load input obtained from POST run provided
SLI Composite Structures Activities

• Tasks currently in place for further development
  – Primary composite cryotanks

• Tasks identified, but not currently being pursued
  – Airframe structural interface w/ large integral cryotanks
    • Attached orbiter / payload pod
    • Aerosurfaces
    • Thrust structure
    • Intertank
Advanced Concept Analysis in Support of the Integrated Space Plan

Section 4.3

Exploration Architecture Analysis
Vehicle Processing and Launch Operations Assessment

November 2002
Scope

• Three launch vehicle designs and 5 payload types will be assessed.
  – **Launch Vehicles**
    1. EELV (Exploration Class) – 35-45 MT
    2. Magnum with two Five-Segment Solid Rocket Boosters (FSB)
    3. Shuttle-C25 (large cargo) with two FSB
    4. Ancillary High-Level Assessments
      – Liquid Boosters vs. Solid Boosters
      – Magnum Type Concept and Shuttle-C25 Concept with Four Five-Segment SRBs
      – 2012 Saturn V
  – **Payload Processing Impacts**
    1. Lunar Transfer Vehicle (LTV)
    2. Gateway
    3. Lunar Lander (3-day stay)
    4. Lunar Habitat (30-day stay)
    5. Solar Electric Propulsion (SEP)
    6. Nuclear Payload Assessment/Assumptions

• **Items to be included in assessment for each vehicle:**
  – Groundrules, assumptions and exclusions
  – Overall Launch Site Processing Flow
  – Element Processing Timelines
  – Infrastructure Impacts/Modifications and Modification Schedule
  – High-level Manifest Assessment (sensitivity analysis)
KSC Team Members

Vehicle Processing and Launch Operations
- Cristina Guidi – 1998 Magnum/LFBB Ops Lead, KSC Blueprint Team Lead
- Connie Milton – Infrastructure
- Darrell Foster – ELV/Payloads
- Darin Skelly – ELV/Payloads
- Tom Overton – Shuttle Manifest
- Frank Izquierdo – Shuttle Upgrades
- Jeff Campbell – 1999 Magnum/SRB Ops Assessment Lead
- Chuck Davis – Propellant Handling
- Don Burris – Infrastructure

Supportability Team
- Bob Cunningham
- Bill Roy

Cost Comparison Team
- Glenn Rhodeside
- Jim Roberts
Significant Groundrules and Assumptions

- KSC Manifest must allow for 4 ISS resupply missions per year
- VAB approved for 1.5 flight sets of 5-Segment SRBs (VAB Quantity Distance still under review)
- Shuttle-CX cargo carrier element and Magnum core element will arrive at KSC with engines installed and will require minimal launch site checkout
- No Planetary Protection Requirements
- All Handling/transportation GSE will be provided by launch vehicle and payload provider for launch vehicle and payload processing
- No hazardous “off-line” payload processing requirements (e.g. all payload off-line activities will be performed in SSPF)

Study Exclusions Requiring Follow-on Evaluation

- Launch Processing System (ground software/hardware)
- Special testing (i.e. Demonstration flight, Flight Readiness Firing, “twang” test)
- Launch Pad Environment Impact studies (e.g. Thermal, pressure, acoustic, vibration, lift off drift, excursions, etc.) may have an impact of facility modifications
- Mixed fleet impact/transition planning
- FTE assessments if new mission set is additive to current work load
- Environmental assessment for 2012 Saturn V and Nuclear Systems
General Nuclear Payload Assessment/Assumptions

- “Nuclear System” (i.e RTG, RPS, Reactor, etc.) will meet the analysis and data requirements for both launch approval and ground processing approval

- Ground processing of the “Nuclear System” and its integration into the payload will be performed at the appropriate “offline” payload hazardous processing facility and the appropriate handling and security measure will be implemented

- Final launch vehicle selected can accommodate late access at pad to install nuclear system

- NASA, DoE, and Federal Regulatory Agency (i.e. NRC) will work together to determine the appropriate safety measures and licenses are in place at KSC/CCAFS

- Minimal “servicing” required for the “Nuclear System” once installed at the pad.

- Pad access will be extremely limited once “nuclear System” installed or arrives. If “nuclear system” installed at pad than controlled/limited access to area will be enforced.

NOTE: Further detailed assessments will be performed as nuclear payload requirements are defined
## Preliminary Assessment of Architectures

<table>
<thead>
<tr>
<th>Architecture Launch Campaign Options</th>
<th>Architecture A Delta IV-Heavy Exploration Class</th>
<th>Architecture B Magnum w/ 2 FSB or Shuttle-C25 w/2 FSB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A1:</strong> If the Lunar Transfer Vehicle can be launched in the Shuttle Payload Bay with the exploration crew on-board (in the Shuttle cabin):</td>
<td>A1: If the Lunar Transfer Vehicle can be launched in the Shuttle Payload Bay with the exploration crew on-board (in the Shuttle cabin):</td>
<td>B1: If the Magnum launch vehicle is human-rated and has 100 MT payload lift capability:</td>
</tr>
<tr>
<td>- 5 STS launches per year</td>
<td>- 5 STS launches per year</td>
<td>-5 Magnum/Shuttle-C25 launches per year or 4 Magnum launches with 1 EELV launches per year</td>
</tr>
<tr>
<td>- 5 EELV launches per year</td>
<td>- 7 EELV launches per year</td>
<td></td>
</tr>
<tr>
<td><strong>A2:</strong> If the Lunar Transfer Vehicle cannot be launched in the Shuttle Payload Bay (because of the cryogenic propellants on-board):</td>
<td><strong>A2:</strong> If the Lunar Transfer Vehicle cannot be launched in the Shuttle Payload Bay (because of the cryogenic propellants on-board):</td>
<td>B2: If the Magnum launch vehicle is NOT human-rated and has 100 MT payload lift capability:</td>
</tr>
<tr>
<td>- 5 STS launches per year</td>
<td>- 7 EELV launches per year</td>
<td>-2 STS launches per year</td>
</tr>
<tr>
<td>- 7 EELV launches per year</td>
<td></td>
<td>-5 Magnum/Shuttle-C25 launches per year or 4 Magnum launches with 1 EELV launches per year</td>
</tr>
<tr>
<td><strong>A3:</strong> If the Lunar Transfer Vehicle and exploration crew are launched on a human-rated EELV:</td>
<td><strong>A3:</strong> If the Lunar Transfer Vehicle and exploration crew are launched on a human-rated EELV:</td>
<td></td>
</tr>
<tr>
<td>- 3 STS launches per year</td>
<td>- 7 EELV launches per year</td>
<td></td>
</tr>
<tr>
<td>- 7 EELV launches per year</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### KSC Impacts

#### EELV Impacts
- Both Boeing and LMA developing Exploration class “paper rockets”
- Based on maximum launch rate (7 EELV’s launches first year) architectures A1-A3 are feasible on EELV’s.
  - Recommend multiple EELV providers (Delta IV & Atlas V) be carried forward to allow for LV development and for unknown future commercial launch rates.
  - If single EELV Provider carried forward than recommend additional dedicated “exploration class” EELV Pad for manifest flexibility

#### Shuttle impacts:
- Architecture A1: Launching payloads with cryogenics is not permitted in the Shuttle Payload Bay
- Architectures A1 & A2 are stressing the manifest capability when including the 4 ISS resupply missions (maximum of 9 launches per year) – increase in manpower required
- Facility impacts minimal (minor payload processing modifications)

#### Overall Assessment:
- All Architecture A options are feasible

#### Magnum w/ 2 FSB and Shuttle-C25 w/ 2 FSB at Complex 40/41 were ruled out due to excessive infrastructure requirements (new standalone core processing facility or cargo carrier facility, new Vehicle Integration Facility, new SRB Buildup and Stacking Facility, Major pad modifications)
  - LC-39 Area has been selected as leading candidate for Magnum and Shuttle-C25

#### Overall Assessment:
- All options are feasible however there are infrastructure impacts
- All flight scenarios can be supported with 1 new MLP for Magnum/1 new MLP for Shuttle-C25 and 3 existing MLPs for Shuttle.
  - All flight scenarios can be supported by 2 modified launch pads
  - Five-segment Booster processing will require a new SRB Build-up and Stacking facility because of Quantity Distance restrictions and manifest

- Magnum or Shuttle-C25 launch manifest must accommodate 4 ISS resupply missions per year
- To maintain manifest, will require OPF processing timelines to be less than (80) days and additional workforce will be required

---

**NOTE:** Flight rate above is in addition to the 4 mandatory ISS Resupply missions performed by Shuttle per year
## Concept Configuration

<table>
<thead>
<tr>
<th>Magnum w/ Two FSB</th>
<th>Shuttle-CX w/ Two FSB</th>
<th>2012 Saturn V</th>
<th>Magnum and Shuttle-CX w/ Four FSB</th>
</tr>
</thead>
<tbody>
<tr>
<td>- New SRB Build-up &amp; Stacking Facility</td>
<td>- New Cargo Carrier Processing Facility (CCPF)</td>
<td>- VAB High Bays 1 &amp; 3 Access Platforms</td>
<td>- New Launch Pad required or extensive modifications to existing pads</td>
</tr>
<tr>
<td>- VAB High Bays 1 &amp; 3 Access Platforms</td>
<td>- New SRB Build-up &amp; Stacking Facility</td>
<td>- 1 New Saturn V -dedicated MLP with Launch Umbilical Tower</td>
<td>- New Stacking/Integration Facility due to Quantity Distance (QD) limitations in the VAB</td>
</tr>
<tr>
<td>- Additional New RPSF Surge Facility</td>
<td>- VAB High Bays 1 &amp; 3 Access Platforms and High Bays 2 &amp; 4 ET Checkout Cells modifications</td>
<td>- New Cargo Transporter (shroud)</td>
<td>- Four 5-Segment SRBs invalidate the QD requirement</td>
</tr>
<tr>
<td>- 1 New Magnum-dedicated MLP with Launch Umbilical Tower</td>
<td>- Additional New RPSF Surge Facility</td>
<td>- Pad Modifications: Flame Trench &amp; Sound Suppression System, RP-1 loading capability, Methane Loading/venting/capture Capability (payload), Cryo Propellant loading/venting/capture GSE (payload)</td>
<td>- Integration of this vehicle cannot occur in the VAB unless QD requirement is changed to allow 4 stacks at one time</td>
</tr>
<tr>
<td>- New Cargo Transporter (shroud)</td>
<td>- 1 New Additional MLP similar in design to Shuttle MLP</td>
<td>- New MLP</td>
<td>- New MLP</td>
</tr>
<tr>
<td>- Operations &amp; Checkout (O&amp;C): Removal of storage and payload test stand for Magnum core stage standalone processing</td>
<td>- 1 New Extended-ET Barge</td>
<td>- Two (2) New RPSF Surge Facilities</td>
<td>- Two (2) New RPSF Surge Facilities</td>
</tr>
<tr>
<td>- Retrieval and Disassembly: Diver Operated Plug (DOP), Additional Rail Dollies, Slip Crane</td>
<td>- Pad Modifications: PCR Modifications, SRB Forward Skirt Access, GOX Vent Arm Notch Modification, Flame Trench &amp; Sound Suppression System, Methane Loading/venting/capture Capability (payload), Cryo Propellant loading/venting/capture GSE (payload)</td>
<td>- Retrieval and Disassembly: Diver Operated Plug (DOP), Additional Rail Dollies, Slip Crane</td>
<td>- Retrieval and Disassembly: Diver Operated Plug (DOP), Additional Rail Dollies, Slip Crane</td>
</tr>
</tbody>
</table>

## Infrastructure Impacts

- New SRB Build-up & Stacking Facility
- VAB High Bays 1 & 3 Access Platforms
- Additional New RPSF Surge Facility
- 1 New Magnum-dedicated MLP with Launch Umbilical Tower
- New Cargo Transporter (shroud)
- Pad Modifications: Additional LH2 sphere, SRB Forward Skirt Access, Flame Trench & Sound Suppression System, Methane Loading/venting/capture Capability (payload), Cryo Propellant loading/venting/capture GSE (payload)
- Operations & Checkout (O&C): Removal of storage and payload test stand for Magnum core stage standalone processing
- Retrieval and Disassembly: Diver Operated Plug (DOP), Additional Rail Dollies, Slip Crane

## Environmental Issues

- Acoustic effects to surrounding community
- SRB exhaust deposition and new pad construction impact on ecosystem
# KSC Launch Site – Vehicle Pros and Cons

<table>
<thead>
<tr>
<th>Concept Configuration</th>
<th>Magnum w/ Two FSB</th>
<th>Shuttle-CX w/ Two FSB</th>
<th>2012 Saturn V</th>
<th>Magnum and Shuttle-CX w/ Four FSB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
<td>• Infrastructure modifications are moderate</td>
<td>• Infrastructure modifications are moderate</td>
<td>• Infrastructure modifications are minor</td>
<td>• NONE</td>
</tr>
</tbody>
</table>
| **Cons**              | • Quantity Distance issue with Five segment booster  
  • Construction of two new facilities required | • Quantity Distance issue with Five segment booster  
  • Construction of three new facilities required | • Infrastructure impacts are extreme  
  • Quantity Distance issue with Five segment booster | |

Section 4.3  KSC/C. Guidi  
Nov. 2002  357
Due to the required increase of solid propellant for FSB, significant processing challenges must be overcome.

- **Quantity Distance (QD)** for VAB limits the number of segments allowed within the VAB at any time:
  - Current limit is approximately 4.4 million lbs. (2 flight sets of 4-Segment SRBs)
  - FSB propellant weight is approximately 5.6 million lbs. (2 flight sets of 5-Segment SRBs)

- If this propellant quantity limit is retained for 5 segment booster, no more than 15 segments (1.5 flight sets) would be allowed to be housed in the VAB:
  - This restriction would create a bottle neck in VAB processing operations which would prevent the current long term manifest from being met.
Backup Charts
Delta IV LV Launch Site Flow Processing

**Booster Processing**
- Delta Mariner delivers CBCs, S-IV upper stages, and S-IV fairings to launch site
- Horizontal integration and testing of CBC and second stages
- Transport to launch pad
- Erect vehicle on launch pad
- Optional GEM-30 solid rocket motors transported to launch pad

**Payload Integration/encapsulation (parallel)**
- Payload lifted via crane and attached to launch vehicle
- Hook up ECS and transport to launch pad
- Erect and store fairing bisections or trimmers
- Prepare fairing bisections for payload encapsulation
- Integrate payload to RAF and perform integrated checkout
- Install payload attach fitting on build-up stand
- Payload processing facility

Section 4.3  KSC/C. Guidi  Nov. 2002
Overall Launch Site Processing Flow
(Magnum w/ FSB)
Overall Launch Site Processing Flow
(Shuttle-C25 w/ FSB)
### Facility Modification Timeline

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- **Design Period**
- **Mod/Activation Period**
Backup – Infrastructure Impacts
For Architecture B only
Modification required for **any vehicle design** that uses 5-Segment Boosters

- **Segment Railcars**
  - ~ 6 more rented railcars at higher weight capacity will be needed for FSB
    - Accommodates longer / heavier fwd segment

- **Exit Cone Elevator Mod**
  - Due to longer exit cone

- **Additional surge facility**
  - Construct additional Surge Facility capable of holding 4 forward segments

Data from USA Ground Operations for FSB Abort to Orbit Study
New SRB Build-up & Stacking Facility

• **Modification required for any vehicle design that uses 5-Segment Boosters**

• **70,000 sq.ft. Processing Highbay**
  – MLP mount mechanisms
  – Vertical lift and Horizontal rolling doors
  – 800-ton bridge crane

• **Options include and need further assessment:**
  – Stacking segments on the MLP (similar to current VAB process) – *impacts MLP turnaround timelines*
  or
  – Assembling the entire stack in a stacking cell and transferring the booster to MLP – *segment pinhole design needs to evaluated for load characteristics. Also requires a larger crane capacity.*

Data from NASA Study March 1990
Reference Drawing 79K29971

Section 4.3 KSC/C. Guidi
VAB Modifications
(Magnum w/FSB)

• Vehicle Assembly Building (VAB) integration cells will be required to support the Magnum Vehicle
  • Highbays 1 and 3 were selected for Magnum integration

• Extendible vehicle access platforms Modifications

  Magnum-Driven Mods
  – Install new platforms at higher levels and modify lower platforms

  FSB-Driven Mods
  – Provide access to new fwd segment and ET forward attach
  – Modify platforms “C” and “E”
  – Relocate AP- 46/47 and AP-100
VAB Modifications (Shuttle-C25 w/FSB)

• Vehicle Assembly Building (VAB) integration cells will be required to support the Magnum Vehicle

• Integration Cells (Highbays 1 and 3)

  Cargo Carrier-Driven Mods
  – Modify platforms due to increased girth of cargo carrier

  FSB-Driven Mods
  – Provide access to new fwd segment and ET forward attach
  – Modify platforms “C” and “E”
  – Relocate AP-46/47 and AP-100

• ET Checkout Cells (Highbays 2 and 4)

  – Modify platforms due to increased length from Shuttle ET configuration (must maintain capability to process Shuttle ET)

  Or
  – Incorporate “Ship and Shoot” concept to eliminate facility modifications
Pad Modifications
(Magnum w/FSB)

• Both pads will be modified to have both Shuttle and Magnum or Shuttle-C25 capabilities

Magnum Unique Pad Modifications:
– Additional LH2 storage sphere and associated lines
– Flame Trench & Sound Suppression System
– Methane Loading/venting/capture Capability (payload)
– Cryo Propellant loading/venting/capture GSE (payload)

FSB-Driven Mods
– Install new Forward Skirt Access platform at approximately the 241’ level

Shuttle-C25 Pad Modifications:
– RCS Room interference mods
– Hammerhead crane removed
– PCR interference due to larger diameter
– Flame Trench & Sound Suppression System
– Methane Loading/venting/capture Capability (payload)
– Cryo Propellant loading/venting/capture GSE (payload)

FSB-Driven Mods
– Install new Forward Skirt Access platform at approximately the 241’ level
– Modify GOX Vent arm to provide booster clearance

• TBD Payload Prop loading capability at pads
New Cargo Carrier Processing Facility  
(Shuttle-C25 only)

New Facility for Shuttle C25 Cargo Carrier Processing

- Comprises three (3) main functional areas:
  - Operations Support Annex (OSA) 70,000 sq. ft.;
  - Logistics and Staging (L&S) 60,000 sq. ft.;
  - Integration and Checkout (I&C) High Bay 50,000 sq. ft.
  - An airlock (25,000 sq. ft.) accommodating vehicle entry into the I&C high bay

- Fueling of payloads and flight vehicles shall not be a function of the CCPF Process and check out the Shuttle-C25;
- Integrate segmental payloads into a single payload;
- Integrate and test single, multiple and segmental payloads with the Shuttle "C";
• Due to the physical size of the Magnum core vehicle, the Operations and Checkout (O&C) Building is best suited to process the core vehicles simultaneously.

• Modifications to the O&C require removal and storage of payload test stands and clean room.

Three Magnum Cores processing in the Operations and Checkout Building (O&C).
Fourth core shows contingency storage--Top View.

This assumes no hazardous commodities on board during all times in O&C.
MLP Acquisition

• One New Mobile Launcher Platform (MLP) will be required to support the Magnum w/ FSB Program OR the Shuttle-C25 w/ FSB Program and not interfere with the Space Shuttle Program

• Increased number of MLPs is due to 5-Segment SRB processing timelines and short timeline between unmanned and crewed Lunar Missions (2 launches within 30 days)

Magnum MLP Unique Features:

• Launch Umbilical Tower with 5 swing arms
  • Human-rated Magnum will require personnel access arm to payload shroud area and white room for crew ingress
• FSB – driven mods (see below)

Shuttle-C25 MLP:

• Modifications to the existing Shuttle MLP design are driven by the 5-Segment Booster design
  • New holddown posts
  • Modify pedestals for increased pre-launch loads
  • Modify Blast Shield (add ablative)
Pad Modifications
(Magnum w/FSB)

• Both pads will be modified to have both Shuttle and Magnum or Shuttle-C25 capabilities

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- Integrate segmental payloads into a single payload;
- Integrate and test single, multiple and segmental payloads with the Shuttle "C";
Magnum Core
Standalone Processing Facility

- Due to the physical size of the Magnum core vehicle, the Operations and Checkout (O&C) Building is best suited to process the core vehicles simultaneously.

- Modifications to the O&C require removal and storage of payload test stands and clean room.

Three Magnum Cores processing in the Operations and Checkout Building (O&C). Fourth core shows contingency storage--Top View.

This assumes no hazardous commodities on board during all times in O&C.
Payload Processing Facility - SSPF

• All lunar payloads (*Lunar Transfer Vehicle, Gateway, Lunar Lander, Lunar Habitat, kick stage*) will be processed, integrated and encapsulated in the Space Station Processing Facility (SSPF) while also allowing for ISS resupply processing

• No major modifications required
AF Hangar Modifications

- Modification required for any vehicle design that uses 5-Segment Boosters
  - Fabricate 2 new dollies for forward segment
  - Redesign and fabricate 4 DOPs to conform to larger throat and exit cone
  - Crane operations modification
Advanced Concept Analysis in Support of the Integrated Space Plan

Section 4.4

Exploration Architecture Analysis
Supportability

November 2002
Supportability

Supportability Concept - missions beyond LEO must become independent of support from Earth because of extended, or nonexistent, supply chain

• Maintenance Concept Defined - enable robust, autonomous maintenance capabilities for future missions.
  • Enable comprehensive onboard failure diagnosis capabilities.
  • Repair rather than replace.
  • When replacement is required, replace at the lowest possible hardware level - minimize mass requirements.
  • Fabricate structural and mechanical replacements rather than carry unique spares.

• Enhanced Crew Support Functions – reduce crew time for overhead tasks & reduce mass for crew support
  • Enhanced habitability – e.g. launder clothes, efficient housekeeping operations
  • Transparent inventory management
  • Recycle waste products

Maintainability Design/Requirement Themes

• Require commonality and standardization at LRU-level, SRU-level, and lower level among major architecture elements.
• Design for the operational environment (e.g. pressure differential effects on structure, 0-g human factors, number of closeout fasteners).
• Design for maintainability, graceful degradation, upgrades, and adaptation.
Supportability

**Enabling Technologies**

- **Avionics Repair** (e.g. robust diagnostic capabilities - failure isolation to component, verification test capabilities, hands-off electronics rework)
- **In-Situ Fabrication** (e.g. solid freeform fabrication, welding, machining, NDE/QA, metrology)
- **Crew Support** (e.g. washing machine, transparent inventory management, waste disposal, hygiene, food preparation)

**DoD Analogs** - ongoing technical interaction with DoD to leverage their experience supporting advanced systems in harsh operational environments

- **Air Force** – F/A-22 program: advanced maintenance concept, diagnostics, and technical information management
- **Army** – TACOM’s Mobile Parts Hospital: *in-situ* fabrication capability, NASA/DoD Interagency Coordinating Committee established; Corps of Engineers’ Cold Regions Research and Engineering Laboratory in conjunction with NSF: maintenance operations at Antarctic bases and maintainability considerations in South Pole Station modernization project
- **Navy** – NAVAIR & NAVSEA: Microminiature electronics repair; 1998 benchmarking study by KSC of submarine support operations
- **Interagency Coordinating Committee** – Informal working group including NASA, Army TACOM, Army ARL, Air Force AFRL, Navy NAVSEA, Navy ONR, Navy NRL to collaborate on development of electron beam solid freeform fabrication technology
Supportability

Maintenance Concept

• Enable robust, autonomous maintenance capabilities for future missions.

• Provide system availability that meets program defined values while minimizing the mass and volume of spares and crew time required for maintenance.

  – Enable autonomous failure diagnosis and repair by crew.
  – Perform Organizational maintenance and repair at the lowest hardware level that is feasible.
  – Perform Organizational maintenance via remove-and-replace of SRUs to the maximum extent possible when lower level repair is not feasible.
  – Perform Organizational maintenance via remove-and-replace of LRUs for all other hardware.
  – Manifest/stow common and standardized hardware onboard.
  – Preposition critical spares.
  – Fabricate structural and mechanical replacements rather than carry unique spares.
  – Manifest unique spare hardware with crews.
  – Perform preventive maintenance as required.
  – Perform Intermediate and Depot maintenance on the ground when cost-effective.
  – Enable utilization of common SRU/LRU/piece part/components across entire vehicle set.
  – Consider reconfigurable hardware – use changes with mission phase.
  – Utilize ground-based assessment of onboard system health and failure isolation for missions of brief duration.
Supportability

Maintainability Design/Requirement Themes

- Require commonality at LRU-level, SRU-level, and lower level among major architecture elements.
- Establish design requirements for operational environment (e.g. pressure differential effects on structure, 0-g, human factors, number of closeout fasteners).
- Keep all hardware to be maintained internal – minimize EVA.
- Eliminate avionics LRU boxes – implement rack-mounted boards (trade – e.g. mass impacts/benefits, TCS impact, smoke/fire detection and protection, etc.).
- Minimize tools (ISS tool kit: almost 500 items).
- Maximize commonality and standardization (enables wide use and minimizes tools).
  - Avionics boards
  - Fasteners
  - Connectors
  - Other components (e.g. pumps, power supplies, fans)
  - Piece parts
- Robust diagnostics and post-repair verification: quick, unambiguous fault isolation to designated repair level (BIT, BITE, standalone).
- Build for maintainability (e.g. access, number of fasteners).
- Do not combine English and metric hardware (reduces tool requirements).
- Design for upgrade and adaptation.
Supportability Technology Analysis

Goal

– Crews will be autonomous for maintenance and repair operations.
– Mass and volume required to support maintenance and repair will be substantially reduced from current requirements.
– Mass and volume requirements for crew clothing will be substantially less than current.
– Inventory management process will be transparent to crew.

Gaps

– Need enhanced Built-in-Test capabilities in system hardware.
– Need enhanced standalone system diagnostic capabilities available to crew.
– Need capability to repair hardware at component level to minimize mass and volume of spares.
  Requires significantly increased component commonality and standardization.
– Need capability to fabricate structural and mechanical replacement components as needed.
– Need to provide crew with information required to support these more robust repair capabilities.
– Need clothes laundering capability to minimize total quantity of clothing.
– Need hands-off inventory system (e.g. radio frequency identification tags).
## Supportability TRL Summary

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Supportability

Current Maintenance Technology Development Activities

– **Reduced-g Soldering: component-level repair of avionics**
  - Collaboration with GRC and NCMR
  - Almost 600 samples produced during KC-135 parabolas (includes a limited number of 1/6-g parabolas and 1/3-g parabolas), plus 1-g control samples
  - Analysis continuing – initial results show increased porosity in low-g, attempting mitigation approaches

– **Potential collaboration with NAVAIR: component-level repair of avionics**
  - Advanced diagnostic capabilities
  - Surface mount device soldering repair

– **Solid Freeform Fabrication: in-situ fabrication of spares**
  - Collaboration with Langley
  - Developing innovative process/system
  - Provisional patent application submitted by JSC and Langley
  - NASA and DoD forming SFF Interagency Coordinating Committee (includes ONR, NRL, NAVSEA, Army TACOM, Army Research Lab, Air Force Research Lab)

*Thin-wall hollow tube produced by Lockheed Martin Tactical Aircraft Systems with laser Solid Freeform Fabrication process.*
## Supportability

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Section 4.4 JSC/K. Watson

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## Supportability

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**LEGEND**
- ⤶ Strategic Research and Technology Decision Point
- △ Major Technology Development Milestone
- ⚡ Major Technology Flight Demonstration

Section 4.4 JSC/K. Watson

Nov. 2002
## Supportability

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**LEGEND**
- **Strategic Research and Technology Decision Point**
- **Major Technology Development Milestone**
- **Major Technology Flight Demonstration**

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Advanced Concept Analysis in Support of the Integrated Space Plan

Section 5.0
Technology Roadmaps

November 2002
Technology Overview

- Objectives of Technology Assessment
- Assumptions for Technology Assessment
- State of Technology
- Blueprint Summary Key Technologies
  - Technology long poles
    - Earth’s Neighborhood
    - Mars
- Recommendations
  - To Agency (In work)
  - To Enterprises (In work)
  - To Architecture team
  - To Design Team
Objectives of Technology Assessment

• Focused Agency technology investments today provides the potential for conducting new missions and building future systems with better performance to meet defined requirements. Independent of specific architectures, there are several key fundamental core technologies, that if developed will put the agency in a good posture for decision making in the near future.
  – The technology focus investment strategy proposes to implement the following:
    • Derive the research and technology development needs from evolving architectural concepts and develop roadmaps for their accomplishment.
    • Identify and endorse programs that are currently addressing the research and technology development needs.
    • Identify gaps in existing programs that need to be augmented or refocused to address the research and technology development needs.
    • Identify and recommend new initiatives to fill gaps in research and technology development needs.
    • Periodically reassess evolving architectures and provide updated recommendations to technology development programs.
    • Periodically assess technology development programs to assure progress towards meeting the defined needs.
Assumptions for Current Technology Assessment

- Funding would begin in the first quarter of CY 2003.
  - Made it possible to determine how long it would take to develop the technologies required for beyond-LEO exploration, if reasonable funding was turned on immediately.
- DDT&E phases for each element would be 6 years.
  - The actual DDT&E schedules for the individual elements are not known at this point in time.
  - Allowed the assessment team to derive the required date for the technologies to achieve Technology Readiness Level (TRL) 6.
- Initial launch date of first Earth’s Neighborhood element is in 2012.
- Assumed infrastructure development / mission sequence
  - $L_1$ capability → Short duration lunar surface missions → Long duration lunar surface missions → Mars missions
State of Technology

• A **SEVERE** GAP in technology development exists between the basic research TRLs (1-3) and the qualified technology TRLs (7-9).
  – Funding for the middle TRLs (4-6) for technologies critical to Human/Robotic Exploration beyond LEO have had limited investment over the last several years.
  – This gap was identified in the technology review of the Earth’s Neighborhood element studies.
Given the previous assumptions, the list of critical technologies have been divided into three categories:

- **Category 1:** If technologies achieve TRL 6 after the elements’ DDT&E Phase is scheduled to begin.
- **Category 2:** If technologies achieve TRL 6 at approximately the same time the elements’ DDT&E Phase is scheduled to begin.
- **Category 3:** If technologies achieve TRL 6 before the elements’ DDT&E Phase is scheduled to begin.
Blueprint Summary Key Technologies

- Earth’s Neighborhood “Category 1” Technologies and Areas of Research
  - EVA Suit and Personal Life Support System (PLSS)
    - Suit: Materials; Flexible, robust joints; heated, flexible gloves
    - PLSS: Materials; packaging; mass reduction
    - CO₂ removal system
    - Thermal control system
    - Information management systems
    - Electrical systems: High energy density power storage; low power sensors
  - High energy density fuel cells
  - Liquid H₂ cryocoolers
  - Inflatable structures: Habitats and Airlocks
  - Robotic systems for L₁ telescope construction
    - Earth-based control systems of L₁-based robotics
    - Robotic systems capable of working together to complete a task
    - Robotic systems capable of handling connection of electrical and fluid interfaces
  - Bio-astronautics
    - Ionizing Radiation
      - Analysis tools to evaluate crew dosages during architecture and element design phases
      - Innovative methods of protecting crew against ionizing radiation
Blueprint Summary Key Technologies

• Mars Long-lead Technologies and Areas of Research
  – Closed-loop life support systems
    • Closed air revitalization system
    • Liquid processing and recycling
    • Solid waste processing and recycling
  – In-situ propellant production systems
  – Nuclear power systems – Surface power & In-space propulsion
  – Bio-astronautics
    • Micro-g countermeasures
      – Artificial-g environment created by spacecraft
      – Medical countermeasures coupled with exercise devises
    • Ionizing Radiation
      – Ability to evaluate crew dosages during architecture and element design phases
      – Methods of protecting crew against ionizing radiation
Recommendations To Architecture Team

- Analyze whether identified long pole technologies can be eliminated by modifying the architecture elements.
- Identify science-driven requirements that will require technology development (e.g. Excavation equipment, mobility systems, sensors etc.).
- Be more specific in quantifying architectural and element level requirements.
- The following technologies were identified as potentially critical or mission enhancing. Future studies should evaluate the following technologies for their criticality in the trade space:
  - In-Situ Resource Utilization
  - Communication Requirements
  - Inter-Vehicular Health Monitoring
  - Logistics – (e.g. Consumables re-supply)
  - Supportability
  - Nuclear Power (surface & in-space)
  - Software Development
  - Computer and data management systems
  - MEMS applications
Recommendations to the Design Team

• A detailed study should be performed utilizing the techniques employed by the design team to identify cross-cutting sub-system component technologies.
  – The review demonstrated that there are a number of common component level technologies that when pushed will satisfy the needs of a variety of critical path systems such as light weight radiators, Cryocoolers, high density power, etc.
  – This information would be used to develop component level requirements such that a particular technology would be designed to satisfy the requirements of several different systems and to determine investment priorities.

• Study should be performed to determine if existing EVA suits could satisfy early L₁ missions.

• An integrated architectural level approach should be kept in mind while designing the elements.
  – It was found during the technology assessment that there were several different designs used across many of the elements for the same system (e.g. Thermal control leads used three different coolants in three different elements, which was found to be unnecessary.)
### Integrated Technology Roadmaps

#### Element Legend

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<td>MTV</td>
<td>Mars Transfer Vehicle</td>
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<td>Solar Electric Power (SEP) Stage</td>
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Advanced Concept Analysis in Support of the Integrated Space Plan

Section 6.0
Risk Assessment

November 2002
Risk Assessment

- Risk Assessment Documentation
  - A Draft Exploration Blueprint risk assessment plan is completed - Defines practice of risk management in the formulation phase.
  - Preliminary risks using the continuous risk management process
  - Probabilistic risk assessments (PRA) will be conducted as reference mission architectures are developed in the formulation phase.
- There will continually be tradeoffs between mission performance and risk mitigation, for example:

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  **Zero-g Risk Mitigation**

  - Risk of Zero-g Effects on the crew
  - Risk of deploying a large and complex vehicle
  - Risk of Zero-g Effects on the crew
  - Risk of deploying a large and complex vehicle
PRA Modeling Technique

End States | Events | Time (sec) | Week | Events
---|---|---|---|---
4 1 2400 | HL/DAV SEP Launch (Mars 1)
4 2 60 | HL/DAV SEP Solar Array Deploy and Checkout
4 3 604800 | HL/DAV SEP Orbit Operations
4 4 604800 | HL/DAV SEP Orbit Operations
4 5 604800 | HL/DAV SEP Orbit Operations
4 6 604800 | HL/DAV SEP Orbit Operations
4 7 2400 | HL1 Launch (Mars 2)
4 8 259200 | SEP/HL1 Auto Rendezvous and Dock
4 9 343200 | SEP/HL1 SEP Orbit Operations

Event Sequence

Event-System Matrix

Elements and Systems

Event Trees and End States

Results

Mission Success
Degraded Mission in Mars Orbit (MIMO)
Crew Return - Failed TMI
Mission Delay - Loss of Equipment
Loss of Shuttle Equipment
Crew Stranded in Mars Orbit
Crew Stranded on Planet
Loss of Shuttle Crew and Equipment
Loss of Crew and Equipment

Prob of Success
0.94554
1.00000
0.99997
0.99997
0.99997
0.99997
0.94553

Loss of Crew and Equipment
Mission Delay - Loss of Equipment
0.0545
0.0000
0.0000
0.0000
0.0000
0.0000
0.0545

Mission in Mars Orbit
Crew Stranded on Planet
Crew Stranded in Mars Orbit

Redundancy Failure Rates (fpmh)

HL/DAV Solar Electric Propulsion
Solar Array Deployment Mechanism
Structure
Thermal Protection System
System Engines
Propulsion System
Tankage (Xe)
RCS
PMAD
Power Generation
Avionics
Control System

End States Events Time (sec) Week
4 1 2400 1 HL/DAV SEP Launch (Mars 1)
4 2 60 HL/DAV SEP Solar Array Deploy and Checkout
4 3 604800 2 HL/DAV SEP Orbit Operations
4 4 604800 3 HL/DAV SEP Orbit Operations
4 5 604800 4 HL/DAV SEP Orbit Operations
4 6 604800 5 HL/DAV SEP Orbit Operations
4 7 2400 6 HL1 Launch (Mars 2)
4 8 259200 7 SEP/HL1 Auto Rendezvous and Dock
4 9 343200 8 SEP/HL1 SEP Orbit Operations

Mission Delay - Loss of Equipment
0.2425068

Loss of Shuttle Equipment
0.0009534

Crew Stranded in Mars Orbit
0.0000005

Crew Stranded on Planet
0.0000182

Loss of Shuttle Crew and Equipment
0.0001163

Loss of Crew and Equipment
0.2032401

Event System Matrix

Elements and Systems
Mission End States

- Mission Success
- Degraded Mission in Planetary Orbit (failure to land)
- Crew Return – (failed Trans-planetary injection)
- Mission Delay - Loss of Equipment
- Crew Stranded in Planetary Orbit
- Crew Stranded on Planet
- Crew Stranded in Heliocentric Orbit
- Loss of Crew and Equipment
Exploration Mission Expected Results

• For a given mission architecture:
  – Which end states drive the risk?
  – Which elements, systems, or components drive the risk?
  – Where in the mission are the riskiest events?
  – When are systems the most susceptible to failure?
  – What environmental conditions have the greatest effect on probability of failure on an element, a system or component, or the crew?
  – Given a set of conditions, what failure modes are most or least likely to occur?
  – How does risk change over the mission life?
  – How do changes in the design or improved data uncertainty change the results?
Probabilistic Risk Assessment

• Probabilistic Risk Assessment Overview
  – Define Mission Architectures (L1, Lunar, Mars)
  – Define Mission End States
  – Define Initiating Events
  – Assess Pivotal Events
  – Conduct Data Mining and Development Based on TRLs
  – Conduct Sensitivity Studies Based on TRLs and Projected Improved Reliabilities

• Perils and Pitfalls
  – Beware of Biased and Skewed Data (There is Hidden Agenda Everywhere!)
  – Ensure the Concurrence of Assumptions by all Interested Parties
  – Mission Failure Values of $1 \times 10^{-4}$ ($1/10,000$) and Less are Generally Not Believable (for Space Missions)
## Probabilistic Risk Assessment Plan

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System Safety Precedence

(There are variations to these criteria that say essentially the same thing. Sources: Mil-Std-882C, NHB 5300.4, NHB 1700.1, NSTS 22254, NSTS 07700, Vol. X)

1. Design for minimum risk. Hazards should be eliminated by design wherever possible.
2. Known hazards which cannot be eliminated by design should be reduced to an acceptable level by the use of safety devices as part of the system.
3. Where it is not possible to preclude the existence or occurrence of a known hazard devices shall be employed for the timely detection of the condition and the generation of an adequate warning signal.
4. Where it is not possible to reduce the magnitude of an existing or potential hazard by design, or the use of safety or warning devices, special procedures shall be developed to counter the hazardous condition.
PRA Talking Points

• You will hear many buzz words regarding tools for probabilistic and other types of risk assessment; here are your talking points:
  – The probabilistic risk assessment methodology is a suite of graphical techniques for assessing risk. These include:
    • Event Trees,
    • Fault Trees,
    • Reliability Block Diagrams;
    • Rarely used are digraphs, petri nets, root cause analysis, and statistical process control.
  – PRA Computer Tools
    • QRAS – (Quantitative Risk Assessment System),
      – An Event Tree and Fault Tree editor and evaluator.
      – Designed and developed by the University of Maryland for NASA HQ (Code Q).
      – Previous versions did not have a fault tree editor. Limited use at MSFC for Shuttle PRA. New version available Dec. ‘02
PRA talking points

– PRA Computer Tools (continued)

  • **SAPHIRE** – *(Systems Analysis Programs for Hands-on Integrated Reliability Evaluations)*.
    – An Event Tree and Fault Tree editor and evaluator.
    – Designed and developed for the U. S. Nuclear Regulatory Commission by Idaho National Engineering and Environmental Laboratory (INEEL).
    – Currently used in Shuttle and ISS PRA activity; has some innocuous bugs.

  • **Other Computer Tools Used at NASA**
    – ECTree: An Excel-based Event Tree Editor developed by SAIC on a government (NASA) contract.
    – Galileo ASSAP: *(Advanced System Safety Analysis Program)* Developed by the University of Virginia for dynamic risk assessments on a government (NASA) contract.
    – RAPTOR: Reliability Block Diagram Editor originally developed by the Air Force, now owned by RELIASS

  • **Commercial tools** (many commercial fault tree and event tree computer tools $$$)
    » CAFTA package
    » RELEX
    – @Risk and Crystal Ball – Monte Carlo simulators
PRA talking points

• Which one do we recommend?

• All of them, but SAPHIRE is probably the best overall since most of the local practitioners have been trained on it. Current versions of all of these tools will likely be obsolete in a couple of years.

• Many local analysts use a combination of the previous chart.

• Bottom-line: It doesn’t matter what tool you use; it only matters that the analysis represents the system.
Previous Risk Assessments on Exploration Missions
Human Mars Mission Success Results (SEP Dual Lander)

Probability of Mission Success

Analysis Period

Nuclear Thermal Reactor/
Split Dual Mission Risk

End States

- Mission Success
- Mission Delay - Loss of Equipment
- Mission in Mars Orbit (MIMO)
- Loss of Crew and Equipment
- Crew Return - Failed TMI
- Crew Stranded on Planet
- Crew Stranded in Mars Orbit

Probability

0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

Mission Success
Mission Delay - Loss of Equipment
Mission in Mars Orbit (MIMO)
Loss of Crew and Equipment
Crew Return - Failed TMI
Crew Stranded on Planet
Crew Stranded in Mars Orbit
Nuclear Thermal Reactor/
Split Dual Mission Risk (log Probability scale)

End States

- Mission Success
- Mission Delay - Loss of Equipment
- Mission in Mars Orbit (MIMO)
- Loss of Crew and Equipment
- Crew Return - Failed TMI
- Crew Stranded on Planet
- Crew Stranded in Mars Orbit
Previous Exploration Studies

Mars 2018 and 2022, NTR and SEP, Short-Stay and Long-Stay,
Element Failure Rate = 0.6 fpmh, Varying Launch Vehicle Reliability

1. The launch success rate for Delta II, Ariane, Atlas, and Titan is about 97%, 93%, 90%, and 91%, respectively.
2. The worldwide percentage of success for 1998 is about 94%
3. Titan IV is mission success rate is about 94%
4. Shuttle is by far the most reliable launch vehicle at 99.7% (QRAS analysis, 1998).

Launch Vehicle Reliability

Mission Probability

Large Launch Vehicles

Small Launch Vehicles

NTR Small Launch Vehicle
NTR Large Launch Vehicle
SEP Large Launch Vehicle
SEP Small Launch Vehicle
NTR Large Launch Vehicle with Earth Return Vehicle
2022 NTR Large Launch Vehicle Long-Stay
2022 SEP Large Launch Vehicle Long-Stay
Previous Exploration Studies

Mars 2018, NTR,
Large Launch Vehicle Reliability = 0.995,
Element Failure Rate = 0.6 fpmh

This chart depicts the percentage change in mission end states from given event (X-axis) to end of mission.

- Mission Success
- Degraded Mission in Mars Orbit
- Crew Return - Failed TMI
- Mission Delay - Loss of Equipment
- Crew Stranded in Mars Orbit
- Crew Stranded at Destination
- Loss of Crew and Equipment
Previous Exploration Studies

Mars 2018, NTR, Large Launch Vehicle Reliability = 0.995, Element Failure Rate = 0.6, End-of-Mission End States

This chart depicts the percentage change in mission end states from given event (X-axis) to end of mission.
Previous Exploration Studies

Mars 2018, NTR,
Large Launch Vehicle Reliability = 0.995,
Element Failure Rate = 0.6 fpmh,
Crew Peril End States

This chart depicts the percentage change in mission end states from given event (X-axis) to end of mission.
Lunar Landing via L1
Lunar Landing Mission End States

- Loss of Crew and Equipment
- Mission Delay
- Mission Success

Probability
Mars Mission
Dormant/Active Comparison

Mission Events

Systems in Operation

Dormant
Active

Transhab
Spiral

Jettison
TH SEP

Transhab
Transit

Landing
Surface
Mission

Hab Lander &
DAV Lander
Transit

Launch
Vehicles

Earth
Return

Habitat
Lander
Landing
Mission Risks for Human Exploration
(from previous quantitative studies 1998-2000)

- **Launch vehicle reliability must be improved** – The existing launch vehicle reliability runs from ~0.9 to ~0.97 with Shuttle at ~0.996 (best in the industry). Recommend a cargo launch vehicle reliability no worse than Shuttle. This architecture assumes a launch vehicle probability of 0.997.

- **Pre-deploying redundant vehicles decreases the probability of mission success, but decreases the probability of loss of crew.**

- **Deploying the cargo and manned vehicles in a “combo” mission increases the probability of mission success, but increases the probability of loss of crew.**

- **The difference in NTR vs. SEP mission success probabilities** – Presently, both configurations have essentially the same mission risk. The additional NTR launch vehicle cancels out (approximately) the SEP time of system operation during spiral-up to HEO.
Risk Planet

- PRA
- Hazards
- Hazards and CILs
- PRA and FMEA
- FMEAs
Advanced Concept Analysis in Support of the Integrated Space Plan

Section 7.1
Common Core Crew Vehicle Requirements

November 2002
Objective:
- Establish the requirements for a common core crew vehicle which can satisfy multiple, Agency-wide, needs.

Approach:
- Initiate a process for coordinating the needs and requirements for the next generation crew vehicles in order to establish a common set of requirements.
- Crew vehicle requirements should include needs for:
  - ISS Crew Return Vehicle (from low-Earth orbit)
  - Crew Transfer Vehicle (to and from low-Earth orbit)
  - Exploration Transfer Vehicles (beyond low-Earth orbit and return)

Recommendation:
- Initial assessment of common core crew vehicle requirements include the following:
  - Reconfigurable pressurized volume for 4-7 deconditioned crew
  - One day mission duration independent from a service module
  - Enable autonomous / manual operations
  - Provides propulsive orbital maneuvering capability
  - Controlled aerodynamic flight
  - Primary landing mode shall be on dry land
Common Crew Vehicle Design Capture

Core Crew Vehicle
- Common crew element satisfying multiple mission capabilities
- Key Design Requirements:
  - Re-configurable for 4-7 crew
  - Independent one day mission duration
  - Autonomous / manual operations
  - Propulsive orbital maneuvering
  - Controlled aerodynamic flight

ISS Crew Return
- Provides safe and expeditious recovery of astronauts from low-Earth orbit
- Core Vehicle Configuration Changes:
  - Configured for 4 deconditioned crew
  - Medical emergency provisions
  - Emergency undock capability
  - ISS interfaces and six-month to two-year on-orbit stay
- Key Issues:
  - EELV launch compatibility including automated delivery to ISS
  - Degree of vehicle reusability

LEO Crew Transfer
- Crew transfer to low-Earth orbit and return
- Core Vehicle Configuration Changes:
  - Crew escape for aborts
  - Configured for 5 crew (3 ISS transfer)
  - 12 day mission duration for ISS support
  - Service Module for extended mission duration (propulsion, power, thermal control, life support consumables)
- Key Issues:
  - EELV launch compatibility and human rating
  - Degree of vehicle reusability

Near-Earth Transfer
- Transport crew to lunar vicinity and return to Earth
- Core Vehicle Configuration Changes:
  - Configured for 4-6 crew (mission dependent)
  - Crew escape for aborts
  - 12+8 day mission
  - Deep-space environmental conditions
  - Service Module for extended mission duration (propulsion, power, thermal control, life support consumables)
- Key Issues:
  - Lunar return velocities
  - Large launch vehicle
  - Degree of vehicle reusability
Core Crew Vehicle Notional Design Approach

- **Function:** Common crew element which satisfies multiple mission capabilities

- **Key Design Philosophy:**
  - The system shall provide a reconfigurable pressurized volume for 4-7 deconditioned crew
    - Rationale: Mission requirements for the various mission modes vary from 4-7 (ISS crew return), 5 (for ISS crew transfer), to 6 (for lunar science servicing and Mars). Providing a pressurized volume which is reconfigurable allows for a single design to accommodate anticipated modes for both Low-Earth-Orbit and exploration missions. Emphasis should be placed on maximizing reconfiguration of subsystems in order to accommodate varying mission modes.
  - The system shall provide a one day mission duration independent from a service module
    - Rationale: Mission durations on the order of one day captures the common requirement between the crew emergency return from ISS, final phase of lunar return, and Mars return. Mission durations greater than this core mission duration can be accomplished with a supplemental service module which provides additional power, consumables, and thermal control.
  - The system shall enable autonomous / manual operations
    - Rationale: Providing the capability of operating autonomously without relying upon means of external control (such as from Earth control centers), with appropriate manual override is necessary for the missions and time delays expected for the various mission modes.
  - The system shall provide a propulsive orbital maneuvering capability of 300 m/s
    - Rationale: All mission modes require on-orbit orbital maneuvering capabilities including orbital phasing maneuvers, attitude control, and de-orbit. Additional propulsive capabilities for larger maneuvers can be accomplished with a supplemental service module.
  - The system shall provide controlled aerodynamic flight
    - Rationale: Providing entry cross range capability increases landing site availability, landing opportunities, as well as landing site targeting.
  - The primary landing mode shall be on dry land
    - Rationale: Landing on land increases crew safety, reduces recovery operational costs, and enhances vehicle reusability potential. Emphasis should be placed on developing a common vehicle shape (slender body mid-L/D outer mold line) with an appropriate level of vehicle reusability.
Summary

- Defining the requirements on a multipurpose vehicle requires consideration of all potential mission modes.

- Strategies exist that can satisfy the top-level requirements which are common between mission modes.

- Further analysis of the impacts of the mission modes on the multipurpose vehicle is required in order to finalize core requirements.
Proposed Process
The following presentation provides an approach and process for defining the requirements for the next generation crew vehicles.

This is an initial step in that process.

Further coordination and integration between programs across the Agency is required before a final set of requirements for a common core crew vehicle can be established.
Approach

1. Compare the primary functional needs and requirements for the next generation crew vehicles including:
   - ISS Crew Return Vehicle
   - Crew Transfer Vehicle (including assured access to ISS)
   - Exploration Transfer Vehicle (including transfers to high earth orbit for potential Mars mission concepts)
   - Entry Vehicle for Mars missions

2. Begin to establish the set of requirements for a common core crew vehicle which satisfies the above mission modes.
ISS Crew Return Vehicle

- **Primary CRV function is the expeditious return of crew from ISS due to:**
  - Crew medical emergencies
  - ISS emergency situations
  - Grounded Shuttle fleet

- **Key functional needs which drive the CRV design:**
  - Capability to return 4 crew (7 desired)
  - Capability for a quick departure from an uncontrolled ISS
  - Capability to return a sick or injured crewmember
  - Total mission duration less than one day
  - Capability to be stored for a long duration (2-years) (TBD) at ISS
  - The desire for the system to be reusable
  - The CRV shall perform a soft runway landing (wings and wheels)
Notional Mission Profile
ISS Crew Return

1. Emergency Departure
2. Phasing
3. Deorbit
4. Entry
5. Landing
The Crew Transfer Vehicle (CTV) provides an alternate crew delivery and return capability to and from low-Earth orbit:

Key functional needs which drive the CTV design:
- Capability to exchange 3 ISS crew (implies a total crew complement of 4-5 depending on operational requirements)
- Capability to be launched on US EELV-H launch vehicles
- Capability to be launched on future US launch vehicles (reusable launch vehicle)
- Provide adequate crew escape methods during ascent
- Total mission duration of 12 days for ISS crew exchange missions
- System should be reusable and able perform a soft runway landing (wings and wheels)
- The CTV shall be capable of performing other missions, such as satellite servicing, when combined with other (additional) mission elements.
Notional Mission Profile
Crew Transfer Vehicle

1. Launch
1a. Abort
1b. Landing

2. Rendezvous & Docking

3. ISS Mission

4. Departure / Phasing

5. Deorbit

6. Entry

7. Landing
Provides the capability to transfer mission crew from Earth, to the lunar vicinity, and return back to Earth:

Includes capability for transfers to high earth orbit for potential Mars mission concepts

Key functional needs which drive the XTV design:
- Capability to support up to 6 exploration mission crew
- Total mission duration of 12 days
- The desire for the system to be reusable
- Capability to accommodate lunar return velocities
Mars Earth Return Vehicle

- Provides the capability to return exploration mission crews from Mars return trajectories to the surface of the Earth:

- Key functional needs which drive the Mars Earth Return Vehicle design:
  - Capability to support up to 6 exploration mission crew
  - Capable of being stored in a dormant state during the Mars mission
  - Total active mission duration of one day
  - Capability to accommodate Mars return velocities
Notional Mission Profile
Exploration Mission

1. Launch
2. Trans Lunar Injection
3. Exploration Mission
4. Aerocapture / Phasing
5. Deorbit
6. Entry
6b. Mars Direct Entry
7. Landing
1a. Abort
1b. Landing
# Key Crew Vehicle Key Functional Needs Summary

<table>
<thead>
<tr>
<th>Crew Emergency Return from ISS</th>
<th>Crew Transfer to ISS</th>
<th>Lunar Orbit or L1 Mission</th>
<th>Crew Return From Mars Missions</th>
</tr>
</thead>
</table>
| Expeditious recovery of crew from ISS  
  - Undock < 10 min  
  - Medical < 24 hrs  
  - All attitudes, \( \pm 2^\circ/\text{sec} \)  
  - 4 crew (7 desired)  
  - Shirt Sleeve Environment  
  - Autonomous or manual operation  
  - Orbital maneuvering and controlled aerodynamic flight  
  - Soft runway landing (day or night)  |  
  - Crew transfer to and from ISS  
  - EELV launched  
  - 5 crew  
  - Crew escape system  
  - Autonomous or manual operation  
  - Orbital maneuvering and controlled aerodynamic flight  
  - Soft runway landing (day or night)  |  
  - Crew transfer to lunar vicinity and return  
    - Earth-Moon L1  
    - Lunar orbit  
    - Lunar surface  
  - 4 & 6 crew  
  - Shirt Sleeve Environment  
  - Autonomous or manual operation  
  - Orbital maneuvering and controlled aerodynamic flight  
  - Land landing (day)  |  
  - Crew return from Mars return trajectories  |
| ISS compatible  
  - Simultaneous space / ground communications  
  - Long-term storage at ISS (2 years)  
  - Reliability 0.999  
  - Probability of no penetration (MMOD) <0.9953  
  - Reusable  
  - Evolvable to a CTV  |  
  - ISS compatible  
  - Simultaneous space / ground communications  
  - Total mission duration ~ 12 days  
  - Reliability (TBD)  
  - N/a  |  
  - (N/A)  
  - Simultaneous space / ground communications  
  - Mission duration ~12 days active / 8 days dormant  
  - Reliability (TBD)  
  - N/a  |  
  - (N/A)  
  - Simultaneous space / ground communications  
  - Total mission duration ~ 1 day  
  - Reliability (TBD)  
  - N/a  |
The Strategy of a Common Core Crew Vehicle

- The crew vehicle requirements for all current and future mission modes should be considered when developing the requirements for the next generation crew vehicle.

- Comparison of the key functional requirements between mission modes results in the following common core requirements:
  - Re-configurable for 4-7 crew
  - Independent one day mission duration
  - Autonomous / manual operations
  - Propulsive orbital maneuvering
  - Controlled aerodynamic flight
  - Land landing

- Capabilities beyond the scope of the core requirements can be met with additional systems such as:
  - Service modules for consumables, power, thermal control
  - Injection stages for larger propulsive maneuvers
Common Crew Vehicle Design Capture

Core Crew Vehicle
- Common crew element satisfying multiple mission capabilities
- Key Design Requirements:
  - Re-configurable for 4-7 crew
  - Independent one day mission duration
  - Autonomous / manual operations
  - Propulsive orbital maneuvering
  - Controlled aerodynamic flight

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- Provides safe and expeditious recovery of astronauts from low-Earth orbit
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- Key Issues:
  - EELV launch compatibility including automated delivery to ISS
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Near-Earth Transfer
- Transport crew to lunar vicinity and return to Earth
- Core Vehicle Configuration Changes:
  - Configured for 4-6 crew (mission dependent)
  - Crew escape for aborts
  - 12+8 day mission
  - Deep-space environmental conditions
- Service Module for extended mission duration (propulsion, power, thermal control, life support consumables)
- Injection stage for trans-lunar injection
- Key Issues:
  - Lunar return velocities
  - Large launch vehicle
  - Degree of vehicle reusability
Vehicle Shape Issues

- **Are wings and wheels required?**
  - Many of the mission modes (CRV and CTV) derive a requirement for soft runway landings, which implies wings and wheels, in order to satisfy multiple higher-level requirements including:
    - Cross range as one approach to meeting loss of crew requirements
    - Landing accelerations for medical and system certification purposes
    - Quick turnaround between flights
  - Wings are incompatible for missions beyond low-Earth orbit
    - Peak heating limits nose and wing radius of curvature – thus eliminating wings from consideration
  - Maintaining pressure in wheels for long periods in space may be an issue
  - Wings may be incompatible for launch modes where the vehicle is exposed to the free air stream.
  - Source of this requirement researched – not a hard requirement

- **If wings are considered a strong Level I requirement, then an additional requirement should be added:**
  - The system shall be capable of accommodating outer mold lines of multiple vehicles
    - With this approach, the common core vehicle requirements would be contained within a common crew cabin or reduced to common system components
Core Crew Vehicle Notional Design Approach

- **Function:** Common crew element which satisfies multiple mission capabilities
- **Key Design Philosophy:**
  - **The system shall provide a reconfigurable pressurized volume for 4-7 deconditioned crew**
    Rationale: Mission requirements for the various mission modes vary from 4-7 (ISS crew return), 5 (for ISS crew transfer), to 6 (for lunar science servicing and Mars). Providing a pressurized volume which is reconfigurable allows for a single design to accommodate anticipated modes for both Low-Earth-Orbit and exploration missions. Emphasis should be placed on maximizing reconfiguration of subsystems in order to accommodate varying mission modes.
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  - **The system shall provide controlled aerodynamic flight**
    Rationale: Providing entry cross range capability increases landing site availability, landing opportunities, as well as landing site targeting.
  - **The primary landing mode shall be on dry land**
    Rationale: Landing on land increases crew safety, reduces recovery operational costs, and enhances vehicle reusability potential. Emphasis should be placed on developing a common vehicle shape (slender body mid-L/D outer mold line) with an appropriate level of vehicle reusability.
Summary

- Defining the requirements on a multipurpose vehicle requires consideration of all potential mission modes.

- Strategies exist that can satisfy the top-level requirements which are common between mission modes.

- Further analysis of the impacts of the mission modes on the multipurpose vehicle is required in order to finalize core requirements.
Backup
Crew Vehicle Key Functional Needs Notes

1. Providing the capability to quickly undock from ISS from a dormant state significantly impacts all system response times. Requires system architecture which can autonomously perform quick system checks and startup including position and attitude determination.

2. Basic medical capabilities should be provided on all crew vehicles. Providing a dedicated medical emergency function is unique CRV requirements. This includes such functions as providing a dedicated crew medical officer station, unique medical accommodations (pure oxygen, seats, restraints, isolation, etc.). Providing a core vehicle with a reconfigurable pressurized volume can enable this capability.

3. Separation from a rotating space station at 2°/sec is a unique CRV requirement which drives docking mechanisms and vehicle control system response authority.

4. Soft runway landing is an implementation rather than a requirement which should be driven by other higher level requirements such as medical landing accelerations, operational costs, crew safety, etc. Soft implies that there is an acceptable vertical speed at touchdown which is not specified. Runway implies that the CRV will have wings and/or wheels. Wings cannot be used for missions beyond low Earth orbit due to peak heating limits. Other approaches exist which can maximize, if not enable, vehicle reusability including steerable parachutes (parafoils) and non-steerable parachutes (round) with landing attenuation devices (strokable struts, air bags, retro-rockets).

5. Long-term storage at ISS is a unique CRV requirement. The two-year storage requirement drives technology selections, redundancy and maintenance strategies, and operational servicing and checkout strategies. The strategy of rotating a new CRV every 2 years, as this requirement implies, should be traded against a CRV with a shorter (6-month) life which is swapped during each crew rotation mission such as Soyuz. System impacts for long-term storage include elimination of cryogenic fluids (propulsion and power), micro-meteroid protection, propulsion system stability and isolation, thermal and environmental conditioning.
Vehicle reusability is driven primarily by technology selections, system architecture designs, and most importantly landing conditions. Vehicle reusability usually implies soft runway landings utilizing wings and wheels which are incompatible for missions beyond low Earth orbit due to peak heating requirements. Strategies which focus on selective reusability, rather than total system reuse, can be accommodated within beyond LEO missions.

Providing a crew transfer capability independently from the STS by utilizing EELV launchers will limit the overall crew transfer vehicle design and size. Key drivers include maximum vehicle mass (approximately 20 mt), vehicle diameter (approximately 4.5 m), and vehicle shape (limited area and lift). EELV control authority issues may be inconsistent with the desire to utilize wings on the crew transfer vehicle. In addition, human rating issues may require EELV modifications as well as incorporation of crew escape systems for ascent aborts. Developing a core vehicle without wings can allow commonality across mission modes as well as enable multiple delivery modes (STS and EELV).

This mission duration is driven by ISS crew transfer missions as well as on-orbit servicing missions. System drivers for longer missions are primarily habitable volume requirements and consumables (power and life support).

Lunar return missions will drive the overall thermal protection system and vehicle shape. Thermal protection systems which can accommodate much higher peak heating are required due to the higher entry velocities (11.0 km/s for lunar return versus 7.5 km/s for low Earth orbit). This necessitates vehicle shapes which limit leading edge radius of curvature (no wings such as slender bodies with mid-L/D) and incorporation of ablative thermal protection systems for areas of high peak heating at stagnation points. Reusable thermal protection systems can be substituted for ablators for low-Earth orbit only missions.

This mission duration is driven by lunar missions which include approximately 12 days of transfer and orbital operations and 8 days of dormancy during satellite servicing (performed from independent mission assets) or lunar exploration missions.

Thermal protection systems and vehicle shapes must accommodate Mars return entry speeds of approximately 13.0 km/s.
Advanced Concept Analysis in Support of the Integrated Space Plan

Section 7.2

Bioastronautics Critical Path Roadmap: Reducing the Risks for Human Exploration-Class Missions

November 2002
Some Physiological Risks and Impacts of Extended Space Flight (L1/Lunar Missions)

- Physical tolerance of stresses during aerobraking, landing and launch phases, and strenuous surface activities

Bone loss
- no documented end-point or adapted state
- countermeasures in work on ground but not yet flight tested

Cardiovascular alterations
- pharmacological treatments for autonomic insufficiency in work

Muscle atrophy
- basic mechanisms under study
- resistive exercise in work

Neurovestibular adaptations
- vehicle modifications, including centrifuge under consideration
- may require auto-land capability

Space Medicine - Routine and Contingency Ops must cope with these issues.

Mars – All the above, plus radiation effects, both acute and chronic
• Risks and critical questions have been identified and prioritized for mission scenarios
  – Radiation concerns limit deep-space exposure: most susceptible person < ~50 days; least susceptible person < ~270 days (NCRP, 2000: 3% excess cancer, based on age and gender)
  – Neurological, cardiovascular concerns about precision piloting for Earth return after ~20 days
  – Medical response plan to be determined by risk level to be accepted, mission requirements (potential for injury, etc.)
  • TRL varies inversely with available resources (such as: mass/volume available; presence of trained care-giver)
BCPR Background

- Joint NASA JSC/NSBRI undertaking, initiated 1997
- Twelve joint Risk Area Teams in three categories

- **Habitation Systems:**
  - Advanced Life Support (ALS)
  - Environmental Health (EH)
  - Food and Nutrition (F&N)
  - Human Behavior and Performance (HB&P)

- **Health Care Systems:**
  - Clinical Capabilities
  - Multi-system Alterations

- **Human Adaptation and Countermeasures:**
  - Bone Loss
  - Cardiovascular Adaptations (CV)
  - Human Behavior & Performance (HB&P)
  - Immunology, Infection and Hematology (II&H)
  - Muscle Atrophy & Alterations (MA)
  - Neurovestibular Adaptations (NVA)
  - Radiation Effects
BCPR Background

• Assessed Mars DRM
  – Produced set of 55 risks, ~250 critical questions (CQ)
• Now analyzing subsets of risks, etc., specific to 180-day ISS, 30-day STS, 3 & 30-day lunar surface missions, etc.
• Countermeasure tracking
• Risk quantification activity
Risk Resolution Timeline: Bad News

- 55 risks identified for Mars DRM.
  - Subset of 43 risks (not including ECLSS) tentatively identified for lunar surface 3-day and 30-day missions.
- 248 CQs identified for Mars DRM
  - 185 required studies
    - Ground-based data: 108
    - Requiring in-flight data: 77
      - SWAG: 130 “trials” @ 7 crewmembers/trial (optimistic!!)
      - All 55 risks by 2010 => 79% too few ISS 7-person crews
      - Lunar subset of 43 risks by 2010 => 27% too few ISS 7-person crews
Risk Resolution Timeline: Good News

- Not ALL risks must be resolved before Go/No Go.
  - Every single risk resolved reduces overall threat to crew for mission and lifetime.
  - Periodic reassessment by BCPR to track overall risk level.
- BCPR is being applied to Code U NRAs
  - Ground-Based Research in Space Radiation Biology and Space Radiation Shielding Materials (NRA-02-OBPR-02), proposals due 25 Nov. 02.
  - Others
Bioastronautics Risk Mitigation Definitions

What is the likelihood the risk will occur?

<table>
<thead>
<tr>
<th>Level</th>
<th>Probability</th>
<th>Probability of occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Very High</td>
<td>95 – 100%</td>
</tr>
<tr>
<td>4</td>
<td>High</td>
<td>75 – 95%</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
<td>25 – 75%</td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
<td>5 – 25%</td>
</tr>
<tr>
<td>1</td>
<td>Very Low</td>
<td>0 – 5%</td>
</tr>
</tbody>
</table>

What is the worst case consequence (Crew or Mission) if the risk occurs with the current level of mitigation?

<table>
<thead>
<tr>
<th>Level</th>
<th>Crew Health, Safety, Performance</th>
<th>Mission Success</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No impact to crew</td>
<td>No impact to mission whatsoever; no loss of mission objectives</td>
</tr>
<tr>
<td>2</td>
<td>Short- term, minor injury, illness, incapacitation, or impairment to crewmember</td>
<td>Relatively small impact to mission; loss limited to only a few of the mission objectives</td>
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<td>Serious injury, illness, incapacitation or impairment but not long term</td>
<td>Considerable impact and considerable loss of mission objectives</td>
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<td>4</td>
<td>Significant and long term impairment, but not permanent</td>
<td>Significant mission impact; many mission objectives lost, however mission is not aborted</td>
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<td>5</td>
<td>Irreversible, catastrophic impairment, or death</td>
<td>Significant mission impact; total loss of mission objectives; Mission aborted</td>
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## BCPR Risks and Risk Areas for Mission Scenarios (1of 4)

**PRELIMINARY**

<table>
<thead>
<tr>
<th>ID</th>
<th>Risk Title</th>
<th>Risk Area</th>
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<th>ISS</th>
<th>Moon surface via L1</th>
<th>Mars DRM</th>
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<td>3 (18) days</td>
<td>30 (44) days</td>
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<td>Loss of Skeletal Muscle Mass, Strength, and/or Endurance</td>
<td>Muscle</td>
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<td>Inability to Adequately Perform Tasks Due to Motor Performance, Muscle</td>
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<td>Endurance, and Disruption in Structural and Functional Properties of Soft</td>
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<td>Trauma and Acute Medical Problems</td>
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<td>Impaired Response to Orthostatic Stress</td>
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<td>Human Performance Failure Because of Sleep and Circadian Rhythm Problems</td>
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<td>Bone Fractures Due to Deficiencies in Motor Skill, Muscle Strength and</td>
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<td>Muscular Fatigue</td>
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<td>Inability to Sustain Muscle Performance Levels to Meet Demands of</td>
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<td>Disorientation and Inability to Perform Landing, Egress, or Other Physical</td>
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<td>Tasks, Especially During/After G-Level Changes (Acute spontaneous &amp;</td>
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<td>provoked vertigo, nystagmus, oscillopsia, poor dynamic visual acuity)</td>
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<td>36</td>
<td>Vestibular Contribution to Cardioregulatory Dysfunction (Post landing</td>
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<td>Impaired Neuromuscular Coordination and/or Strength (Gait ataxia, postural</td>
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<td>Damage to Central Nervous System from Radiation Exposure</td>
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<td>Sickness Symptoms or Treatments, Especially During/After G-Level Changes</td>
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<td>esp. Earth return</td>
<td>esp. Earth return</td>
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<td></td>
<td>(Including short term memory loss, reaction time increase, drowsiness,</td>
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<td>fatigue, torpor, irritability, ketosis)</td>
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<td>Radiation Effects on Fertility, Sterility, and Heredity</td>
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<td>Development and Treatment of Space-Related Decompression Sickness</td>
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<td>Altered Pharmacodynamics and Adverse Drug Reactions</td>
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<td>Post-landing Alterations in Various Systems Resulting in Severe</td>
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<td>Performance Decrement and Injuries</td>
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<td>7&amp;</td>
<td>Inadequate Nutrition (Malnutrition) &amp; …Due to inability to Provide</td>
<td>Food &amp;</td>
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<td>53</td>
<td>and Maintain a Bioregenerative System &amp; Difficulty of Rehabilitation</td>
<td>Nutrition &amp; ALS</td>
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<td>(7&amp;53)</td>
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<td>Following Landing Due to Nutritional Deficiencies &amp; Human Performance</td>
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<td>Failure Due to Nutritional Deficiencies</td>
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<td>Carcinogenesis</td>
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<td>Injury to Soft Connective Tissue, Joint Cartilage, Intervertebral Disc</td>
<td>Bone Loss</td>
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<td>Rupture w/ or w/o Neurological Complications</td>
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<td>Renal Stone Formation</td>
<td>Bone Loss</td>
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<td>Occurrence of Serious Cardiac Dysrhythmias</td>
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<td>Manifestation of Previously Asymptomatic Cardiovascular Disease</td>
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## BCPR Risks and Risk Areas for Mission Scenarios (3 of 4)

**PRELIMINARY**

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<td>180-215 days</td>
<td>3 (18) days</td>
<td>30 (44) days</td>
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<td>Altered Wound Healing</td>
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<td>26</td>
<td>Altered Host-Microbial Interactions</td>
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<td>Inadequate Supplies (including maintenance, emergency provisions, and edible food)</td>
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<td>Unsafe Food Systems</td>
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<td>Acceleration of Age-Related Osteoporosis</td>
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<td>Human Performance Failure Because of Poor Psychosocial Adaptation</td>
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<td>Altered Homodynamic and Cardiovascular Dynamics caused by Altered Blood Components</td>
<td>IIH</td>
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<td>Possible Chronic Impairment of Orientation or Balance Function Due to Microgravity or Radiation (Imbalance, gait ataxia, vertigo, chronic vestibular insufficiency, poor dynamic visual acuity)</td>
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<td>Early or Acute Effects from Radiation Exposure</td>
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<td>Synergistic Effects from Exposure to Radiation, Microgravity and other Spacecraft Environmental Factors</td>
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<td>2 &amp; 52</td>
<td>Inability to Provide and Recover Potable Water &amp; … Due to Environmental Health Contaminants</td>
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<tr>
<td>ID</td>
<td>Risk Title</td>
<td>Risk Area</td>
<td>STS EVO</td>
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<td>180-215 days</td>
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<td>Inability to Maintain Acceptable Atmosphere in Habitable Areas &amp; … Due to Environmental Health Contaminants</td>
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<td>Inadequate Stowage and Disposal Facilities for Solid and Liquid Trash Generated During Mission</td>
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<td>Inability to Adequately Process Solid Wastes</td>
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<td>Difficulty of Rehabilitation Following Landing</td>
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<td>2Yellow</td>
<td>3Green</td>
<td>3Green esp. Earth return</td>
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<td>Human Performance Failure Because of Human System Interface Problems &amp; Ineffective Habitat, Equipment, Design, Workload, or In-flight Information and Training Systems</td>
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<td>Immunodeficiency/Infections</td>
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<td>27 &amp; 50</td>
<td>Allergies and Hypersensitivity Reactions &amp; Allergies and Hypersensitivity Reactions from Exposure to the Enclosed Spacecraft &amp; Other Environmental Factors</td>
<td>IIH EH</td>
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<td>32</td>
<td>Impact of Deficits in Skeletal Muscle Structure and Function on Other Systems</td>
<td>Muscle</td>
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<td>21</td>
<td>Human Performance Failure Because of Neurobehavioral Dysfunction</td>
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<td>Diminished Cardiac Function</td>
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</tbody>
</table>

**PRELIMINARY**
Bioastronautics

- Bioastronautics Endorses the following:
  - Science-driven mission selection
  - Mission-driven technology development
  - OBPR Priorities ranked as 1\textsuperscript{st} and 2\textsuperscript{nd} Priority by REMAP
  - Expanded application of Bioastronautics Critical Path Roadmap in guiding funding of tasks for risk reduction
    - Ground-based radiobiology research towards countermeasures
  - Artificial gravity development
    - Ground-based studies of acceptable AG limits
    - Earliest possible human-rated short-radius AG testbed in space
    - Earliest possible delivery of animal centrifuge to ISS
    - Continued development of concept for Artificial Gravity spacecraft providing up to 1-g
Bioastronautics

• Bioastronautics advocates these Augmentations:
  – Increase ISS crewmember throughput for biomedical investigations
    • Increase crew size
    • Decrease increment duration
    • *Reduce crew workload to increase research opportunities on ISS*
  – *Develop and* demonstrate advanced medical care capabilities consistent with mission and risk
    • “Stand-and-fight” on-board provisioning *vs.* abort to Earth
    • On-board medical autonomy as a standard practice
  – Use ground analogs (*BNL, INTEGRITY, NEEMO, lab, bed rest studies, etc.*) to augment flight opportunities
    • *Biological effects of radiation dose, advanced life support and monitoring, countermeasure effectiveness, behavior and performance tools, etc.*
  – Evaluate future vehicles’ systems on ISS
    • Improve crew safety, health, and habitability
Bioastronautics makes these Recommendations:

- Manifest STS & ISS missions for specific risk-reduction activities
  - Examples: » Medical Ops – procedures and tools
    » Countermeasures – procedures and tools
    » Environmental monitoring – procedures and tools
    » BCPR Research – some risks addressable on short flights

- Place humans at center of future vehicle and mission design efforts
  - Humans as critical systems instead of as supplements to all other systems
  - Human requirements to be defined, integrated — and implemented!
  - Human Rating Standards: NASA Std 3000, SMACs, NPG-8705 (in work), JSC-28354 (approved) (Human Rating Req’ts for Space Flight Systems), SSP 50260 (MORD), SSP50480 (ISS Med Ops Implementation Plan)
Advanced Concept Analysis in Support of the Integrated Space Plan

Section 7.3

Human Exploration Requirements for Future Nuclear Systems

November 2002
Contents

- Roadmap Objectives

- NExT Requirements Document

- Human NEP Requirements

- Human Surface Power Requirements
Nuclear Roadmap Overview

- Where-when-&-how nuclear “fits” into exploration strategies is highly dependent on how architectures develop over next few weeks
- Nuclear technology is challenging & expensive – need to use where makes sense (enabling or highly enhancing)
- Nuclear surface power “shines” for one or more of the following:
  - Little sunlight (significant night-times or far from sun)
  - Higher power levels & durations
  - Repeated or extended visits to same place (a base vs. Apollo sorties)
- Related System Applications can be “roadmapped” together:
  - Lunar, Mars nuclear surface power 10’s kWe
  - NEP for outer planets science missions 100’s kWe
  - SEP for near-earth tugs 500-2,000 kWe
  - NEP for human Mars missions 6,000+ kWe
- Related constituent technologies can be also mapped:
  - Reactor fuels, materials, power conversion, radiators, electric thrusters, … etc.
- References for requirements, end-point systems to be “blueprinted”:
  - “Human Exploration Requirements for Future Nuclear Systems”; Draft 5 recently completed
  - Architecture & System studies underway
- Related activity underway to “roadmap” low power NEP to high power commissioned by Gary Martin (Code M) and Ray Taylor (NSI)
**Space Nuclear Roadmap**

**Goal:** Chart a unified space fission power and propulsion vision for the agency’s next 2 decades of exploration

**Objectives:**
- Identify desired system/concepts and requirements
- Identify primary technology and infrastructure options, pros & cons
- Assess cross-applicable technology options and common infrastructure options
- Develop a roadmap that can link technology and infrastructure developments, downselects, and system developments leading to desirable missions

**Groundrules:**
- Strategy should address projected robotic and human needs of the agency over the next two decades
- An early robotic science mission in the 2010 timeframe will pathfind the program
- Resulting fission systems should enable new mission capabilities relative to non-fission approaches (or why bother?)
- Technology and infrastructure approaches should be mature enough to support IOC’s w/ fair degree of confidence
- System Requirements come from:
  - Robotic: Recent NSI studies
  - Human: “NExT Human Exploration Requirements for Future Nuclear Systems”
Contents

- Roadmap Objectives
- NExT Requirements Document
- Human NEP Requirements
- Human Surface Power Requirements
**Document Title:**

“NEXT Human Exploration Requirements for Future Nuclear Systems”,
Draft 5, 9/29/02

**Purpose:** "This document shall serve to consolidate and to communicate current needs and requirements for nuclear systems and technologies in support of advanced human exploration missions." (Section 1.1)

**Objective:** Influence ongoing technology programs, in particular NSI, to address human nuclear needs

**Out-of-Scope:** "Nuclear needs and requirements for robotic exploratory missions are explicitly considered out-of-scope for this document, as this issue is being actively and extensively pursued elsewhere within the agency." (1.2)
Caveats: "current best understanding… subject to future change" (start of a living document - not carved in stone) (1.2)

• Not intended to include detailed DRM descriptions (other document) (1.2)

• Compromise in mission approach: Started w/ rigorous linkage to single architectural scenario - ended up blending different approaches

• Compromise in "Level": First out of gate (w/ SLI) - includes some mixing of different level requirements (mission, system, technology)

• Compromise between Requirements Doc. And White Paper (to communicate and rationalize need)

• Does focus on two important applications (see below).

• Does not specify constituent technologies.

• Does not specify internal system design or implementation.
Requirements Background, Cont.

**Scope (Section 2.2-2.4):**

- Current Most Immediate Interest: application to "First Wave" of advanced human missions beyond LEO
- First Selection Criterion - Enabling Performance (or why bother with nuclear at all?)
- Second Selection Criterion - Near-Term Feasibility and Maturity (lower risk to achieve ~10-15 year implementation)

**Focused Applications (Section 2.5):**

- NEP Missions for Humans and Cargo beyond Earth Orbit
- Fixed Surface Nuclear Reactor Power Systems for Moon, Mars, and Asteroids
Contents

• Roadmap Objectives

• NExT Requirements Document

  • Human NEP Requirements

• Human Surface Power Requirements
Nuclear Electric Propulsion Advantages

• High propulsive performance
  – Captures energetically challenging Mars missions in all opportunities (for ~ same prop mass)
• High power availability
  – Robust power for crew, spacecraft systems (<1% of propulsion requirements)
• Potential technology convergence with advanced robotic exploration and NSI
  – Reactor, power conversion, thrusters
  – Human exploration nuclear power requirements ready to submit to Nuclear Space Initiative
• Potential convergence with technology development of surface nuclear power
  – Moon - > 14 days (non-polar) at fixed location
  – Mars – “long” stay
• Allows Sustainable, Evolvable Exploration Capability
  – High reactor energy content and low prop mass fraction allows high degree of vehicle reusability for Mars missions
  – Evolution of power/propulsion possible to even more ambitious missions
NEP Enables New Human Exploration Capabilities

- Nuclear Electric Propulsion enables new class of “medium surface stay” (few month) human Mars missions
  - Factor of ~3-5 longer stay and higher productivity than past opposition missions
  - Reduces infrastructure and technology to support multi-year conjunction missions
- ~1.5 year total mission
- 3 month stay at Mars
- 110-190 MT wet piloted NEP vehicle
- No LEO Nuclear Ops. via staging from earth-moon libration point
- Lander predeployed to high Mars orbit
- 6 MWe Nuclear Power
- 4000-7000 sec Isp Electric Propulsion
- 1.0 g artificial gravity aids
  - Crew health & safety
  - “Hardware” testing & certification
  - Power and fluid technology & design
**Function:** The NEP system transports crew and/or cargo in support of human exploration missions. The NEP system also provides primary onboard power for habitat and vehicle subsystems. The NEP system may also provide primary attitude control during thrusting periods.

**Functional Allocation of NEP System Elements:** The NEP system shall be comprised of the following elements and subsystems:

- *Nuclear Power System* – provides conditioned electrical power. Includes reactor, shield, control, power conversion, heat rejection, and power management and distribution subsystems.

- *Electric Propulsion System* – converts electrical power into kinetic jet power and thrust. Includes electric thruster, power processing, thrust vector control, thermal, and propellant feed subsystems.

- *Tankage* – stores and thermally controls propellant.

- *Propellant* – serves as reaction mass for vehicle propulsion, and may vary with specific thruster type and specific impulse range.

- *Bus Module* – contains all remaining vehicle support and infrastructure subsystems such as structure, mechanisms, command and data handling (C&DH), attitude control, etc.

- *Payload Modules* – the mission specific payload, such as crew habitats, science instruments, landers, etc.
Human NEP Design Goals and Objectives

- Enable fast transits to reduce crew exposure to harm.
- Allow demanding missions to be performed for reduced launch mass.
- Entail multi-mission savings through reuse and low resupply mass.
- Exhibit robust operation and high reliability over the design lifetime.
- Provide enhanced abort options for a variety of scenarios over broad segments of the mission.
- Enhance mission flexibility thru widened departure windows.
- Provide a power rich environment for crew subsystems.
- Perform primary vehicle attitude control during thrusting periods.
- Where practical, common nuclear power and electric propulsion technologies should be used across human and robotic system applications.
- Where practical, common subsystems and components should be used across human and robotic systems.
- While meeting requirements for performance and safety, the system should be based on technologies of sufficient maturity to ensure successful and cost-effective development.
- The system should facilitate ground testing, and minimize need for new or complex facilities.
- The system should facilitate integration, packaging, storage, and approval for launch.
- The system should feature minimal deployment needs, and be easily integrated on orbit.
- The system should facilitate stable operation, and autonomous, crew, or ground control.
## NEP Survey

### Table 1. Survey of Human Mars Missions Utilizing NEP.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Electric Power (MWe)</th>
<th>Full Power Life (yr)</th>
<th>Num. Missions</th>
<th>Specific Mass (kg/kW e)</th>
<th>Mission Class</th>
<th>Artifical Gravity</th>
<th>Stay Time (days)</th>
<th>Total Mission Duration (days)</th>
<th>Initial Mass (metric tons)</th>
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<tr>
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<td>6</td>
<td>4</td>
<td>3</td>
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<td>Opposition</td>
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<td>90</td>
<td>590</td>
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<td>8</td>
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<td>5</td>
<td>Opposition</td>
<td>Yes</td>
<td>90</td>
<td>550</td>
<td>167</td>
</tr>
<tr>
<td>Clark, 1994</td>
<td>8</td>
<td>5</td>
<td>2</td>
<td>11.1</td>
<td>Conjunction</td>
<td>No</td>
<td>550</td>
<td>960</td>
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<td>George, 1992</td>
<td>10</td>
<td>2</td>
<td>1</td>
<td>7.3</td>
<td>Opposition</td>
<td>No</td>
<td>30</td>
<td>418</td>
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<td>George, 1992</td>
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<td>1</td>
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<td>Opposition</td>
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<td>367</td>
<td>285</td>
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<tr>
<td>George, 1993</td>
<td>10</td>
<td>2</td>
<td>1</td>
<td>7.3</td>
<td>Conjunction</td>
<td>No</td>
<td>626</td>
<td>899</td>
<td>286</td>
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<td>McD/Doug, 92</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>Conjunction</td>
<td>Yes</td>
<td>489</td>
<td>887</td>
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<tr>
<td>Boeing, 1991</td>
<td>40</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>Conjunction</td>
<td>Yes</td>
<td>600</td>
<td>1090</td>
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## Requirements Summary
*(Draft 5, 9/29/02)*

<table>
<thead>
<tr>
<th>Human NEP</th>
<th>Surface Power</th>
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<tbody>
<tr>
<td><strong>No.</strong></td>
<td><strong>Subject</strong></td>
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<tr>
<td>4.1</td>
<td>Power</td>
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<td>4.2</td>
<td>Life</td>
</tr>
<tr>
<td>4.3</td>
<td>Specific Impulse</td>
</tr>
<tr>
<td>4.4</td>
<td>Thruster Efficiency</td>
</tr>
<tr>
<td>4.5</td>
<td>Specific Mass</td>
</tr>
<tr>
<td>4.6</td>
<td>Restartable</td>
</tr>
<tr>
<td>4.7</td>
<td>Throttleable</td>
</tr>
<tr>
<td>4.8</td>
<td>Microgravity</td>
</tr>
<tr>
<td>4.9</td>
<td>Artificial Gravity</td>
</tr>
<tr>
<td>4.10</td>
<td>(reserved)</td>
</tr>
<tr>
<td>4.11</td>
<td>Reliability</td>
</tr>
<tr>
<td>4.12</td>
<td>Earth Release</td>
</tr>
<tr>
<td>4.13</td>
<td>Dose to Crew</td>
</tr>
<tr>
<td>4.15</td>
<td>Initial Criticality</td>
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<td>4.16</td>
<td>Inadvertent Criticality</td>
</tr>
<tr>
<td>4.17</td>
<td>Disposal</td>
</tr>
<tr>
<td>4.18</td>
<td>(reserved)</td>
</tr>
<tr>
<td>4.19</td>
<td>(reserved)</td>
</tr>
<tr>
<td>4.20</td>
<td>(reserved)</td>
</tr>
<tr>
<td>4.21</td>
<td>Contamination</td>
</tr>
</tbody>
</table>
Contents

• Roadmap Objectives

• NExT Requirements Document

• Human NEP Requirements

• Human Surface Power Requirements
Surface Nuclear Power Function

• **Function**: The nuclear surface power system provides primary power generation and distribution for human exploration missions to the surface of the Moon, Mars, and asteroids.

• **Functional Allocation of Surface Power System Elements**: The nuclear surface power system shall be comprised of one or more of each of the following elements:
  
  • **Nuclear Power Element** – provides unconditioned electrical power. Includes reactor, shield, control, power conversion, and heat rejection subsystems.
  
  • **Primary PMAD Element** – provides control, regulation, and distribution of electrical power to (possibly remote) users.
  
  • **Deployment Element** – provides all necessary deployment services between landing and initial startup. May include surface transport to a remote location, radiator deployment and other assembly, transport and connection of power distribution cables, and construction or excavation of in-situ radiation shielding.
Surface Nuclear Power
Design Goals and Objectives

- Provide a *power rich* environment for human surface missions.
- Exhibit robust operation and *high reliability* over the design lifetime.
- Allow for a *low incremental* increase in crew *radiation dose* through time, distance, and shielding.
- Exhibit simple, stable *operation* capable of autonomous *control*.
- Design for ease of *deployment* with minimal required assembly or construction.
- Be compatible with the varied thermal and chemical *environments* of the Moon, Mars, and expected asteroid environment.
- Exhibit modest *mass*.
- Exhibit modest packaged *volume*.
- Where practical, *common* nuclear power *technologies* should be used across human and robotic system applications.
- Where practical, *common* subsystems and *components* should be used across human and robotic systems.
- While meeting requirements for performance and safety, the system should be based on technologies of *sufficient maturity* to ensure successful and cost-effective development.
- The system should *facilitate* ground *testing*, and minimize need for new or complex facilities.
- The system should *facilitate* integration, packaging, storage, and approval for *launch*. 
Table 2. Survey of Power Needs for Human Surface Missions.

<table>
<thead>
<tr>
<th>REFERENCE</th>
<th>Destination</th>
<th>Day Average Power (kWe)</th>
<th>Night Average Power (kWe)</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Lunar Outpost (Ref. 8)</td>
<td>Moon</td>
<td>13</td>
<td>9</td>
<td>PV/RFC</td>
</tr>
<tr>
<td>DRM 1.0; ISRU only (Ref. 9)</td>
<td>Mars</td>
<td>60</td>
<td>60</td>
<td>Nuclear</td>
</tr>
<tr>
<td>DRM 1.0; Habitat only (Ref. 9)</td>
<td>Mars</td>
<td>25</td>
<td>25</td>
<td>Nuclear</td>
</tr>
<tr>
<td>DRM 3.0; ISRU only (Ref. 10)</td>
<td>Mars</td>
<td>45</td>
<td>45</td>
<td>Nuclear</td>
</tr>
<tr>
<td>DRM 4.0; Habitat, Rovers (Ref. 11)</td>
<td>Mars</td>
<td>37</td>
<td>9</td>
<td>PV/Battery/RF C</td>
</tr>
</tbody>
</table>
## Requirements Summary
*(Draft 5, 9/29/02)*

<table>
<thead>
<tr>
<th>Human NEP</th>
<th></th>
<th>Surface Power</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No.</strong></td>
<td><strong>Subject</strong></td>
<td><strong>Value</strong></td>
<td><strong>No.</strong></td>
</tr>
<tr>
<td>4.1</td>
<td>Power</td>
<td>6-20 MWe</td>
<td>6.1</td>
</tr>
<tr>
<td>4.2</td>
<td>Life</td>
<td>4 yr</td>
<td>6.2</td>
</tr>
<tr>
<td>4.3</td>
<td>Specific Impulse</td>
<td>4000-7000 sec</td>
<td>6.3</td>
</tr>
<tr>
<td>4.4</td>
<td>Thruster Efficiency</td>
<td>&gt;50%</td>
<td>6.4</td>
</tr>
<tr>
<td>4.5</td>
<td>Specific Mass</td>
<td>4-7 kg/kWe</td>
<td>6.5</td>
</tr>
<tr>
<td>4.6</td>
<td>Restartable</td>
<td>see spec.</td>
<td>6.6</td>
</tr>
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<td>---</td>
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<tr>
<td>4.11</td>
<td>Reliability</td>
<td>see spec.</td>
<td>6.11</td>
</tr>
<tr>
<td>4.12</td>
<td>Earth Release</td>
<td>see spec.</td>
<td>6.12</td>
</tr>
<tr>
<td>4.13</td>
<td>Dose to Crew</td>
<td>5 rem/yr</td>
<td>6.13</td>
</tr>
<tr>
<td>4.15</td>
<td>Initial Criticality</td>
<td>see spec.</td>
<td>6.15</td>
</tr>
<tr>
<td>4.16</td>
<td>Inadvertent Criticality</td>
<td>see spec.</td>
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<td>see spec.</td>
<td>6.21</td>
</tr>
</tbody>
</table>
Advanced Concept Analysis in Support of the Integrated Space Plan

Section 7.4

Lunar (EN) Precursor Mission

November 2002
Lunar robotic precursor missions will acquire new data sets, demonstrate technologies and emplace infrastructure in advance of human missions.

No lunar robotic missions are currently planned by NASA:
- NRC “New Frontiers” report has elevated the interest in a South Pole-Aitken Sample Return mission.
- ESA’s 2003 SMART-1 mission will map the lunar south pole and demonstrate advanced technologies.
- Japan’s 2005 SELENE mission will acquire orbital data.

Science data and technology precursor requirements could be filled with 2-3 focused orbiters and landers:
- Polar mapping orbiter – south pole mapping and propulsion technology demonstration.
- Shadowed south pole crater lander – astrobiology, landing GN&C technologies, mobility, ISRU, survivability.
- South Pole-Aitken sample return – precursor to Mars sample return (sampling operations, sample protection, Earth targeting and entry).
# Lunar Precursors

<table>
<thead>
<tr>
<th>Planned / in development</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>2004</td>
</tr>
<tr>
<td>2005</td>
<td>2006</td>
</tr>
<tr>
<td>200x</td>
<td>200y</td>
</tr>
<tr>
<td>20zz</td>
<td></td>
</tr>
</tbody>
</table>

## LUNAR-A (Japan) - 2003
- Near side and farside antipode penetrators
- Seismometer
- Heat flow probe
- Accelerometer
- 30 m resolution monochromatic camera (comm orbiter)

## SMART-1 (ESA) - March 2003
- Miniature high resolution camera (AMIE)
- Near-infrared spectrometer (SIR)
- X-ray spectrometer (D-CIXS)
- Radio science experiment (RSIS)

## SELENE-A and SELENE-B (Japan) - 2005/6
- Surface Imaging
- Far side gravitational mapping
- X-ray spectrometer
- Gamma ray spectrometer
- Terrain camera
- Laser altimeter
- Radar sounder
- Magnetometer
- Plasma imager
- Charged particle spectrometer

## Lunar Mapping Orbiter
- 1 meter imaging of landing sites
- Remote sensing of potential landing sites
- Lunar year survey of lunar pole shadow and lighting
- Global altimetry
- Synthetic aperture radar mapper

## Permanently Shadowed Crater Lander-Rover
- Vertical and lateral distribution of ice in permanently shadowed craters
- Drilling
- Ice abundance and composition measurement
- Astrobiology

## South Pole-Aitken Sample Return
- Return of surface and subsurface samples
- Landing site characterization

## Science and Technology
- SEP flight test (Hall thruster)
- Low-thrust spiral trajectory
- 15-17 month weak stability boundary transfer
- Advanced solar array
- Deep space optical communications experiment
- X- and Ka band telemetry experiment (KaTE)

## SELENE-B
- Solar electric propulsion
- Low thrust trajectories
- Advanced solar arrays
- High bandwidth communications
- Libration point (L1) transfer orbit

## Remote drilling
- ISRU experiment (lunar water)
- Surface mobility
- Low temperature thermal control and survivability
- System health monitoring
- Robotics
- Lander-based GN&C
- Hazard avoidance
- Precision landing

## Mars Sample Return precursor:
- Surface sample operations
- Earth targeting
- Earth entry
- Sample protection
- Autonomous rendezvous and docking (if required)
- Electric propulsion (Earth return)
- Farside communications relay
- Farside radio science antenna
Prior lunar missions have created a large data set, except in the lunar polar regions.

Additional data required:

- **Science**
  - South Pole-Aitken returned samples
  - High resolution (<10 m) compositional mapping (some data will be generated by the SMART-1 and SELENE missions)
  - Multi-station, long-duration (10 year) seismic network
  - Far side gravity field mapping (may be addressed by SELENE-A)
  - High-resolution polar imagery and global topography (some data will be generated by the SMART-1 and SELENE-A missions)

- **Resources**
  - Determine the nature and distribution of hydrogen concentrations at the lunar poles
  - Search for ice in the permanent shadows
  - Prepare for human exploration
    - High-resolution imagery (<1 m) - critical at highly shadowed polar sites
    - Geochemical and mineralogical mapping for site selection
Lunar (EN) Robotic Precursors Technology Demonstrations

- Technologies can be demonstrated in Earth’s Neighborhood which will decrease the risk of future human missions
  - Electric propulsion, low-thrust trajectories, Libration point trajectories
  - Advanced solar arrays
  - High bandwidth, deep space communications
  - Automated drilling
  - Water extraction and in-situ resource utilization
  - Surface mobility, robotic sampling
  - Autonomous surface operations
  - Precision landing and hazard avoidance
  - Surface thermal control and thermal cycle survivability
  - Advanced system health monitoring

- Lunar South Pole-Aitken Sample Return can also serve as a technology and operational precursor to Mars Sample Return
  - Surface sampling operations
  - Autonomous rendezvous and docking
  - Sample preservation
  - Earth targeting
  - Earth entry
Backup Charts

- Requirements
1. A lunar robotic precursor program shall provide lunar environmental data sets which pose the greatest risk to future human missions (references: LExSWG report, 1992, and M. Duke, 2002)
   a. Orbital or landed missions shall map the landing operations area for humans in sufficient detail to identify hazards
   b. Orbital missions shall gather <1 meter resolution imagery of the highly shadowed polar sites
   c. Orbital missions shall provide geochemical and mineralogical mapping for site selection
   d. Orbital or landed missions shall measure the nature and distribution of hydrogen concentrations at the lunar poles
   e. Orbital or landed missions shall search for ice in the permanent shadows
   f. Samples shall be returned from the South Pole-Aitken Basin for study in Earth laboratories
   g. Orbital missions shall provide <10m resolution compositional mapping data
   h. Landed missions shall emplace a multi-station, long-duration (10 year) seismic network
   i. Orbital missions shall map the far side gravity field
   j. Orbital missions shall provide high-resolution polar imagery and global topography
2. **A lunar robotic precursor program shall demonstrate key technologies in order to reduce the risk to future human missions (reference: tbd)**

   a. Landers shall demonstrate terminal phase hazard avoidance and precision landing
   b. Landed experiments shall demonstrate water extraction, ISPP (propellant production) and ISCP (consumable production)
   c. Missions shall demonstrate electric propulsion, low-thrust trajectories, and Libration point trajectories
   d. Missions shall demonstrate advanced solar arrays
   e. Missions shall demonstrate high bandwidth, deep space communications
   f. Missions shall demonstrate automated drilling
   g. Missions shall demonstrate surface mobility
   h. Missions shall demonstrate autonomous surface operations
   i. Missions shall demonstrate surface thermal control and thermal cycle survivability
   j. Missions shall demonstrate advanced system health monitoring
   k. Missions shall demonstrate autonomous rendezvous and docking
   l. Missions shall demonstrate sample preservation
   m. Missions shall demonstrate Earth targeting
   n. Missions shall demonstrate Earth entry
Requirements to Other Programs – Lunar Robotic Precursors

3. A lunar robotic precursor program shall deliver infrastructure necessary for the accomplishment of future human missions (reference: tbd)
   a. Orbital missions shall emplace high data rate communication infrastructure for continuous communications support of future human missions
   b. Orbital and landed missions shall carry navigation infrastructure to support precision entry, descent and landing of future human missions.
   c. Landed missions shall emplace high capacity power systems
Advanced Concept Analysis in Support of the Integrated Space Plan

Section 7.5
Mars Precursor Missions

November 2002
NASA’s Mars Exploration Program (MEP) features a science-driven mix of orbital and landed missions.

Opportunities for human exploration experiments begin with the 2007-2009 opportunities.

- Scout missions
- 2009 Mars Science Laboratory

Augmentation of the MEP is required to support human exploration precursor activities.

- Development of miniaturized instruments to acquire highest priority data sets (surface radiation, soil properties, landing site surveys)
- Development of enabling flight system technologies (hazard avoidance, precision landing, Mach 3 parachutes, mid-L/D aeroentry, nuclear surface power)
- Acceleration of Mars Sample Return
Backup Material
Robotic Precursors

- Exploration Roadmap precursor mission product coordination

  - Earth’s Neighborhood
    - Earth’s Neighborhood precursor science and exploration requirements
    - Earth’s Neighborhood technology requirements
      - new technology requirements to THREADS
      - precursor technology demos
    - Earth’s Neighborhood precursor mission concepts
  
  - Mars (and beyond)
    - Mars precursor science and exploration requirements (NRC, MEPAG)
    - Mars technology requirements
      - MTP augmentation
      - new technology requirements to THREADS
    - Mars precursor mission concepts
    - Experiment concepts
    - Opportunities to augment existing missions
    - Stand-alone NEXT Mars precursor mission concept
Mars Precursor Science and Exploration Requirements
Requirements to Other Programs – Mars Robotic Program

1. The Mars Exploration Program (Code S Robotic Mars missions) shall provide Mars environmental data sets which pose the greatest risk to future human missions (references: NRC “Safe on Mars” report, 2002 and MEPAG August 2001 report “Mars Exploration Program Scientific Goals, Objectives and Investigation Priorities”)
   
   a. Landed missions shall measure the radiation level (charged particles and neutrons) on the Martian surface (highest priority, ref: NRC “Safe on Mars” report, 2002)
   
   b. Orbital or landed missions shall map the landing operations area for humans in sufficient detail to identify hazards
   
   c. Landed missions shall measure certain mechanical and adhesive properties of Martian soil and dust
   
   d. Landed missions shall measure the concentrations of certain hazardous heavy metals (Cr VI)
   
   e. Landed missions shall measure soil Ph and buffer capacity
   
   f. Landed missions shall determine the presence and concentration of organic carbon
Mars Precursor Technology Demonstration Requirements
1. **The Mars Exploration Program (Code S Robotic Mars missions) shall demonstrate key technologies in order to reduce the risk to future human missions (reference: MEPAG August 2001 report “Mars Exploration Program Scientific Goals, Objectives and Investigation Priorities”)**
   a. Landers shall demonstrate terminal phase hazard avoidance and precision landing
   b. Entry systems shall demonstrate mid-L/D aeroentry/aerocapture vehicle flight
   c. Entry systems shall demonstrate high-Mach parachute deployment and performance
   d. Landed experiments shall demonstrate ISPP and ISCP (consumable production)
   e. Landed experiments shall demonstrate access to and extraction of water from soils, regolith, and groundwater systems
   f. Landed platforms shall demonstrate deep drilling
   a. Orbital missions shall emplace high data rate communication infrastructure for continuous communications support of future human missions
   b. Orbital and landed missions shall carry navigation infrastructure to support precision entry, descent and landing of future human missions.
   c. Landed missions shall emplace high capacity power systems
Mars Technology Program (MTP)
Augmentation Requirements
1. Augmentations to the Mars Technology Program (Code S Robotic Mars mission base and focused programs) shall focus development efforts on technology programs that are mutually beneficial to robotic and human Mars missions. (references: NRC “Safe on Mars” report, 2002 and MEPAG August 2001 report “Mars Exploration Program Scientific Goals, Objectives and Investigation Priorities”)
   a. The Mars Technology Program shall develop terminal phase hazard avoidance and precision landing systems
   b. The Mars Technology Program shall develop mid-L/D aeroentry/aerocapture systems
   c. The Mars Technology Program shall develop high-Mach parachute systems
   d. The Mars Technology Program shall develop human-scale rover systems
   e. The Mars Technology Program shall develop deep drilling systems
   f. The Mars Technology Program shall develop in-situ propellant and consumables production systems
   g. The Mars Technology Program shall develop systems to access to and extract water from soils, regolith, and groundwater systems
   h. The Mars Technology Program shall develop life detection instruments
   i. The Mars Technology Program shall develop ppm detectors for Cr VI, Cd, As
   j. The Mars Technology Program shall develop sub-ppb detectors for organic carbon
Safe on Mars – Precursor Measurements Necessary to Support Human Operations on the Martian Surface

National Research Council Report
(May 2002)
Summary Briefing

John Connolly/JSC
September 6, 2002
Summary Results

- **Highest priority is to measure radiation (charged particles and neutrons) on the Martian surface.**
  - “The committee recommends that this in-situ test be made a priority in the Mars program and conducted as soon as reasonable possible.”

- **Additionally:**
  - Map the landing operations area for humans in sufficient detail to identify hazards
  - Measure certain mechanical and adhesive properties of Martian soil and dust
  - Measure the concentrations of certain hazardous heavy metals (Cr VI)
  - Measure soil Ph and buffer capacity
  - Determine the presence and concentration of organic carbon

- **If the measurements recommended by the Committee can be performed in-situ on Mars surface, and if no organic carbon is detected above the life detection threshold, no sample return is required prior to the first human visit**
Background

- The NASA-sponsored Mars Exploration Program/Payload Analysis Group (MEPAG) produced a FY2000 document detailing the Martian environmental data sets required to prepare for human exploration of Mars.

- The NRC was tasked by NASA to independently answer a similar question:
  - Examine the role of robotic Mars exploration missions in assessing the risks to human exploration of Mars due to possible environmental, chemical and biological agents on the planet.
  - Consider how the Mars robotic program can provide answers to mitigate these risks prior to a human mission.
  - Document the measurements which must be made on Mars prior to the first human mission.

- The new NRC report is a Mars-focused follow-on to the NRC’s 1993 report “Scientific Prerequisites for the Human Exploration of Space.”

- The committee presented only the requirements “essential” for NASA to pursue in order to mitigate possible hazards to the first humans to Mars.

- The committee presented the results of this report to Orlando Figueroa, John Rummel, HQ Code M and S reps on April 29th, 2002.
The recommendations were divided into three categories:
- Physical Environment Hazards
- Chemical Environment Hazards
- Potential Biological Environment Hazards

Additional comments were offered on two other topics:
- Rover Technologies and Robotics
- Risk Standards

“The requirements identified in this report are indeed the only ones essential for NASA to pursue in order to mitigate potential hazards to the first human missions to Mars”
Physical Environment Hazards

Recommendation

- Map the 3-dimensional terrain morphology of landing operation zones for human missions.
- Determine rock size distribution and shape in-situ at the (human mission) landing site.
- Characterize the range of mechanical properties of the Martian regolith at the landing site or comparable terrain. Specifically, perform experiments to determine the regolith’s aggregate strength, stability, bearing strength, bulk modulus, yield strength, and internal friction angle.
- Determine the adhesive properties of Martian soil and airborne dust.
- Perform experiments to measure the absorbed radiation dose in a tissue-equivalent material on Mars at a location representative of the expected (human mission) landing site. These experiments should be made a priority in the Mars Exploration Program.

Recommended implementation

- Imaging from orbit
- Surface in-situ measurement
- Surface in-situ measurement
- Surface in-situ measurement
- Surface in-situ measurement
### Chemical Environment Hazards

#### Recommendation

- **Conduct a precursor in-situ measurement** to determine if hexavalent chromium is present in the Martian soil or airborne dust at more than 150 ppm. This measurement may take place anywhere on Mars where well-mixed, uniform airborne dust is present. If such a measurement is not possible, a sample of airborne dust and fine particles of Martian soil must be returned to earth for evaluation.

- **Measure the pH and buffer capacity of soil and airborne dust** either via an in situ experiment or on Earth with returned samples.

#### Recommended implementation

- **Surface in-situ measurement; returned sample if in-situ measurement is not possible**

---

**MECA wet laboratory.** Built for 2001 lander.

**Sample Wheel Mechanism.**

**MOD/MECA/TEGA instrument proposed for 2003 lander.**
Potential Biological Environment Hazards

**Recommendation**

- **Conduct a precursor in situ experiment at a location as reasonably close to the human mission landing sites as possible to determine if organic carbon is present.**
  - Measure materials from the surface and down to a depth to which astronauts may be exposed.
  - If no measurement technique can be used to determine if organic carbon is present above the life detection threshold (to be set by NASA, but 0.1 ppb example quoted), or if organic carbon is detected above that threshold, a sample should be returned to Earth for characterization prior to sending humans to Mars.
    - If experiments determine that organic carbon is present in concentrations greater than the life detection threshold the subsurface soil should be considered a toxic hazard until proven otherwise.
    - NASA must then determine which compounds constitute the organic carbon by returning a sample from that specific location to Earth.

---

**Recommended implementation**

- **Surface in-situ measurement; returned sample if in-situ measurement is not possible or if organic carbon is detected**

---

**Mars Organic Detector instrument selected for 2003 lander (1999).**
**Cancelled following MPL failure.**
Programmatic Topics

- **Rover Technologies and Robotics**
  - NASA’s current focus on small, slow robotic rovers with short lifetimes and modest power supplies does not provide an adequate research base for the development of the rovers needed for the human exploration of Mars.
  - The engineering knowledge being gained from the science rover experience will not scale up nor will it easily apply to human assistant rovers or larger human transport rovers.
- **Risk Standards**
  - Because NASA has not allocated risk factors and reliability requirements for missions beyond Earth orbit, it should establish risk standards necessary to provide preliminary guidance to Mars mission planners and hardware designers.
- **Technology Assumptions**
  - Static discharge system
  - Filtration systems
  - Humidification systems
- **“Press Ahead”**
  - “The Committee believes that, even should a sample be required because organic carbon has been found, a baseline plan for a mission to Mars and even hardware development may still proceed under the assumption that a sample return will not find anything significant enough with regard to Martian biology to invalidate the baseline mission plan.”
Is it necessary to return a Martian soil and/or airborne dust sample to Earth prior to the first human mission to Mars to assure astronaut health and safety?

- If the measurements recommended by this report can be performed in-situ on Mars surface, and if no organic carbon is detected above the life detection threshold, no sample return is required prior to the first human visit.

- If a precursor in-situ organic carbon experiment indicates the presence of organic carbon on Mars above the life detection threshold, a sample must be returned to Earth from the location and depth where the organic carbon is discovered if no suitable life-form confirmation technologies are available.
Map to MEPAG (1)

**MEPAG**

**GOAL IV: PREPARE FOR HUMAN EXPLORATION**

**A. Objective: Acquire Martian environmental data sets**

1. **Investigation: Determine the radiation environment at the Martian surface and the shielding properties of the Martian atmosphere.**
   **Measurements**
   a. Measure charged particle spectra, at the surface and in orbit, accumulated absorbed dose and dose rate in tissue as a function of time over time, particularly at solar maximum and solar minimum.
   b. Determine the radiation quality factor, determine the energy deposition spectrum from 0.1 keV/um to 1500 keV/um, and separate the contributions of protons, neutrons, and HZE particles to these quantities.
   c. Measure neutron energy spectrum from 100 keV to 50 MeV or above. The ability to obtain information on the source of the neutrons (depth in soil, atmosphere) is a strongly desirable feature and therefore provisions for assessing direction of incidence of the neutrons is required.
   d. Simultaneous surface and orbital measurements are required to determine the shielding component of the atmosphere.
   e. Simultaneously measure the atmospheric pressure at the surface of Mars and the atmospheric dust loading.
   f. Measure the natural radioactivity of the planet’s surface materials (soil and rocks).

2. **Investigation: Characterize the chemical and biological properties of the soil and dust.**
   **Measurements**
   a. In situ determination of the toxic trace elements and mineral species including, but not limited to As, Be, Cd, Cl, F, and Pb.
   b. Determine the toxic and genotoxic potential of dust and soil to biological cell analogs (enzymes, lipids, nucleic acids, etc), to identify reactivity of quasi-cellular systems from which the potential for acute toxicity for human explorers could be inferred.
   c. Determine the chemical reactivities with a sensitivity of ppm (of particular interest are changes in the reactivities upon heating, with exposure to humidity, and with emphasis on the identification and volatility of the gases evolved) and, up to a maximum depth of 150 cm. Understand the solubility in water of martian soil (total weight loss after water is equilibrated with the soil), the before and after composition of the soil, and the composition of the aqueous phase in equilibrium with Martian soil.
   d. Determine the depth of the superoxidation zone at several locations.
   e. **In situ** sensors or analytical tools to determine the content of carbon and complex organic compounds in wind-blown dust, surface soil, and materials from secluded environments to a sensitivity of 10 (?) PPM.
   f. Biohazard assessment.
   g. Determine physical properties (size, shape, hardness, adhesion) of representative dust samples.

**NRC**

**• Highest priority NRC recommendation**
- Measure radiation at surface (charged particles and neutrons) in a tissue-equivalent material
  - Energy spectrum not specified
  - Simultaneous measurement from orbit inferred by the detailed description of transport code calibration?
- No requirement for atmospheric pressure or dust loading measurement

**• NRC recommends measurement of Chromium VI concentration**
- Report also cites As, Cd and other cancer-causing compounds
  - **NRC recommends measurement of organic carbon to a depth which humans will be exposed**
  - **NRC recommends measuring the Ph and buffer capacity of Martian soil and dust**
  - No requirement to measure mechanical properties of dust EXCEPT adhesive properties
3. Investigation: Understand the distribution of accessible water in soils, regolith, and Martian groundwater systems. Requires geophysical investigations and subsurface drilling and in situ sample analysis.

**Measurements**

a. Map the Martian subsurface for ice and liquid water reservoirs.
b. Measure the vertical distribution (and ultimately comprehensive 3-dimensional subsurface maps) of permafrost, water ice and liquid water with a vertical resolution of ~ 10 m at selected sites.
c. Determine the adsorbed and bound water content of soil samples from several provenances (air-borne dust, surface fines, sand dunes) with precision of ±10% down to levels of 0.1%. Determine the release temperature of water over the range 0°C-600°C.

4. Investigation: Measure atmospheric parameters and variations that affect atmospheric flight. Requires instrumented aeroentry shells or aerostats.

**Measurements**

a. Measure and record pressure versus altitude, and temperature for all Mars entry vehicles during the E/D/L phase of the mission.
b. Measure basic surface meteorology: temperature, pressure, wind speed and direction at different sites.
c. Monitor global weather patterns from orbit.
d. Measure the frequency and magnitude of dust storms selected surface locations; characterize the processes active in these storms in terms of the associated wind speeds, pressure changes, atmospheric dust loading.
e. Detect local atmospheric vorticity in terms of frequency of local "dust devil" development, quantity of dust lofted, associated wind speeds and pressure differentials.

5. Investigation: Determine electrical effects in the atmosphere. Requires experiments on a lander.

**Measurements**

a. Measure the electrical properties of dust in the atmosphere and observe the consequences of dust electrification.
b. Determine the atmospheric electrification due to turbulent motion in dust clouds and dust storms; determine the population of atmospheric ions and whether there is a diurnal variation; determine what types of discharges occur on Mars.
c. Determine the electrostatic charge state (magnitude, sign, and longevity of charges) for both aerosols and soil particles up to 100 microns.
d. Determine Paschen curves (electrical breakdown in gases) for Mars as a function of temperature, pressure, wind, dust load in atmosphere, and season for meteorological use and as a tool for designing and safeguarding equipment for Mars exploration.

**Table:**

<table>
<thead>
<tr>
<th>MEPAG</th>
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<tbody>
<tr>
<td>3. Investigation: Understand the distribution of accessible water in soils, regolith, and Martian groundwater systems. Requires geophysical investigations and subsurface drilling and in situ sample analysis.</td>
<td>• No requirement to measure water accessibility</td>
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<td><strong>Measurements</strong></td>
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# Map to MEPAG (3)

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<tr>
<td><strong>6. Investigation:</strong> Measure the engineering properties of the Martian surface. Requires in-situ measurements at selected sites. <strong>Measurements</strong>&lt;br&gt;a. Measure soil bearing strength and surface penetration resistance.&lt;br&gt;b. Measure soil cohesion and angle of repose.&lt;br&gt;c. Measure soil magnetic and electrostatic properties (adhesion potential, strength of adhesion and character of the charge).&lt;br&gt;d. Measure surface temperature and touch temperature of surface features.&lt;br&gt;e. Measure surface heat capacity.&lt;br&gt;f. Measure surface albedo.&lt;br&gt;g. Measure surface thermal conductivity/insulation properties.&lt;br&gt;h. Determine the particle size and distribution, in the range 0.01 to 10.0 microns (0.01 to about 10 cm surface depth), with higher emphasis on particles much smaller than 1.0 micron.&lt;br&gt;i. Determine the total columnar suspended load of dust in the atmosphere.&lt;br&gt;j. Measure average surface sink temperature.&lt;br&gt;k. Determine soil and dust chemical composition.&lt;br&gt;l. Measure the conductivity, resistivity, dielectric constant, and piezoelectric properties of the subsurface to a depth of 10 m as a function of latitude, time of year, and geological environment.&lt;br&gt;m. Measure subsurface distribution of ground ice.</td>
<td><strong>NRC recommends measuring the regolith’s aggregate strength, stability, and sinkage properties, including bearing strength, bulk modulus, yield strength, and internal friction angle.</strong>&lt;br&gt;<strong>No requirement to measure shielding properties of Martian regolith</strong>&lt;br&gt;<strong>No requirement to measure the ability to support plant life</strong>&lt;br&gt;<strong>NRC recommends mapping the 3-dimensional terrain morphology of landing operation zones</strong>&lt;br&gt;<strong>NRC recommends determining rock size distribution and shape in situ at the (human mission) landing site or on comparable terrain,</strong>&lt;br&gt;<strong>No requirement to measure the ability to support plant life</strong></td>
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<td><strong>7. Investigation:</strong> Determine the radiation shielding properties of Martian regolith. Some of the in situ measured properties may be verified with a returned sample. <strong>Measurements</strong>&lt;br&gt;a. Determine the radiation shielding characteristics of Martian regolith as a function of cover depth. Radiation sensors would be placed under various depth of regolith cover, and their readings correlated with an unburied sensor.</td>
<td><strong>NRC recommends measuring the regolith’s aggregate strength, stability, and sinkage properties, including bearing strength, bulk modulus, yield strength, and internal friction angle.</strong>&lt;br&gt;<strong>No requirement to measure shielding properties of Martian regolith</strong>&lt;br&gt;<strong>No requirement to measure the ability to support plant life</strong>&lt;br&gt;<strong>NRC recommends mapping the 3-dimensional terrain morphology of landing operation zones</strong>&lt;br&gt;<strong>NRC recommends determining rock size distribution and shape in situ at the (human mission) landing site or on comparable terrain,</strong>&lt;br&gt;<strong>No requirement to measure the ability to support plant life</strong></td>
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<tr>
<td><strong>8. Investigation:</strong> Measure the ability of Martian soil to support plant life. Requires in-situ measurements and process verification. <strong>Measurements</strong>&lt;br&gt;a. Conduct in situ process verification of plant growth experiment through full plant growth, seed and re-germination cycle.</td>
<td><strong>NRC recommends measuring the regolith’s aggregate strength, stability, and sinkage properties, including bearing strength, bulk modulus, yield strength, and internal friction angle.</strong>&lt;br&gt;<strong>No requirement to measure shielding properties of Martian regolith</strong>&lt;br&gt;<strong>No requirement to measure the ability to support plant life</strong>&lt;br&gt;<strong>NRC recommends mapping the 3-dimensional terrain morphology of landing operation zones</strong>&lt;br&gt;<strong>NRC recommends determining rock size distribution and shape in situ at the (human mission) landing site or on comparable terrain,</strong>&lt;br&gt;<strong>No requirement to measure the ability to support plant life</strong></td>
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<td><strong>9. Investigation:</strong> Characterize the topography, engineering properties, and other environmental characteristics of candidate outpost sites. Site certification for human outposts requires a set of data about the specific site that can best be performed by surface investigations. Specific measurements are listed in other investigations.</td>
<td><strong>NRC recommends measuring the regolith’s aggregate strength, stability, and sinkage properties, including bearing strength, bulk modulus, yield strength, and internal friction angle.</strong>&lt;br&gt;<strong>No requirement to measure shielding properties of Martian regolith</strong>&lt;br&gt;<strong>No requirement to measure the ability to support plant life</strong>&lt;br&gt;<strong>NRC recommends mapping the 3-dimensional terrain morphology of landing operation zones</strong>&lt;br&gt;<strong>NRC recommends determining rock size distribution and shape in situ at the (human mission) landing site or on comparable terrain,</strong>&lt;br&gt;<strong>No requirement to measure the ability to support plant life</strong></td>
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<tr>
<td><strong>10. Investigation:</strong> Determine the fate of typical effluents from human activities (gases, biological materials) in the Martian surface environment. <strong>Measurements</strong>&lt;br&gt;a. Determine the rate of reaction of typical materials exposed to the Martian environment.&lt;br&gt;b. Monitor the rate of dispersion of analog materials in the Martian environment.</td>
<td><strong>NRC recommends measuring the regolith’s aggregate strength, stability, and sinkage properties, including bearing strength, bulk modulus, yield strength, and internal friction angle.</strong>&lt;br&gt;<strong>No requirement to measure shielding properties of Martian regolith</strong>&lt;br&gt;<strong>No requirement to measure the ability to support plant life</strong>&lt;br&gt;<strong>NRC recommends mapping the 3-dimensional terrain morphology of landing operation zones</strong>&lt;br&gt;<strong>NRC recommends determining rock size distribution and shape in situ at the (human mission) landing site or on comparable terrain,</strong>&lt;br&gt;<strong>No requirement to measure the ability to support plant life</strong></td>
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Conclusions

- The 2002 NRC study gives priority to the many measurements listed in the 2000 MEPAG document

\[ \text{NRC} \subset \text{MEPAG} \]

- Characterizing the radiation at the surface of Mars continues to be the highest priority
- Organic carbon detection will determine if a sample return is needed prior to the first human mission
- Prior to MCO/MSL failures, a cooperative (Code S/U/M) program was in place to obtain these data sets
- Current Mars Exploration Program is not explicitly addressing these data needs
Recommended Actions

- In-situ radiation measurement at the earliest opportunity
- In-situ measurement of genotoxic elements and compounds (Cr VI, Cd, As)
- In-situ measurement of organic carbon
- Technology efforts required for:
  - Instruments
    - Life detection
    - ppm detectors for Cr VI, Cd, As
    - ppm detectors for organic carbon
  - Human Systems
    - Static discharge system
    - Habitat filtration systems
    - Habitat humidification systems
    - Human-scale rovers
Launch Vehicle Capability Trade Study

Presented To: Gary Martin

NASA Headquarters
April 25, 2003
## Presentation Outline

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<th>Presenter</th>
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<td>Phil Sumrall</td>
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<td>Launch Vehicles</td>
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<td>Earth’s Neighborhood Mission</td>
<td>Jim Geffre</td>
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<td>Accessible Planetary (Mars) Surface Mission</td>
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<td>Wrap-up</td>
<td>Phil Sumrall</td>
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Launch Vehicle Capability Trade Study

Background

• Doug Cooke requested on January 17, 2003 that a trade study of HLLV sizing for exploration missions be undertaken.

• Study should be MSFC-led and performed by an inter-center team, taking maximum advantage of existing data.

• Study should address delivery of complete assemblies, assembly on-orbit, fuel delivery, etc.

• Trades should consider cost, mission risk, and other figures of merit.

• Study scope and trade space should be planned to provide for a March, 2003 deliverable.
Launch Vehicle Capability Trade Study

Approach

- Two missions selected for study (data exists, represent wide scope of mission requirements):
  - Earth’s Neighborhood (Sun-Earth L2 Telescope Mission)
  - Accessible Planetary (Mars) Surface (Human Mars Exploration Mission)

- Launch vehicle definitions will be taken from recently completed “Architecture Study Number One”, ELVs, etc.

- Figures of Merit (FOM) will be derived for this study using NExT FOM as a point of departure.

- Independently assess the launch vehicle capabilities (performance, volume) against the reference missions to establish operational scenarios.

- Populate the FOM matrix to the extent possible within the study constraints.
Launch Vehicle Capability Trade Study

Products

• Assessment of EELV-Heavy and Heavy Lift Launch Vehicle (HLLV) capabilities with respect to two reference missions: Earth’s Neighborhood and Accessible Planetary (Mars) Surface

• New FOM for ETO launch vehicles

• Assessment of gaps in current study and identification of future work to fill the gaps
## Launch Vehicle Capability Trade Study

### Participants

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<tr>
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<tr>
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<td>321-867-2565</td>
<td><a href="mailto:Warren.I.Wiley@NASA.gov">Warren.I.Wiley@NASA.gov</a></td>
</tr>
</tbody>
</table>
Ground Rules and Assumptions

• Mission Requirements
  - Earth’s Neighborhood: 2 missions per year
  - Accessible Planetary (Mars) Surface: 1 mission every launch opportunity (26 months)
    • Utilize a 450 metric tons (mt) IMLEO Mars Mission
    • Assumes aggressive technology implementation

• Launch Vehicle Assumptions
  - EELV Heavy (Delta or Atlas)
  - Shuttle-Derived HLLV
  - Crew Transfer with OSP/EELV Heavy

• All In-Space Mission Assembly Accomplished at ISS (Assumed, not necessarily recommended)

• Assess Launch Vehicle Trades thru Mission Assembly only
# Figures of Merit

| Performance                                                                 | Safety                                                                 | Technology                                                            | Schedule                                                                 | Cost                                                                 |
|----------------------------------------------------------------------------|------------------------------------------------------------------------|                                                                     |                                                                         |                                                                      |
| Provides the most flexibility for meeting future human exploration and development of space needs | Ensures crew safety and mission assembly completion                     | Entails lowest technology risk                                         | Provides shortest assembly timeline and least schedule risk            | Provides lowest initial and/or total life cycle costs                 |
| • Station utilization impact                                               | • Launch reliability                                                   | • Launch vehicle technologies required                               |                                                                         |                                                                      |
| • Payload mass                                                             | • Complexity of on-orbit assembly                                       | • Assembly and certification of complex interfaces (e.g. aerobrakes)  |                                                                         |                                                                      |
| • Payload volume                                                           | • Number of assembly flights                                           | • Architectural technology advancements required                       |                                                                         |                                                                      |
| • Number of launches                                                       | • Number of supporting EVA’s                                           | • Launch rate                                                         |                                                                         |                                                                      |
|                                                                              | • Means of crew delivery                                               | • Launch processing                                                   |                                                                         |                                                                      |
|                                                                              |                                                                        | • Test and checkout                                                   |                                                                         |                                                                      |
|                                                                              |                                                                        | • On-orbit assembly                                                   |                                                                         |                                                                      |
|                                                                              |                                                                        | • Launch window constraints                                           |                                                                         |                                                                      |
|                                                                              |                                                                        | • Launch reliability                                                  |                                                                         |                                                                      |
|                                                                              |                                                                        |                                                                          |                                                                         |                                                                      |
|                                                                              |                                                                        |                                                                          |                                                                         |                                                                      |
|                                                                              |                                                                        |                                                                          |                                                                         |                                                                      |

- DDT&E & Recurring
- Launch & Ground Operations
- In-space Operations (Not quantified)
- Additional Support Flights and Elements
- Cost of unreliability
- Synergy with other mission requirements
Launch Vehicle Capability Assessment

Performance
- Increased payload mass and volume and reduced number of launches is viewed as positive.
- Reduced number of assembly flights to the Station should have least impact on Station utilization.

Safety
- Increased launch reliability increases probability of mission success and crew safety.
- Increased number of assembly flights reduces probability of mission success and crew safety.
- Increased complexity of on-orbit assembly reduces probability of mission success.
- Increased number and complexity of supporting EVA’s reduces crew safety.
Technology

• Neither launch vehicle capability is viewed as having technology risks.

• Increased number of flights and complexity of assembly drives need for increased technology risk for mission assembly.

• The chosen Accessible Planetary (Mars) Surface Mission case assumes significant technology breakthroughs. Failure to achieve these technology breakthroughs increases other risks associated with reduced launch capabilities.

• Complexity of on-orbit assembly tasks and interfaces, e.g. aerobrakes, has a significant adverse impact on technology risk.
Launch Vehicle Capability Assessment (cont.)

Schedule

• Increased launch rates, launch processing, test and checkout, and on-orbit assembly increase schedule risks.
• Increased on-orbit assembly increases risk associated with launch window constraints.
• Reduced launch reliability increases schedule risk associated with mission assembly.

Costs

• DDT&E and Recurring
• Infrastructure: ground processing, production capacity, on-orbit assembly
• Support flights and elements
• Cost of unreliability
• Synergy with other mission launch requirements
On-Orbit Assembly Key Functional Requirements

- Provide capability to assemble, checkout, and maintain vehicle elements (either on the ground or in-space) prior to departure for exploration destinations
- Provide capability for housing transient mission crew, support crew, and mission equipment
- Provide capability to process exploration mission elements by supporting the following:
  - Vehicle mating/assembly and de-mating/disassembly
  - Space construction of elements
  - Element and integrated vehicle on-orbit check-out
  - Maintenance and servicing of elements
  - Provide housekeeping resources and services to elements and vehicles
  - Loading and unloading of mission equipment
- Provide capability to support on-orbit supply and re-supply of:
  - Life support consumables
  - Propellants
  - Mission equipment
- Provide debris protection for assembly elements and in-space vehicles while resident at the ISS
Mission Classes

Accessible Planetary (Mars) Surface

Earth’s Neighborhood

Getting Set by Doing
• Traveling up to 1.5 million km
• Staying for 50-100 Days
• Enabling Large Optical Systems
• Living in Deep Space

Going for Visits
• Traveling up to 1.5 AU
• Mission Duration of 1-3 Years
• Enabling Tactical Investigations
• Visiting and Working on Another Planet
Observations and Findings

Earth’s Neighborhood Mission
• A heavy lift launch capability is favored by all Figures of Merit and is highly enhancing for this class of mission.
• Assessment of investment in on-orbit assembly vs heavy lift capability is needed.
• Number of launches of EELV-H to support Earth’s Neighborhood is about the same as number of Heavy Lift launches needed to support the Accessible Planetary (Mars) Surface Mission.
• Investment costs of EELV-H borne by other mission applications.

Accessible Planetary (Mars) Surface Mission
• A heavy lift launch capability is enabling for this class of mission.
• Feasibility of using Station to support magnitude of on-orbit assembly highly uncertain.
• Feasibility of successfully assembling subassemblies into major elements such as aerobrakes, NEP, and habitats is highly uncertain.
• Risks and costs associated with unreliability is significant for launch rates associated with EELV-H vehicle class.

General
• Life cycle cost assessment incomplete for both mission classes and vehicle options.
• A vehicle trade study is needed to assess a range of vehicle and propulsion concepts to identify the preferred approach for a HLLV capability.
Heavy Lift Launch Vehicle (HLLV) Options

Shuttle-Derived HLLV Class

Atlas V 552

EELV Heavy Class

Delta IV-H

Shuttle-Derived HLLV
Atlas V Heavy Launch Vehicle Configuration

Vehicle Configuration:
- Common Core Booster in Production
- Common Core Booster:
  - Lox RP-1
  - RD-180 engine
  - 933,370 lbf thrust (Vac)
  - $I_{sp}$ 338 sec (Vac)
- Payload: 20.6 mt (45k lbm) to 185 km Circ @ 28.5°
  - 17.0 mt (37k lbm) to 460 km Circ @ 51.6°
- Payload Fairing: 17.7’ x 76.8’ (5.4m x 23.4m)

Upperstage:
- Pressure stabilized tanks
- Cryogenic RL-10A-4-2
  - 22,300 lbf thrust (Vac)
  - $I_{sp}$ 450 (Vac)
- .021k mt (45,826 lbm) propellant loading
- Engine restart capability

Performance data limited to 6g’s, minor performance loss for 3g’s

Further analysis is required to better define the influence of various launch vehicle concepts with architectural performance, risk, schedule and cost.
Vehicle Configuration:
- Common Core Booster In Production
- Common Core Booster:
  - LH₂/ Lox
  - RS-68
  - 745,000 lbf thrust (Vac) ea booster
  - ISP 410 sec (Vac)
- Payload: 22.5 mt (50k lbm) to 185 km Circ @ 28.5°
  - 22.5 mt (50k lbm) to 460 km Circ @ 51.6°
- Payload Fairing: 16.4’ x 65.0’ (5.0m x 19.8m)

Upperstage:
- RL-10B-2
  - LH₂/ Lox
  - 24,750 lbf thrust (Vac)
  - ISP 466 sec (Vac)
- .027k mt (60,000 lbm) propellant loading
- Engine restart capability

Performance data limited to 6g’s, minor performance loss for 3g’s

Further analysis is required to better define the influence of various launch vehicle concepts with architectural performance, risk, schedule and cost.
Shuttle-Derived HLLV Configuration

Vehicle Characteristics
Cargo Only
Payload (56 x 278 km @ 28.5°) 93.5 mt (.206 mlbs)
Payload (56 x 460 km @ 51.6°) 85.0 mt 9.187 mlb
Gross Liftoff Mass 2.4k mt (5.4 mlb)
T/W @ Liftoff 1.40
Max Q 646 psf
Max Acceleration 3.8 g
Shroud Mass N/A
Payload Fairing 25' X 90' (7.62m x 27.43m)

Booster (5-segment):
Propellants HTPB
Ascent Propellant Mass 1.3k mt (2.9 mlb)
Burnout Mass .195k mt (.430 mlb)
Separation Conditions Mach= 4.8, Q= 17.0 psf, alt= 177 kft
Sea Level Thrust 3.33 mlb each
Sea Level Isp 265 sec

External Tank (SLWT w/ 5 ft stretch):
Propellants LO2/LH2
Ascent Propellant Mass .762k mt (1.68 mlb)
Burnout Mass .063k mt (140.4 mlb)
Engines 3 SSME Engines (104%)
Vacuum Thrust 492 klb ea Vac Isp= 453 sec
Sea Level Thrust 397 klb ea SL Isp = 365 sec

The vehicle shown above was used in this study as representative of the Shuttle-Derived HLLV Class of heavy lift vehicles.

Further analysis is required to better define the influence of various launch vehicle concepts with architectural performance, risk, schedule and cost.
Exploration Launch Assumptions

• Launch Vehicle Maximum Payload
  - Delta IV-H: 22.5 mt (50k lbm) to 185 km Circ @ 28.5°
    22.5 mt (50k lbm) to 460 km Circ @ 51.6°
  - Atlas V 552: 20.6 mt (45k lbm) to 185 km Circ @ 28.5°
    17.0 mt (37k lbm) to 460 km Circ @ 51.6°
  - Shuttle-Derived HLLV: 93.5 mt (206k lbm) to 56 x 278 km Ellip @ 28.5°
    85.0 mt (187k lbm) to 56 x 460 km Ellip @ 51.6°

• Launch Reliability
  - EELV-H: 98%
  - Shuttle-Derived HLLV: 99%

• Launch Cost
  - EELV-H (Cargo): $140M
  - EELV-H (OSP): $300M
  - Shuttle-Derived HLLV: $800M

• Other
  - 70% launch vehicle packaging efficiency
  - One OSP support flight per 3 Cargo flights and one OSP flight per mission for mission crew positioning

Further analysis is required to better define the influence of various launch vehicle concepts with architectural performance, risk, schedule and cost.
### Launch Vehicle Capability Trade Study Comparison Matrix

<table>
<thead>
<tr>
<th>Concept Configuration</th>
<th>Concept Description</th>
<th>Performance (Destination)</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
</table>
| Shuttle-Derived HLLV  | 1.5 Stage Vehicle  
- Sidemount Payload Carrier  
- 25' x 90' Pld envelope  
- ET LOX/LH2 Core  
- 5 ft. stretch LH2 tank  
- 3 SSME Engines on Carrier  
- 2 Five-Segment SRBs  
- Launch Cost $800M  | 93.5 mt (206k lbm)  
(56 x 278 km Ellipt.. @28.5°)  
85.0 mt (187k lbm)  
(56 x 460 km Ellipt.. @51.6°)  | - Uses ET Design Heritage/Facilities  
- Uses Existing Engines  
- Greater Payload Delivery Capability  
- Mass  
- Volume  
- SRBs Recovered  | - Higher Unit Cost  
- SSME Expended  
- Ground Processing Concerns with Solids  
- Higher Dollars per Pound to Orbit  
- Not an Existing LV, will Require DDT&E  
- Mods Required to VAB and SRB Facilities  
- Conflict with Ongoing Shuttle Processing |
| Delta IV-H            | 2.5 Stage Vehicle  
- 5 meter Payload Fairing  
- RL10B-2 Second Stage Eng.  
- In-line Payload Fairing  
- LOX/LH2 Booster Core  
- 2 Additional Strap-on LRBs  
- Launch Cost $140M to $170M  | 22.5 mt (50k lbm)*  
(185 km Circ.. @28.5°)  
22.5 mt (50k lbm)  
(460 km Circ.. @51.6°)  | - Existing Common Core Booster  
- Uses Existing Facilities  
- Lower Unit Cost  
- Has Growth Potential  
- Lower Dollars per Pound to Orbit  
- Safer Handling of Boosters  | - Less Payload Delivery Capability  
- Mass  
- Volume  
- Several Launches Required for Missions  
- # of Launches becomes a Design Driver  
- More Infrastructure for High Launch Rates |
| Atlas V 552          | 2.5 Stage Vehicle  
- 5 meter Payload Fairing  
- 2-engine Centaur 2nd Stage  
- In-line Payload Fairing  
- LOX/RP Booster Core  
- 5 Strap-on SRBs  
- Launch Cost $110M  | 20.6 mt (45k lbm)  
(185 km Circ.. @28.5°)  
17.0 mt (37k lbm)  
(460 km Circ.. @51.6°)  | - Existing Common Core Booster  
- Uses Existing Facilities  
- Lower Unit Cost  
- Has Growth Potential  
- Lower Dollars per Pound to Orbit  | - Less Payload Delivery Capability  
- Mass  
- Volume  
- Several Launches Required for Missions  
- # of Launches becomes a Design Driver  
- More Infrastructure for High Launch Rates  
- Ground Processing Concerns with Solids |

* A loft requirement to establish a line-of-sight with the tracking station results in a decrease in performance at lower altitudes.

Further analysis is required to better define the influence of various launch vehicle concepts with architectural performance, risk, schedule and cost.
Earth’s Neighborhood Mission
Earth’s Neighborhood Mission Description

**Architecture**

**Elements**

**Exploration Transfer Vehicle & High Energy Injection Stage**
- Transports crew and cargo between ISS and Lunar L₁
- Nominal return to ISS with contingency direct Earth return

**L₁ Gateway Outpost**
- “Gateway” to the Lunar surface
- Outpost for staging missions to Moon, Mars and telescope construction

**Astronomical Instruments**
- Advanced science platforms to be assembled and/or serviced by humans and robots
- Platforms remotely deployed to Sun-Earth L₁/L₂

**Crew departs from and returns to ISS**

**Earth-Moon L₁**

**Low-Energy Transfer “Interplanetary Superhighway” (Uncrewed)**

**Sun-Earth L₁/L₂**

**Moon**
Earth-Moon L_1 Characteristics

Environment
- No orbital debris. Weak instability of L_1 will actively remove artificially created debris.
- Nearly continuous solar energy (>99.91%), no thermal cycling
- Nearly continuous full sky viewing (>99.96%)
- True deep space radiation, thermal environment, zero-g
- Continuous view of Lunar nearside, Earth, terrestrial magnetosphere

Operations
- Excellent transportation node for lunar surface, particularly polar regions
- Four days from Earth, two days from Moon (high thrust)
- Low-energy access to/from Solar Libration Points

<table>
<thead>
<tr>
<th>L_i</th>
<th>Distance from Earth's Center (km)</th>
<th>Distance from Moon's Center (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L_1</td>
<td>326740</td>
<td>57660</td>
</tr>
<tr>
<td>L_2</td>
<td>449748</td>
<td>65348</td>
</tr>
<tr>
<td>L_3</td>
<td>380556</td>
<td>764956</td>
</tr>
<tr>
<td>L_4</td>
<td>384400</td>
<td>384400</td>
</tr>
<tr>
<td>L_5</td>
<td>384400</td>
<td>384400</td>
</tr>
</tbody>
</table>
**Sun-Earth L2 Characteristics**

**Environment**
- No orbital debris. Weak instability of L₂ will actively remove artificially created debris.
- Continuous solar energy, no thermal cycling
- Continuous full sky viewing
- True deep space radiation, thermal environment, zero-g

**Operations**
- Identified as advantageous location for advanced astronomical facilities
- Eighteen days from Earth (high thrust)
- Low-energy access to/from Lunar Libration Points
Ground Rules and Assumptions

• Science objectives and precursor requirements will be optimally integrated to meet the overall program science strategy

• Support multiple destinations
  ➢ Sun-Earth L1/L2 (operational location for astronomical instruments)

• Serve as a test bed for future exploration
  ➢ Technologies
  ➢ Operations
  ➢ Systems

• Crew size of 6

• Use ISS as a low-Earth orbit assembly and staging location

• Assemble, checkout, and maintain astronomical observatories in-space
Exploration Transfer Vehicle (XTV)

XTV Service Module

- **Launch Mass:** 2,810 kg (6196 lbm) (dry) / 16,295 kg (35.9k lbm) (wet)
- **Special Launch Considerations:** Contains cryo propellants (O2/CH4)
- **# of Launches:** Once per Mission
- **Total ΔV:** 2,405 m/s

XTV Crew Module

- **Launch Mass:** 10,150 kg (2.3k lbm)
- **Special Launch Considerations:** None
- **# of Launches:** 1 (remains docked to ISS)
Architecture Elements

**Insertion Orbit:** ~400 km circ x 51.6°

**Launch Mass:** 6,910 kg (15.2k lbm) (dry) / 44,095 kg (97k lbm) (wet)

**Special Launch Considerations:** Contains cryo propellants (O2/H2)

**# of Launches:** Once per Mission

**Total ΔV:** 3,120 m/s
Architecture Elements

L1 Gateway

Insertion Orbit: ~400 km circ x 28.5°

Launch Mass: 23,400 kg (51.6k lbm)

Special Launch Considerations: Requires Shuttle Outfitting Mission, Inflatable Section Deflated

# of Launches: Once

Total ΔV: Station-keeping (50 m/s/year)
## Earth’s Neighborhood Mission

### Mission Launch Summary

<table>
<thead>
<tr>
<th></th>
<th>EELV-H</th>
<th>Shuttle-Derived HLLV</th>
<th>EELV-H</th>
<th>Shuttle-Derived HLLV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Launch Vehicle Use</strong></td>
<td><strong>Useful Payload</strong></td>
<td></td>
<td><strong>Useful Payload</strong></td>
<td></td>
</tr>
<tr>
<td>Annual</td>
<td>$3.20B</td>
<td>72%</td>
<td>$2.20B</td>
<td>94%</td>
</tr>
<tr>
<td>Per Mission</td>
<td>$1.60B</td>
<td>85%</td>
<td>$1.10B</td>
<td>97%</td>
</tr>
<tr>
<td><strong>Flight Rate</strong></td>
<td>10 / 6 / 16</td>
<td>2 / 2 / 4</td>
<td>5 / 3 / 8</td>
<td>1 / 1 / 2</td>
</tr>
<tr>
<td>(Cargo/OSP/Total)**</td>
<td><strong>Recurring</strong></td>
<td></td>
<td><strong>Launch Cost</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Probability of Launch Success</strong></td>
<td>72%</td>
<td>94%</td>
<td>85%</td>
<td>97%</td>
</tr>
<tr>
<td><strong>Recurring Launch Cost</strong></td>
<td>$3.20B</td>
<td>$2.20B</td>
<td>$1.60B</td>
<td>$1.10B</td>
</tr>
</tbody>
</table>

### Notes:
- Assumes 2 Earth’s Neighborhood missions per year
- Support flights assume launch by EELV + OSP
- * Includes 70% launch packaging efficiency
- ** One OSP support flight assumed for every 3 cargo flights plus one OSP flight per mission to position mission crew
Earth’s Neighborhood Mission

EELV - H

Shuttle-Derived HLLV

Cargo

OSP

Mission Flights

Yearly Flights

Mission Flights

Yearly Flights
### Summary FOM Assessment

<table>
<thead>
<tr>
<th>Perf</th>
<th>Safety</th>
<th>Technology</th>
<th>Schedule</th>
<th>Costs*</th>
</tr>
</thead>
<tbody>
<tr>
<td>EELV Heavy</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Shuttle-Derived HLLV</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

*Annual recurring launch costs only. Further assessment of DDT&E, Infrastructure, and Ops costs are required.

### ADVANTAGE

- Minor
- Moderate
- Significant

### DISADVANTAGE

- Minor
- Moderate
- Significant

Further analysis is required to better define the influence of various launch vehicle concepts with architectural performance, risk, schedule and cost.
Summary FOM Assessment

- **Performance**: Shuttle-Derived HLLV capability eliminates on-orbit assembly, thereby improving probability of mission success.

- **Safety**: Elimination of on-orbit assembly EVA with Shuttle-Derived HLLV reduces crew risk.

- **Technology**: No requirement for advanced technology associated with on-orbit assembly with Shuttle-Derived HLLV.

- **Schedule**: Schedule time associated with assembly is eliminated with Shuttle-Derived HLLV.

- **Costs**: Requirement for more OSP flights to support EELV-H makes it the most costly approach.
Accessible Planetary (Mars) Surface Mission
Mars Architecture Key Attributes

• Crew of 6
• Short (30-day) initial visits for focused local science evolving to long (500-day) stays for extensive regional exploration
• Total mission durations range from 365 to 950 days.
• Capability to go to Mars any opportunity
• Maximum use of capabilities developed for Earth’s Neighborhood
• Ability to introduce new technologies as they are developed
• Advanced transportation and enhanced launch capacity required to reduce risk and architecture cost
The Value of Technology Investments
Mars Mission Example

NOTES:
• Results are cumulative and thus trends will be different for different technology combinations/sequences
• The change between points shows the relative mass savings for that particular technology

Mass Savings Normalized to ISS Mass

- All Propulsive Chemical
- Aero-capture
- Advanced Propulsion
- Closed Loop Life Support
- Advanced Materials
- Maintenance & Spares
- Advanced Avionics

Today
Size Comparison of Notional Mission Elements

**Piloted Vehicles**
- NTR Piloted Vehicle
- Mars Lander + Aerobrake
- Exploration Transfer Vehicle
- Reference Spacecraft (for Scale)
- Shuttle Orbiter

**High-Efficiency Transportation**
- Reference Spacecraft (for Scale)
- SEP Stage
- NEP Piloted Vehicle
- Reference Spacecraft (for Scale)
- ISS @ Assembly Complete

**Landers**
- Mars Descent/Ascent Vehicle
- Mars Habitat Lander
- Reference Spacecraft (for Scale)
- Apollo Lunar Module

Dimensions:
- 36 m
- 108 m
- 9.1 m

Section 8.1 JSC/P. Sumrall

Nov. 2002
## Accessible Planetary (Mars) Surface Mission

**Mission Launch Summary**

<table>
<thead>
<tr>
<th>Launch Vehicle</th>
<th>EELV-H</th>
<th>Shuttle-Derived HLLV</th>
<th>EELV-H</th>
<th>Shuttle-Derived HLLV</th>
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</thead>
<tbody>
<tr>
<td><strong>Launch Vehicle</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Useful Payload</strong></td>
<td>15,875 kg (35,004 lbm)</td>
<td>61,670 kg (135,982 lbm)</td>
<td>15,875 kg (35,004 lbm)</td>
<td>61,670 kg (135,982 lbm)</td>
</tr>
<tr>
<td><strong>Flight Rate</strong></td>
<td>18 / 7 / 25</td>
<td>5 / 3 / 8</td>
<td>29 / 11 / 40</td>
<td>8 / 4 / 12</td>
</tr>
<tr>
<td><strong>Probability of Launch Success</strong></td>
<td>60%</td>
<td>90%</td>
<td>45%</td>
<td>85%</td>
</tr>
<tr>
<td><strong>Recurring Launch Cost</strong></td>
<td>$4.62B</td>
<td>$4.90B</td>
<td>$7.36B</td>
<td>$7.60B</td>
</tr>
</tbody>
</table>

**Notes:**
- Assumes 1 Mars mission every opportunity (26-month frequency)
- All hardware launches are completed within a 20-month period
- Support flights assume launch by EELV + OSP
- * Includes 70% launch packaging efficiency
- ** One OSP support flight assumed for every 3 cargo flights plus one OSP flight per mission to position mission crew
Accessible Planetary (Mars) Surface Mission

EELV - H

<table>
<thead>
<tr>
<th>Cargo</th>
<th>EELV - H</th>
<th>Shuttle-Derived HLLV</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSP</td>
<td>Mission Flights</td>
<td>Yearly Flights</td>
</tr>
<tr>
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<td>Yearly Flights</td>
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## Summary FOM Assessment

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<tbody>
<tr>
<td>EELV Heavy</td>
<td>- - -</td>
<td>- -</td>
<td>- -</td>
<td>- - +</td>
</tr>
<tr>
<td>Shuttle-Derived HLLV</td>
<td>+ + +</td>
<td>+ +</td>
<td>+ +</td>
<td>+ + -</td>
</tr>
</tbody>
</table>

*Annual recurring launch costs only. Further assessment of DDT&E, Infrastructure, and Ops costs are required.

### ADVANTAGE
- Minor
- + Moderate
- ++ Significant

### DISADVANTAGE
- - Minor
- - - Moderate
- - - - Significant

Further analysis is required to better define the influence of various launch vehicle concepts with architectural performance, risk, schedule and cost.
Accessible Planetary (Mars) Surface Mission

Summary FOM Assessment

- **Performance:** Significantly fewer launches are required with Shuttle-Derived HLLV, thereby improving probability of mission success.

- **Safety:** Reduced number and complexity of assembly flights required with a Shuttle-Derived HLLV significantly enhances crew safety.

- **Technology:** The EELV-H increases the amount and complexity of on-orbit assembly of subassemblies such as the aerobrake, significantly increasing the technology risk.

- **Schedule:** Number of flights required by EELV-H significantly lengthens assembly schedule, increases schedule risks associated with launch windows, and increases the schedule risks associated with launch failures.

- **Costs:** Annual recurring launch costs associated with Shuttle-Derived HLLV is somewhat higher.
## Combined Earth’s Neighborhood & Accessible Planetary (Mars) Surface Missions

<table>
<thead>
<tr>
<th>Mission Launch Summary</th>
<th>EELV-H</th>
<th>Shuttle-Derived HLLV</th>
<th>EELV-H</th>
<th>Shuttle-Derived HLLV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual</td>
<td>Combined Per Mission</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Launch Vehicle Usefull Payload*</td>
<td>15,875 kg (35,004 lbm)</td>
<td>61,670 kg (135,982 lbm)</td>
<td>15,875 kg (35,004 lbm)</td>
<td>61,670 kg (135,982 lbm)</td>
</tr>
<tr>
<td>Flight Rate (Cargo/OSP/Total)**</td>
<td>28 / 13 / 41</td>
<td>7 / 5 / 12</td>
<td>34 / 14 / 48</td>
<td>9 / 5 / 14</td>
</tr>
<tr>
<td>Probability of Launch Success</td>
<td>44%</td>
<td>84%</td>
<td>38%</td>
<td>83%</td>
</tr>
<tr>
<td>Recurring Launch Cost</td>
<td>$7.82B</td>
<td>$7.10B</td>
<td>$8.96B</td>
<td>$8.70B</td>
</tr>
</tbody>
</table>

**Notes:**
- Assumes 2 Earth’s Neighborhood missions per year and 1 Mars mission every opportunity (26 month frequency)
- All Mars hardware launches are completed within a 20-month period
- Support flights assume launch by EELV + OSP
- * Includes 70% launch packaging efficiency
- ** One OSP support flight assumed for every 3 cargo flights plus one OSP flight per mission to position mission crew
Combined Earth’s Neighborhood & Accessible Planetary (Mars) Surface Missions

- EELV - H
- Shuttle-Derived HLLV

Cargo:
- Mission Flights
- Yearly Flights

OSP:
- Mission Flights
- Yearly Flights
## Comparison of Mission Class Flight Requirements

<table>
<thead>
<tr>
<th></th>
<th>Earth’s Neighborhood</th>
<th>Accessible Planetary (Mars) Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EELV - H</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cargo</td>
<td>![Cargo Icon]</td>
<td>![Cargo Icon]</td>
</tr>
<tr>
<td>OSP</td>
<td>![OSP Icon]</td>
<td>![OSP Icon]</td>
</tr>
<tr>
<td><strong>Shuttle-Derived HLLV</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cargo</td>
<td>![Cargo Icon]</td>
<td>![Cargo Icon]</td>
</tr>
<tr>
<td>OSP</td>
<td>![OSP Icon]</td>
<td>![OSP Icon]</td>
</tr>
</tbody>
</table>
## Summary FOM Assessment

<table>
<thead>
<tr>
<th>Perf</th>
<th>Safety</th>
<th>Technology</th>
<th>Schedule</th>
<th>Costs*</th>
</tr>
</thead>
<tbody>
<tr>
<td>EELV Heavy</td>
<td>- - -</td>
<td>- -</td>
<td>- -</td>
<td>- - -</td>
</tr>
<tr>
<td>Shuttle-</td>
<td>+ + +</td>
<td>+ +</td>
<td>+ +</td>
<td>+ + +</td>
</tr>
<tr>
<td>Derived HLLV</td>
<td>+ + +</td>
<td>+ +</td>
<td>+ +</td>
<td>+ + +</td>
</tr>
</tbody>
</table>

*Annual recurring launch costs only. Further assessment of DDT&E, Infrastructure, and Ops costs are required.

### ADVANTAGE

- Minor
- Moderate
- Significant

### DISADVANTAGE

- Minor
- Moderate
- Significant

Further analysis is required to better define the influence of various launch vehicle concepts with architectural performance, risk, schedule and cost.
Summary FOM Assessment

- **Performance:** Significantly fewer launches required with HLLV.

- **Safety:** Reduced amount and complexity of on-orbit assembly flights required with an HLLV significantly enhances probability of mission success and crew safety.

- **Technology:** Use of the EELV increases the amount and complexity of on-orbit assembly of subassemblies such as the aerobrake, significantly increasing the technology risk.

- **Schedule:** Number of flights required by EELV significantly lengthens assembly schedule, increases schedule risks associated with launch windows, and increases the schedule risks associated with launch failures.

- **Cost:** Annual recurring launch costs associated with HLLV somewhat less than that of the EELV.
Observations and Findings

Earth’s Neighborhood Mission

• A heavy lift launch capability is favored by all Figures of Merit and is highly enhancing for this class of mission.
• Assessment of investment in on-orbit assembly vs heavy lift capability is needed.
• Number of launches of EELV-H to support Earth’s Neighborhood is about the same as number of Heavy Lift launches needed to support the Accessible Planetary (Mars) Surface Mission.
• Investment costs of EELV-H borne by other mission applications.

Accessible Planetary (Mars) Surface Mission

• A heavy lift launch capability is enabling for this class of mission.
• Feasibility of using Station to support magnitude of on-orbit assembly highly uncertain.
• Feasibility of successfully assembling subassemblies into major elements such as aerobrakes, NEP, and habitats is highly uncertain.
• Risks and costs associated with unreliability is significant for launch rates associated with EELV-H vehicle class.

General

• Life cycle cost assessment incomplete for both mission classes and vehicle options.
• A vehicle trade study is needed to assess a range of vehicle and propulsion concepts to identify the preferred approach for a HLLV capability.
Conduct a Heavy Lift Launch Vehicle trade study to assess alternative vehicle and propulsion concepts in a space exploration architectural setting

- Study should address a range of vehicle concepts
  - Shuttle-evolved and shuttle-derived
  - NGLT-based
  - Clean Sheet “big dumb boosters”
  - Concepts should include expendable, reusable and partially reusable systems
  - Vehicle performance should address a range of payload delivery capabilities to LEO from 40 to 100 tonnes for each concept
- Perform manifesting analyses for each concept across a spread of payload volumetric envelopes (length, diameter)
- Establish requirements and concepts for on-orbit assembly
- For each concept develop life-cycle cost definition to include
  - DDT&E
  - Ground infrastructure for production, processing, and launch
  - Infrastructure and operations of on-orbit assembly
  - Loss of mission assets during assembly phase of mission
Backup
ISS Historical Packaging Efficiency
Augmentation Estimates (Which Mars Mission)

- Habitation 23 mt
- Servicing laboratory 35 mt
- Servicing facility 12 mt
- Resource nodes 31 mt
- Truss and utility bays 17 mt
- Power augmentation 28 mt
- Thermal radiators 6 mt
- Attached payload accommodations 1 mt
- Docking systems 1 mt

154 mt
Initial Mars Short-Stay NTR Case Study Findings
Non-Venus Swing-by Option

It is the consensus of the architecture team that the only way to perform the short-stay, non-Venus swing-by missions in the harder opportunities is to pre-deploy both the lander and return propellant

- Lowers mission mass by approximately 36% (return propellant pre-deployed on minimum energy transfers)
- Increases risk: Rendezvous in Mars orbit must be performed for crew survival (return)
- Increases operating time of crew systems by 114% (as compared to non pre-deploy missions)

Number of launches required poses a significant challenge

- # of EELV-H launches = 54 (1 launch every 2 weeks)
- # of 80 mt Shuttle Compatible launches = 22  (1 launch every 4 weeks )
- Neither of these launch rates can be sustained
  - No margin for launch failure
  - No margin for launch delay
  - Current production/launch rate for Delta-IV is 14 per year (x 4 current capacity)
- Probability of mission success significantly decreases with increased launch rate

<table>
<thead>
<tr>
<th>Launch Vehicle Size / Number of Launches</th>
<th>Launch Vehicle Reliability</th>
<th>Probability of Successful Launches</th>
</tr>
</thead>
<tbody>
<tr>
<td>EELV-H / 54</td>
<td>94%</td>
<td>4%</td>
</tr>
<tr>
<td>EELV-H/ 54</td>
<td>99%</td>
<td>58%</td>
</tr>
<tr>
<td>&quot;Shuttle Comp.&quot; / 22</td>
<td>94%</td>
<td>26%</td>
</tr>
<tr>
<td>&quot;Shuttle Comp.&quot; / 22</td>
<td>99%</td>
<td>80%</td>
</tr>
</tbody>
</table>

“Go Anywhere / Go Anytime” + Small Launch Vehicle

Current Industry Launch Success Rate 94%
Mars Short-Stay Mission
Initial NTR Case Study Results

Worst Opportunity
(2026 No Swing-by)

Best Opportunity
(2018)

Initial Mass in LEO (mt)

Descent / Ascent Vehicle
Piloted Round-Trip
Piloted Earth-Return
Piloted Outbound

ISS at Assembly Complete
(470 t)

Ref. Glenn Research Center

Section 8.1 JSC/P. Sumrall
Increasing “Performance”
Decreasing vehicle wet mass, decreasing trip times, increasing payload, more challenging mission classes

Propulsion
- Chemical
- Nuclear Thermal
- Solar Electric / Chemical
- Solar Electric
- Nuclear Electric

Aerocapture?
- w/o AC
- w/ AC

Conjunction (long stay) vs. Opposition (short stay)
- Conj
- Opp

Split vs. All-up
- Split
- All Up

ISRU?
- w/o ISRU
- w/ ISRU

Excessive Mass
- Config.
- Excessive Size

Questionable Feasibility

1  1988 “Mars Expedition”
2  1989 “Mars Evolution”
3  1990 “90-Day Study”
4  1991 “Synthesis Group”
5  1995 “DRM 1”
6  1997 “DRM 3”
7  1998 “DRM 4”
8  1999 “Dual Landers”
9  1989 Zubrin, et.al
10 1994-99 Borowski, et.al
11  2000 SERT (SSP)
12  Current Studies

*Assumptions not necessarily consistent
Performance Comparison – Transfer DV for Earth Parking Orbit to:
Earth-Moon L1, Sun-Earth L2

What is purpose of this chart?
What is purpose of this chart?
What is the story here?

**Short-Stay Missions**
(Opposition Class)

**Long-Stay Missions**
(Conjunction Class)
Common Core Crew Vehicle Requirements

12-12-2002
Objective: Establish the requirements for a common core crew vehicle which can satisfy multiple, Agency-wide, needs.

Approach: Initiate an analysis process for coordinating the functions and requirements for the range of future crew vehicles to establish a common set of requirements. Crew vehicle requirements should include needs for:

- ISS Crew Return Vehicle (return from low-Earth orbit) Priority 1
- Crew Transfer Vehicle (to and from low-Earth orbit) Priority 2
- Exploration Transfer Vehicles (beyond low-Earth orbit and return) Priority 3
Recommendation for Common Requirements

- Initial assessment of common core crew vehicle requirements include the following:
  - Configurable pressurized volume for 4-7 deconditioned crew
  - One day mission duration independent from a service module
  - Enable autonomous / manual operations
  - Provides propulsive orbital maneuvering capability
  - Return the crew safely to Earth
Key Points to Consider

- **An CRV is simplest function.**
  - Including CTV function is hardest step
  - Including XTV is less of a step

- **Winged Vehicle is more complex than simple entry shape**
  - Additional systems (i.e., actuators/control surfaces)
  - Complex aero/flight control interactions through Mach regimes
  - Complex structural loads during ascent (mass/CG/structure)
  - Potentially results in longer schedule and higher cost
  - Increased operations and crew training for more complex entry/descent and landing

- **Wings preclude Earth’s Neighborhood entry velocities (11 Km/sec)**
  - Wings are impractical above low Earth orbit (mass/heating)

- **What Evolvable means:**
  - Not open ended requirements
  - Replace TPS in critical heating areas when higher velocities are encountered.
  - Crew of up to 6-7
  - Possible later upgrades of some systems-modular systems components also enables better serviceability
There is a greater degree of commonality between the Crew Return Vehicle (CRV) design and the core of the Exploration Transfer Vehicle (XTV) than the Crew Transfer Vehicle (CTV).

<table>
<thead>
<tr>
<th></th>
<th>CRV</th>
<th>XTV</th>
<th>CTV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crew Size</td>
<td>4-7 Crew</td>
<td>4-6 Crew</td>
<td>5 Crew</td>
</tr>
<tr>
<td>Duration</td>
<td>&lt; 1 Day</td>
<td>&lt; 1 Day (^1)</td>
<td>10-12 Days</td>
</tr>
<tr>
<td>Propulsive Maneuver</td>
<td>&lt; 150 m/s</td>
<td>&lt; 300 m/s</td>
<td>450+ m/s</td>
</tr>
<tr>
<td>Volume (^2)</td>
<td>1 day</td>
<td>4 days</td>
<td>3 days</td>
</tr>
<tr>
<td>Entry Speed</td>
<td>7.5 km/s</td>
<td>11.0 km/s</td>
<td>7.5 km/s</td>
</tr>
<tr>
<td>Landing Mode/locale</td>
<td>Near Hospital</td>
<td>Any</td>
<td>Runway 10,000 ft</td>
</tr>
<tr>
<td>Launch Vehicle</td>
<td>STS</td>
<td>STS Derived</td>
<td>EELV &amp; RLV</td>
</tr>
<tr>
<td>Crew Escape System</td>
<td>No</td>
<td>If crew during launched</td>
<td>Yes</td>
</tr>
<tr>
<td>Key Interfaces</td>
<td>STS &amp; ISS</td>
<td>LV and Service Module</td>
<td>EELV (2), RLV, ISS</td>
</tr>
</tbody>
</table>

\(^1\) Additional resources provided by external service module.
\(^2\) Total volume driven by maximum length of time inhabited.
Common Crew Vehicle Design Capture

Core Crew Vehicle
- Common crew element satisfying multiple mission capabilities
- Key Design Requirements:
  - Configurable for 4-7 crew
  - Independent one day mission duration
  - Autonomous / manual operations
  - Propulsive orbital maneuvering
  - Return the crew safely to Earth

ISS Crew Return
- Provides safe and expeditious recovery of astronauts from low-Earth orbit
- Core Vehicle Configuration Changes:
  - Configured for 4 deconditioned crew
  - Medical emergency provisions
  - Emergency undock capability
  - ISS interfaces and six-month to two-year on-orbit stay
- Key Issues:
  - EELV launch compatibility including automated delivery to ISS
  - Degree of vehicle reusability

LEO Crew Transfer
- Crew transfer to low-Earth orbit and return
- Core Vehicle Configuration Changes:
  - Crew escape for aborts
  - Configured for 5 crew (3 ISS transfer)
  - 12 day mission duration for ISS support
  - Resources for extended mission duration (propellant, power, thermal control, life support consumables)
- Additional Systems:
  - EVA systems for on-orbit satellite servicing and repair
- Key Issues:
  - EELV launch compatibility and human rating
  - Degree of vehicle reusability

Near-Earth Transfer
- Transport crew to lunar vicinity and return to Earth
- Core Vehicle Configuration Changes:
  - Configured for 4-6 crew (mission dependent)
  - Crew escape for aborts
  - 12 (active) + 8 (dormant) day mission
  - Deep-space environmental protection
  - Resources for extended mission duration (propellant, power, thermal control, life support consumables)
- Additional Systems:
  - EVA systems for servicing and repair as required
  - Injection stage for trans-lunar injection
- Key Issues:
  - Lunar return velocities
  - Large launch vehicle
  - Degree of vehicle reusability
Vehicle Shapes’ Lift-to-Drag (L/D) Characteristics

AOA ~ Angle of attack

High AOA Wing Bodies

Low AOA Wing Bodies
Require advanced TPS development!

Lifting Bodies

Slender Bodies

Capsules

X-37
Shuttle

HL-20
X-38
M-2

X-38

SHARP
Shuttle (at low AOA)

ELV Shrouds

Biconic

Ellipsled

Viking
Soyuz
Apollo

Complexity, Development Time, $$$

Volumetric Efficiency (volume/mass)

Hypersonic L/D

0 0.5 1.0 1.5 2.0 2.5

BDG/12-09-2002/Common Core Crew Vehicle Requirements
Common Core Vehicle Existence Proof

- NASA Prior History with combined CRV/CTV/XTV Functions
- A concept for landing wingless spacecraft

CTV Function

Lunar Return Function

Skid Landing

CTV/CRV Function
Vehicle Shape Issues

- **Are wings and wheels required?**
  - Many of the mission modes (CRV and CTV) derive a requirement for soft runway landings, which implies wings and wheels, in order to satisfy multiple higher-level requirements including:
    - Cross range as one approach to meeting loss of crew requirements
    - Landing accelerations for medical and system certification purposes
    - Quick turnaround between flights
  - Wings are incompatible for missions beyond low-Earth orbit
    - Peak heating limits nose and wing radius of curvature – thus eliminating wings from consideration
  - Maintaining pressure in wheels for long periods in space may be an issue
  - Wings may be incompatible for launch modes where the vehicle is exposed to the free air stream.

- **If wings are considered a strong Level I requirement, then an additional requirement should be added:**
  - The system shall be capable of accommodating outer mold lines of multiple vehicles
    - With this approach, the common core vehicle requirements would be contained within a common crew cabin or reduced to common system components
Summary

- Defining the requirements on a multipurpose vehicle requires consideration of all potential mission modes.
- Strategies exist that can satisfy the top-level requirements which are common between mission modes.
- Further analysis of the impacts of the mission modes on the multipurpose vehicle is required in order to finalize core requirements.
- Exploration driving requirements- If concepts considering these are included in trade space, Exploration could be enabled:
  - Crew of 6
  - Entry shapes with larger radii of curvature (ie no wings) to preclude heating outside thermal constraints
Backup 1
Entry G-Loads

**LUNAR RETURN:**
- **Reclined:** Requires \( L/D > 0.3 \)
- **Sitting upright & sick/injured reclined:** Requires \( L/D > 0.5 \)

**LEO RETURN:**
- **Sitting upright & sick/injured reclined:** Requires \( L/D > 0.3 \)

De-Conditioned Crew Load Limit Reclined (eyeballs-in)
(ref. NASA-STD-3000 & JSC-28351)

De-conditioned Crew Load Limit Sitting Upright (eyeballs-down) or Sick/Injured Crew Load Limit Reclined (eyeballs-in)

Lunar Return

LEO Return
Entry Heating (vehicles sized for 5-7 crew)

Currently, any lunar return vehicle needs ablative TPS – vehicle with dual TPS capability to meet both OSP and XTV missions??

Lunar Returns

- Ablators (TRL5) or Flight-limited UHTC (Ultra-High Temperature Composites – TRL 3)

- Decreasing radii of curvature

Lunar Returns

- Advanced Reusable Ceramics (TRL3)

- Current Reusable TPS (TRL9)

LEO Returns

- LEO return with current reusable TPS (and windows) requires L/D < 1.1

Temperature (F)

- 6000
- 5000
- 4000
- 3000
- 2000
- 1000

L/D

- 0.5
- 1.0
- 1.5
- 2.0
- 2.5
Landing Sites

- Map shows sites used for shuttle & considered for previous crew return vehicles
- Multiple sites are desired because
  - Primary site closure due to poor conditions
  - Emergency crew or vehicle return when opportunity to primary site will not be soon enough
  - Reduce the maximum time between de-orbit opportunities
For a given set of emergency return requirements, there exists a minimum number of landing sites needed for a particular vehicle L/D. This is dependent on vehicle landing system design & suitable site locations.

- Return from ISS 51.6° inclination orbit.
- Crew return to Earth required to be less than 24 hours to reach medical facilities in time.
- Site locations optimized to minimize time between opportunities.
- Real site locations may increase the maximum time by an orbit or two, or 1.5 to 3 hours. More study required to assess suitable real sites.
- At least 1 additional site is always desired in case of poor conditions at one.
ELV Launch Controllability (OSP sized for 5-7 crew)

Note: Based on limited engineering analysis; structural interface requirements must also be considered; needs more study for various shapes.

Simple ELV compatibility for controllability requires $L/D < 0.7$;
Potentially feasible to $L/D = 1.0$ without change to ELV control

Requires change to ELV control or OSP lift spoilers

Within current ELV launch capability

Similar to current ELV launch shrouds

More destabilizing to ELV
28.5 deg inclination has fewer early abort gaps, but more late abort gaps than 51.6 deg
Bottom Line

Entry G-load Limit

- No return: Lunar return reclined
- LEO return: upright & sick/injured reclined
- Any return sitting upright & sick/injured reclined

LEO Return TPS (all lunar returns would currently require ablators)

- Current reusable TPS
- Advanced Reusable Ceramics
- Ablators (TRL5) and Flight-limited UHTC (TRL3)

Landing Sites Req’d for CRV

- > 4 Landing Sites Req’d
- 3 - 4 Landing Sites Req’d
- 1 or 2 Landing Sites Required

Impact on ELV Control

- Similar to current ELV launch shrouds
- Within current ELV launch capability
- Requires change to ELV control or OSP lift spoilers

Ascent Abort Capability

- Exceeds crew load limit on high-altitude aborts
- Requires land and water landing ascent abort capability

Desirable Range

- L/D
- 0
- 0.5
- 1.0
- 1.5
- 2.0
- 2.5
Other Considerations

- **Volumetric efficiency**
  - Weight is exceedingly critical for EELV launch and missions beyond LEO

- **System complexity and cost**
  - Tends to increase with L/D

- **New TPS materials real applicability**
  - Weight
  - Fabrication
  - Attachment
  - Low emissivity (heat flux) - need for coating

- **Probability of Loss of Crew or Vehicle rather than strictly abort gaps**

- **Landing and recovery techniques and systems**
  - Refurbishment and operations
  - Impact loads

- **Crew seating and loads directions**

- **Structural I/F requirements with ELV**
  - Bending moments
  - Attach points

- **Additional actual landing site locations effects on CRV mission time**

- **Potential shape “add-ons” for different missions**
What Next?

- **Complete general trade studies of shape (L/D) impacts**
  - Launch on ELV
    - Controllability
    - Structural interface requirements
  - Probability of Loss of Crew or Vehicle
    - Launch abort survival in cold water requirements
    - SAR time for various crossrange
    - Vehicle loss impact to overall cost
  - Actual potential landing sites and crossrange requirement to meet CRV mission timeline at 51.6 deg inclination
  - Refurbishment and operations costs of various landing systems

- **More detailed trade studies of candidate vehicles in L/D range dictated by requirements**
  - Perhaps three designs to investigate across desired L/D range
  - System volume and weight
  - TPS requirements and weight
  - Launch and entry abort system requirements
  - Landing systems applicability
  - ELV launch requirements
  - Development and operations costs
Backup 2
ISS Crew Return Vehicle

- **Primary CRV function is the expeditious return of crew from ISS due to:**
  - Crew medical emergencies
  - ISS emergency situations
  - Grounded Shuttle fleet

- **Key functional needs which drive the CRV design:**
  - Capability to return 4 crew (7 desired)
  - Capability for a quick departure from an uncontrolled ISS
  - Capability to return a sick or injured crewmember
  - Total mission duration less than one day
  - Capability to be stored for a long duration (2-years) (TBD) at ISS
  - The desire for the system to be reusable
Notional Mission Profile
ISS Crew Return

1. Emergency Departure
2. Phasing
3. Deorbit
4. Entry
5. Landing
CRV Ops Flow

1. Pre-Launch Ops
   - LV Ignition (Launch)
   - LV Staging & Dynamic Ascent
   - MECO, LV/CRV Separation
2. Ascent
3. On-orbit Ops
4. Entry and Landing
   - CRV Docks / Berth with ISS
   - CRVRemain Quiescent at ISS
   - CRV Undocks with ISS
   - Landing Site Phasing
4. Entry and Landing
   - CRV Deorbit Burn
   - CRV Dynamic Re-Entry
   - Decelerate CRV and Active Entry Guidance
   - Deploy recovery & energy attenuation devices
   - CRV Post-Landing Ops
4. Entry and Landing
   - Egress
   - CRV Remain Quiescent at ISS
   - Decelerate CRV and Active Entry Guidance
   - Deploy recovery & energy attenuation devices
   - CRV Post-Landing Ops

Phase Description

1. Pre-launch
2. Ascent
3. On-orbit Ops
4. Entry and Landing

ISS: International Space Station
LV: Launch Vehicle
CRV: Crew Return Vehicle
The Crew Transfer Vehicle (CTV) provides an alternate crew delivery and return capability to and from low-Earth orbit:

**Key functional needs which drive the CTV design:**
- Capability to exchange 3 ISS crew (implies a total crew complement of 4-5 depending on operational requirements)
- Capability to be launched on US EELV-H launch vehicles
- Capability to be launched on future US launch vehicles (reusable launch vehicle)
- Provide adequate crew escape methods during ascent
- Total mission duration of 12 days for ISS crew exchange missions
- System should be reusable and able perform a soft runway landing (wings and wheels)
- The CTV shall be capable of performing other missions, such as satellite servicing, when combined with other (additional) mission elements.
Notional Mission Profile
Crew Transfer Vehicle

1. Launch
2. Rendezvous & Docking
3. ISS Mission
4. Departure / Phasing
5. Deorbit
6. Entry
7. Landing

Earth

LEO
CTV ISS Ops Flow

1. Pre-Launch Ops
   - On-Pad Egress

2. Ascent
   - LV Ignition (Launch)
   - LV Staging & Dynamic Ascent
   - Jettison Unused CES

3. On-orbit Ops
   - MECO, LV/CTV Separation
   - CTV Docks with ISS
   - Transfer of Crew and/or Logistics
   - CTV Undocks with ISS
   - Landing Site Phasing

4. Entry and Landing
   - Landing Site Redesignation Capable?
   - CTV/CES Initiation
   - CTV Intact Abort
   - YES
   - Landing Site Redesignation Capable?
   - YES
   - Redes. To ALS
   - Decelerate CTV and Activate Entry Guidance
   - CTV Dynamic Re-Entry
   - Deploy recovery & energy attenuation devices
   - CTV Post-Landing Ops

5. Egress
   - CTV Undocks with ISS
   - Contingency Phasing

LV: Launch Vehicle
CTV: Crew Transfer Vehicle
ISS: International Space Station
CES: Crew Escape System
Exploration Transfer Vehicle

- Provides the capability to transfer mission crew from Earth, to the lunar vicinity, and return back to Earth:
- Includes capability for transfers to high earth orbit for potential Mars mission concepts
- Key functional needs which drive the XTV design:
  - Capability to support up to 6 exploration mission crew
  - Total mission duration of 12 days active plus 8 days dormant
  - The desire for the system to be reusable
  - Capability to accommodate lunar return velocities
Mars Earth Return Vehicle

- Provides the capability to return exploration mission crews from Mars return trajectories to the surface of the Earth:

- Key functional needs which drive the Mars Earth Return Vehicle design:
  - Capability to support up to 6 exploration mission crew
  - Capable of being stored in a dormant state during the Mars mission
  - Total active mission duration of one day
  - Capability to accommodate Mars return velocities
Notional Mission Profile
Exploration Mission

1. Launch
1a. Abort
1b. Landing

2. Trans Lunar Injection

3. Exploration Mission

4. Aerocapture / Phasing

5. Deorbit

6. Entry
6b. Mars Direct Entry

7. Landing
**XTV Ops Flow**

**Phase** | **Description**
---|---
1 | Pre-launch
2 | Ascent
3 | LEO Ops
4 | Beyond LEO Ops
5 | LEO Ops
6 | Entry and Landing

**On-Pad Egress**

**Abort Scenario**

**Jettison UNUSED LES**

**LV Staging & Dynamic Ascent**

**LV Ignition (Launch)**

**Pre-Launch Ops**

**Injection Stage Disposal Burn**

**XTV/CES Initiation**

**Intact Abort Capable?**

**Landing Site Redesignation Capable?**

**XTV Dynamic Re-Entry**

**Redes. To ALS**

**Deploy recovery & energy attenuation devices**

**Egress**

**XTV Post-Landing Ops**

CES: Crew Escape System
LV: Launch Vehicle
LEO: Low Earth Orbit
LES: Launch Escape System
LL₁OI: Lunar L₁ Orbit Insertion
TLL₁I: Trans-Lunar L₁ Injection
TEI: Trans-Earth Injection
XTV: Exploration Transfer Vehicle

**Mid Course Correction**

**Service Module Disposal Burn**

**Jettison Service Module**

**Aerocapture into LEO**

**LEO Perigee Raising Burn**

**XTV Deorbit Burn**

**XTV to LEO Parking Orbit**

**MECO, LV/XTV Separation**

**Jettison Stage**

**Injection Stage**

**XTV System Checkout**

**Abort Scenario**

**Abort Scenario**