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Reducing the Risk of Human Missions to Mars Through Testing

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FOREWORD

During the summer of 2002 the NASA Deputy Administrator charted an internal NASA planning group to develop the rationale for exploration beyond low-Earth orbit. This team, termed the Exploration Blueprint, performed architecture analyses to develop roadmaps for how to accomplish the first steps beyond Low-Earth Orbit through the human exploration of Mars. The previous NASA Exploration Team (NEXT) 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.

Following the results of the Exploration Blueprint study, the NASA Administrator has asked for a recommendation by June, 2003 on the next steps in human and robotic exploration in order to put into context an updated Integrated Space Transportation Plan (post- Columbia) and guide Agency planning. NASA was on the verge of committing significant funding in programs that would be better served if longer term goals were better known including the Orbital Space Plane, research on the ISS, National Aerospace Initiative, Shuttle Life Extension Program, Project Prometheus, as well as a wide range of technology development throughout the Agency. Much of the focus during this period was on integrating the results from the previous studies into more concrete implementation strategies in order to understand the relationship between NASA programs, timing, and resulting budgetary implications. This resulted in an integrated approach including lunar surface operations to retire risk of human Mars missions, maximum use of common and modular systems including what was termed the exploration transfer vehicle, Earth orbit and lunar surface demonstrations of long-life systems, collaboration of human and robotic missions to vastly increase mission return, and high-efficiency transportation systems (nuclear) for deep-space transportation and power.

The data provided in this summary presentation was developed to begin to address one of the key elements of the emerging implementation strategy, namely how lunar missions help retire risk of human missions to Mars. During this process the scope of the activity broadened into the issue of how testing in general, in various venues including the Moon, can help reduce the risk for Mars missions.

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Reducing the Risk of Human Missions to Mars Through Testing

October 31, 2003

Study Purpose

- **Assess the potential benefits, in terms of risk reduction or mitigation, that could be gained by executing various Mars mission test bed options**

- **Test bed options include:**
  - Earth-based simulations and analogs,
  - Earth orbital missions, including accommodation on ISS, as well as missions in near-Earth space (robotic and/or human),
  - Lunar orbit and surface missions (robotic and/or human), and
  - Missions to Mars (robotic).

- **The intent is to develop a better understanding of the critical elements of future Mars mission concepts that should be tested prior to committing to the final mission**

- **As testing objectives are defined, they will be grouped into similar logical and achievable campaigns**
  - Similar to how Mercury and Gemini were critical steps in validating systems, techniques, and operational concepts needed for the Apollo missions.

Approach

- Use Mars Design Reference Mission (DRM), other earlier work, as well as emerging mission concepts, such as the Nuclear-Electric Artificial-gravity study, as context for risk identification

- Review information available from previous 1997 risk identification and assessment for relevance

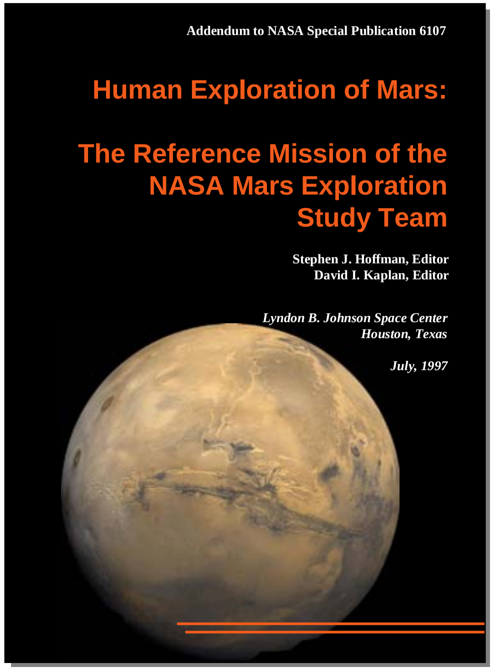
- Poll system area experts to identify safety, technical, and programmatic risks

- Identify those risks that could be mitigated through testing

- For tests that could be performed on the moon,
  - Analyze list for tests for commonalities, synergies
  - Compare infrastructure required for tests with that required for lunar scientific investigations
  - Develop integrated (or, at least, concatenated) list of test objectives and lunar science objectives for integrated lunar architecture approach

Mars Mission Context

- **Two distinctly different example Mars missions used as a basis for test team deliberations**



Addendum to NASA Special Publication 6107

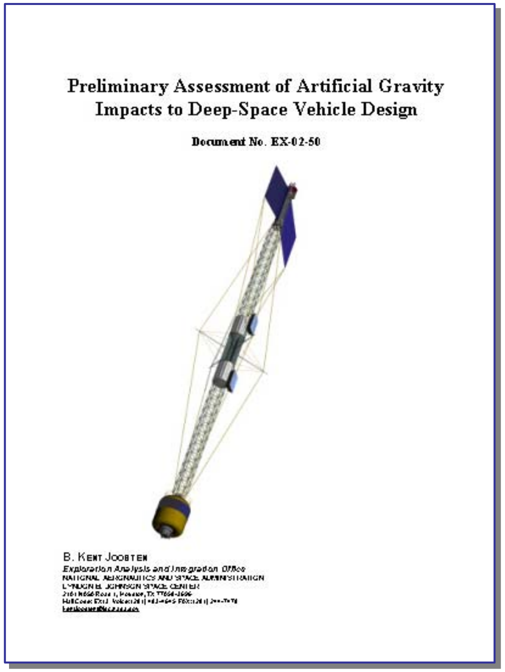
Human Exploration of Mars:

The Reference Mission of the NASA Mars Exploration Study Team

Stephen J. Hoffman, Editor
David I. Kaplan, Editor

Lyndon B. Johnson Space Center
Houston, Texas

July, 1997



Preliminary Assessment of Artificial Gravity Impacts to Deep-Space Vehicle Design

Document No. EX-02-50

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Design Reference Mission 4
- **Long-surface stay**
- **Zero-g Transits**
- **Solar-Electric/Aerobrake Propulsion**

NEP/Artificial-g 2002 Study
- **Short-surface stay**
- **Artificial-g Transits**
- **Nuclear-Electric Propulsion**

Example Critical Mars Mission Events

1 EARTH VICINITY

- Operation of pre-deployed assets for long periods
- System Integration & Checkout
- Training, Planning & Simulation
- Cargo Launch – multiple
- Crew Launch – multiple possible
- Assembly & Checkout
    - Automated rendezvous & Docking
    - Deployment / Assembly
    - Fuel transfer
- Preparation for Departure – “All Systems Go”
- Crew Delivery / Earth Departure
- Vehicle Element Disposal – some options

2 TRANSIT TO MARS

- Deep-space hazard mitigation
- Trajectory Corrections, Deep-Space Maneuvers
- Vehicle Reconfiguration & Maintenance
- Arrival Preparation
- Mars Orbit Insertion or Aerocapture
- Rendezvous with Lander
- Lander Preparation
- Interplanetary Vehicle Safing
- Deorbit, Aero-Entry, and Precision Landing

3 SURFACE EXPLORATION

- Operations of pre-deployed assets for long-periods
- Hazard Avoidance, Terminal Descent
- Vehicle Safing, Power Deployment
- Routine EVAs
- Robust Exploration
- Vehicle Reconfiguration & Maintenance
- Preparation for Liftoff
- Ascent

4 TRANSIT FROM MARS

- Rendezvous and Docking
- Ascent Stage Disposal
- Preparation for Departure
- Mars Departure
- Deep-space hazard mitigation
- Trajectory Corrections, Deep-Space Maneuvers, Possible Venus Swing-by
- Vehicle Reconfiguration & Maintenance
- Arrival Preparation

5 EARTH RETURN

- Direct Entry, or Earth Orbit Insertion & Rendezvous with Earth Orbital Assets
- Interplanetary Vehicle Safing / Disposal
- Deorbit, Entry, and Landing
- Crew Retrieval

Key Questions

1. **What are the critical elements (integrated systems, subsystems or components) that require testing in order to reduce potential Mars mission risks?**

2. **What are the benefits of testing each of the critical elements identified in #1 above at the following locations:**
   a. Earth-based simulations and analogs,
   b. Earth orbital missions (robotic and/or human), including accommodation on ISS,
   c. Missions in near-Earth space (robotic and/or human),
   d. Lunar orbit and surface missions (robotic and/or human), and
   e. Missions to Mars (robotic).

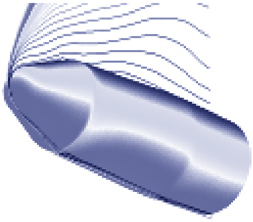
3. **For each applicable location, how would you propose the testing be conducted?**

4. **What is the rough scope of capabilities required to support each test objective at each applicable location described above?**

Aeroassist

Critical Elements to Test

- **Mars approach precision navigation and control**
- **Aeroshells (Design, structure, TPS)**
- **Atmospheric GN&C for pinpoint landing and precise aerocapture**
- **Mars atmosphere density and winds knowledge and modeling**
- **Hazard detection and avoidance**
- **Wind compensation systems**
- **Low-speed decelerators**



Testing Venues & Benefits

- **Earth-based facilities**
  - Wind tunnels and arc jet testing for material certification
  - GN&C, CFD, TPS, and structural simulation facilities
- **Near-Earth Flight Tests**
  - Navigation techniques and hardware demonstrated
  - High-speed entry to test TPS and integrated system performance
  - Supersonic decelerator systems
- **Mars Robotic Missions can demonstrate**
  - Determine Mars atmospheric knowledge and Mars environment
  - Approach navigation techniques and hardware performed
  - Demonstrates integrated system performance – Aerodynamics, aerothermodynamics,TPS, GN&C, and supersonic decelerators

Testing Approach & Support Needed

- **Earth:**
  - High fidelity modeling and dynamic simulation of hardware, software, and operational techniques
  - Earth-based simulations and testing required to certify aeroassist technologies before use
  - Wind tunnels, CFD simulation, GN&C dynamic simulation, arc jet testing, and structural analysis of aeroshell systems
  - Develop and test autonomous hazard detection and avoidance
- **Near-Earth:**
  - Integration of flight test systems with launch vehicles to demonstrate integrated launch/entry effects
  - Validate guidance, navigation, control, thermal protection system, and integrates aeroassist system performance at higher entry speeds for aerocapture and aeroentry
  - Demonstrate supersonic deceleration system performance
- **Lunar:**
  - Proof test of autonomous hazard avoidance system
- **Mars Robotic:**
  - Use ongoing Mars robotic missions as opportunities to understand the Mars environment and to test and validate aeroassist systems for future more demanding missions. This is vital for an integrated, cost effective approach to Mars exploration.
    - Mars atmospheric density and wind knowledge and modeling, including predictability needed.
    - Approach and atmospheric navigation and trajectory control
    - Hazard detection and avoidance
    - Proof testing of aeroassist sub-systems and integrated aeroassist system required for more demanding missions

Summary of Test Team Findings to Date

- **Overall Key Findings**
- **Earth-Based Testing**
- **Testing in LEO (ISS) / Near-Earth**
- **Testing on the Moon**
- **Testing at Mars**

Key Findings To Date

- **Testing of large-scale integrated systems with humans is an absolute necessity in terms of preparing for human Mars missions**
- **Tests of Mars prototype systems in environmentally similar “flight-like” conditions is an essential element of risk reduction**
- **Testing beyond Low-Earth Orbit is required to evaluate the performance of large integrated systems in deep-space conditions**
- **Providing the ground-based capability to perform long-duration tests of large integrated systems is a vital and cost effective element of continuous risk mitigation**
- **Human missions in near-Earth space are an essential element of revitalizing exploration experience and technical competence needed for future deep-space missions**
- **Robust robotic missions are a vital element of risk reduction strategies for future human exploration of Mars**
  - Timely acquisition of critical Mars environmental data (deep-space transit, orbital, atmosphere, surface, and subsurface) is necessary
  - Demonstration of applicable advanced technologies and operational concepts is needed to reduce risk of future technology choices and system designs

Earth-Based Testing
(Preliminary Summary)

- **Ground-Based Testing**
  - **Ground testing is relatively benign** in terms of both risk and cost – it doesn’t leave Earth and is easy to access, change, and repeat
  - Ground-based test facilities and chambers can be used to **economically and repeatedly** test various operational concepts, technologies, components, and systems in a variety of simulated environments
    - Vacuum, thermal, atmospheric, dust, etc.
    - Field tests including simulated environments and terrain, including high-altitude testing
    - Surface models and landing conditions
  - Ground testing with appropriate simulators provides **necessary training & experience, both nominal and contingency** situations, before committing crew to missions in space
  - Ground-based testing allows both individual component and system level **testing for certification** of advanced technologies and systems before use
  - “Ground Flight” concepts allow for development of **effective management techniques**, especially those associated with international and diverse partners
  - Both simulators and field tests allow “**build a little; test a little**” to provide greater insight to “go/no go” technical decisions
  - Ground-based testing of actual flight hardware in simulated real “flight” conditions provides opportunity to model expected as well as unexpected failure modes
  - **Test repeatability** of hardware performance, maintenance procedures, and operational concepts is necessary prior to commitment to long-duration Mars missions
- **Concerns**
  - It is currently **difficult to test complete integrated spacecraft** systems for long-durations
  - **Difficult to simulate low-gravity / zero-gravity** conditions and long duration deep-space environment exposure, including radiation
  - **New test facilities may be required** for some advanced technology concepts and mid/large-sized systems

Testing in LEO / Near-Earth
(Preliminary Summary)

- **Testing in LEO / Near-Earth**
  - Missions in LEO provide the capability to conduct critical **applied research and technology demonstrations** leading to safe and effective long-duration human space flight
  - Flight tests in LEO and Near-Earth can be used to **simulate flight environments for the transit (zero-g)** mission phases
  - Flight tests in LEO or near-Earth space of integrated systems can provide **critical performance data** of both hardware and operational concepts
  - Zero-g testing is critical to understand and validate **gravity-sensitive phenomena** (crew physiology, gas/liquid separation, large scale structure deployments, etc.)
  - **ISS provide an ideal venue for long-duration system testing** including crew interaction with hardware, software, and operational procedures
  - Flight tests in LEO, can be utilized for extended testing which provides better understanding of long-duration system performance in “flight like” conditions
  - Simulation of operational concepts, such as **vehicle deployment and assembly**, prior to commitment to final vehicle design and operational mission concept
  - **Long-term exposure of systems to the deep-space environment**, including radiation and zero-g can be conducted on missions in near-Earth space

- **Concerns**
  - Testing in Low-Earth Orbit is adequate for simulating transits to and from Mars, but **cannot adequately simulate planetary surface conditions**
  - **Testing beyond Low-Earth Orbit required to simulate deep-space conditions**
  - **Resources for testing at ISS may be limited** – independent flight tests of Mars prototype systems will be required

Testing on the Moon
(Preliminary Summary)

- **Testing on the Moon**
  - **Lunar surface tests can demonstrate system performance in actual space environments**
    - Terminal descent and hazard avoidance
    - In-situ resource utilization
    - Science campaigns and instruments, EVA and mobility systems, and operational planning
    - Dust mitigation techniques
    - Radiation protection
    - Advanced operations and automation
  - Lunar surface missions may prove **useful as long-term “dry run” rehearsals** and “what if” scenarios for future human Mars missions
  - **Advanced transportation systems**, such as crew and cargo delivery, can be demonstrated in actual flight conditions
  - **Long-term exposure of systems to the deep-space environment**, including radiation, can be **demonstrated**
  - **Lunar surface operation will provide valuable data on component performance in** dusty environments
  - Operational experience on full-scale systems could be collected and evaluated prior to system deployment on a Mars mission
  - Lunar return speeds would serve as a key demonstration of **aeroassist technologies**

- **Concerns**
  - **Surface environment of the moon is different** from the surface of Mars which may lead to additional design complications and risk

Testing at Mars
(Preliminary Summary)

- **Testing at Mars via Robotic Missions**
  - Mars robotic missions are **key to providing environmental data of Mars** (dust composition, thermal, radiation, terrain, hazards, etc.)
  - Mars robotic missions are ideal and vital for demonstration of **integrated aeroassist technologies** system performance (aerodynamics, aerothermodynamics,TPS, GN&C, supersonic decelerators, navigation, precision landing, hazard avoidance)
  - Robotic missions can **demonstrate numerous advanced technologies** applicable to future human missions (e.g. IVHM, ISRU, power, aeroassist, thermal management, etc.)
  - Mars robotic missions can **demonstrate dust mitigation** techniques for low-g environments
  - Large-scale robotic missions can **demonstrate nuclear power components** and systems operational characteristics, landing dynamics and physics (cratering), as well as serve to pre-deploy future human mission assets
  - **Large-scale unmanned cargo missions which land prior to the human mission can** certify human landing vehicles

- **Concerns**
  - Currently envisioned robotic missions can only test a limited set of advanced technologies due to the limited resources available (mass, power, volume, funding)
  - **Timely acquisition of critical Mars environmental data** as well as demonstration of applicable advanced technologies on future robotic missions is vital to future technology and system planning
  - Facilities for long-duration testing under simulated Mars conditions for mid/large size systems do not currently exist
  - **Large-scale unmanned cargo missions** which land prior to the human mission can certify human landing vehicles, and possibly demonstrate crew ascent vehicle capability

Testing Venue Descriptions

- **Ground-Based Testing**

Laboratory:	Basic laboratory testing of system components in a breadboard or relevant environment. Includes computer simulation testing. Low to mid-TRL (1-6) technology testing.
Integrated Physical Testing:	Physical testing of integrated components in a relevant simulated environment. Includes testing of integrated systems and vehicles to validate the integrated performance of the “whole” . Low to mid-TRL (1-6) technology testing.
Field:	Tests conducted in remote locations on the Earth that provide similar environments expected on planetary surfaces. Low to mid-TRL (1-6) technology testing.

- **Low-Earth / Near-Earth Testing**

ISS:	Includes testing conducted at the ISS in LEO. Both IVA and EVA tests are included. Mid to high-TRL (6-9) technology testing.
Near-Earth:	Includes testing conducted in LEO, but not at ISS as well as testing conducted in Near-Earth space beyond LEO. Mid to high-TRL (6-9) technology testing.

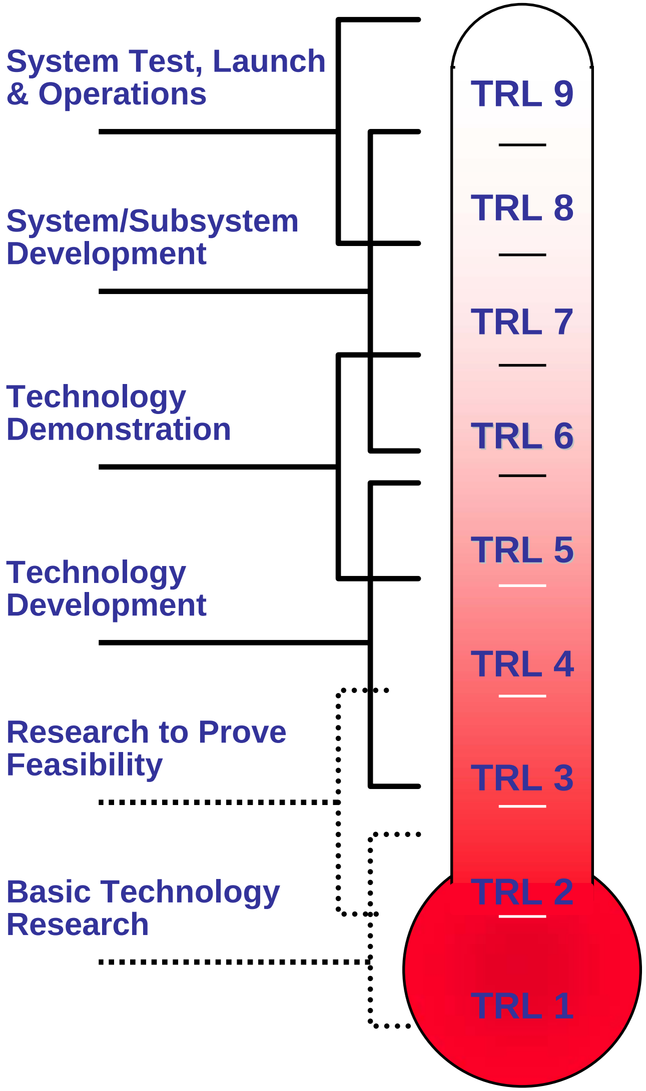
- **Lunar Surface Testing**

Robotic:	Includes all testing conducted on unmanned lunar robotic missions. Generally considered small-scale missions with limited capabilities and resources. Mid to high-TRL (6-9) technology testing.
Short-Stay:	Includes short-stay human missions to the surface of the moon. Missions generally last several days (3-7), include modest capabilities (power, volume), and provide moderate exploration ranges (EVA and rover range). Mid to high-TRL (6-9) technology testing.
Long-Stay:	Includes longer stay human missions to the surface of the moon lasting months. Capabilities provided are significantly improved (power, volume) with the capability for repeated longer range field explorations. Mid to high-TRL (6-9) technology testing.

- **Mars Robotic**

Small:	Considered similar to today’s mission capability with constrained surface delivery capabilities and resources. Mid to high-TRL (6-9) technology testing.
Large:	Robotic missions much larger than those planned today with significantly greater capabilities. Missions which pre-deploy cargo for future human missions are included in this class. Mid to high-TRL (6-9) technology testing.

Technology Readiness Definitions



TRL 9	Actual system "flight proven" through successful mission operations
TRL 8	Actual system completed and "flight qualified" through test and demonstration (Ground or Space)
TRL 7	System prototype demonstration in a space environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)
TRL 5	Component and/or breadboard validation in relevant environment
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 2	Technology concept and/or application formulated
TRL 1	Basic principles observed and reported

Test Relevancy Summary

	Ground Testing			LEO Near-Earth		Lunar Surface			Mars Robotic	
	Laboratory	Physical Integrated Testing	Field Test	ISS	Near Earth	Robotic	Short Stay	Extended Stay	Small	Large
Crew Health and Performance										
Radiation Protection	●	○	○	◖	●	●	●	●	●	●
Long-Duration Crew Performance	◖	◖	◖	●	●	○	◖	●	○	○
Advanced Life Support	●	●	○	●	●	○	◖	●	◖	◖
EVA & Surface Mobility	●	●	●	○	○	○	●	●	◖	◖
Advanced Habitation	●	●	◖	●	●	○	◖	●	○	○
Space Transportation										
Aeroassist / Entry / Descent / Landing	●	◖	○	○	●	◖	●	●	●	●
Propulsion - Chemical	●	○	○	○	●	○	●	●	○	●
Propulsion - Solar Electric	●	◖	○	◖	●	◖	●	●	◖	●
Propulsion - Nuclear Electric	●	○	○	○	●	○	○	○	○	●
Cryogenic Fluid Management	●	○	○	◖	●	◖	●	●	◖	●
Rocket Exhaust Cratering	●	◖	○	○	○	○	◖	◖	○	●
Advance Space Power										
Fuel Cells	●	●	◖	●	●	○	●	●	○	●
Surface Solar	●	◖	◖	○	○	○	◖	◖	●	●
Surface Nuclear	●	○	○	○	○	○	○	●	○	●
Miscellaneous / Systems Related										
Advanced Communications	◖	●	◖	◖	●	◖	●	●	●	●
Advanced Operations - Dust Mitigation	●	●	◖	○	○	◖	●	●	●	●
Advanced Operation - Automation	●	●	◖	●	●	○	●	●	○	●
Automated Rendezvous & Capture	●	●	○	●	●	●	●	●	●	●
Integrated Testing	●	●	◖	◖	●	○	●	●	○	●
Integrated Testing - Mars Ascent	◖	●	◖	○	○	○	●	●	◖	●
Integrated Vehicle Health Management	●	●	◖	◖	●	◖	●	●	◖	●
In-Situ Resource Utilization	●	◖	○	◖	○	◖	◖	●	●	●
Structures & Materials	●	○	○	◖	●	◖	●	●	◖	●
Supportability	●	●	◖	●	●	○	●	●	○	○
Thermal Control	●	●	○	◖	●	○	●	●	○	◖

● Very Relevant ◖ Somewhat Relevant ○ Not Very Relevant

What is a Lunar Test Campaign?

Campaign – ***"A connected series of determined operations or systematic efforts designed to bring about a particular result."***

"… series of determined operations or systematic efforts…"

- Progressive series of flight missions to the Moon
- Each mission builds off of the previous to establish new levels of confidence, prove additional technologies, develop the next level of operational experience, etc.
- Includes missions such as:
  - Small robotic missions
  - Short-stay human/robotic missions
  - Long-stay human/robotic missions

"… bring about a particular result."

- Reduces future human Mars mission risk
  - Proves technologies
  - Provides better understanding of system performance and behavior
  - Develops and refines operational concepts
  - Lays the initial infrastructure for future missions

Campaign Development

- **What have we done thus far?**
  - Identified example critical Mars mission events and associated risks
  - Performed an initial assessment of the types of critical tests to be conducted at various venues (Earth, LEO, Moon, and Mars) for both technologies and operational concepts.

- **In order to develop a lunar test campaign, we need to…**
  - Focus more on tests to be conducted on the Moon and the scope of capabilities needed to perform those tests
  - Use the results from the critical test assessment to develop candidate test projects and missions
  - Establish the time phasing of the missions in order to establish the “series of determined operations…”
  - Integrate the testing campaign with the science campaign that is currently being developed
  - Integrate the testing campaign with the infrastructure analyses that are currently being performed

Summary of

Subject Matter Expert Inputs

As of

26 August 2003

Subject Matter Experts

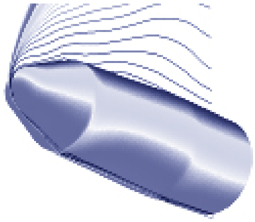
As of 8/25/2003

Aeroassist	C. Graves	JSC
Advanced Communications	D. Rask	JSC
Advanced Automated Rendezvous & Capture	D. Pearson	JSC
Crew Inputs	S. Horowitz	JSC
Crew Health Systems	T. Sullivan	JSC
Cryogenic Fluid Management	D. Plachta	GRC
EVA Systems	J. Kosmo	JSC
EVA Systems	R. Trevino	JSC
EVA Systems	B. Webbon	ARC
In-Situ Resource Utilization	S. Baird	JSC
In-Situ Resource Utilization	G. Sanders	JSC
In-Situ Resource Utilization	W. Larson	KSC
Integrated Testing	D. Henninger	JSC
Integrated Vehicle Health Management	M. Merriam	ARC
Life Support Systems	M. Ewert	JSC
Life Support Systems – Air Revitalization	F. Smith	JSC
Life Support Systems – Water Recovery	L. Shaw	JSC
Life Support Systems – Plant Growth	R. Wheeler	JSC
Life Support Systems – Waste Mgmt.	J. Fisher	ARC
Operations	D. Rask	JSC
Operations	J. Mikula	ARC
Operations – Dust Mitigation	J. D. Rask	JSC
Operations – Dust Mitigation	C. Calle	KSC
Operations – Mars Ascent	D. Rask	JSC
Power Systems – Surface Solar	B. Cataldo	GRC
Power Systems – Surface Nuclear	B. Cataldo	GRC
Power Systems – Fuel Cells	K. Bradley	JSC
Propulsion – Advanced Chemical	G. Sanders	JSC
Propulsion - Rocket Exhaust Cratering	P. Metzger	KSC/APL
Propulsion – Nuclear Electric	B. Cataldo	GRC
Propulsion – Solar Electric	T. Verhey	GRC
Structures & Materials	J. Watson	LaRC
Supportability	K. Watson	JSC
Thermal Control Systems	D. Westheimer	JSC
Thermal Protection Systems	D. Curry	JSC

Aeroassist

Critical Elements to Test

- **Mars approach precision navigation and control**
- **Aeroshells (Design, structure, TPS)**
- **Atmospheric GN&C for pinpoint landing and precise aerocapture**
- **Mars atmosphere density and winds knowledge and modeling**
- **Hazard detection and avoidance**
- **Wind compensation systems**
- **Low-speed decelerators**



Testing Venues & Benefits

- **Earth-based facilities**
  - Wind tunnels and arc jet testing for material certification
  - GN&C, CFD, TPS, and structural simulation facilities
- **Near-Earth Flight Tests**
  - Navigation techniques and hardware demonstrated
  - High-speed entry to test TPS and integrated system performance
  - Supersonic decelerator systems
- **Mars Robotic Missions can demonstrate**
  - Determine Mars atmospheric knowledge and Mars environment
  - Approach navigation techniques and hardware performed
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Testing Approach & Support Needed

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  - Earth-based simulations and testing required to certify aeroassist technologies before use
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  - Develop and test autonomous hazard detection and avoidance
- **Near-Earth:**
  - Integration of flight test systems with launch vehicles to demonstrate integrated launch/entry effects
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- **Lunar:**
  - Proof test of autonomous hazard avoidance system
- **Mars Robotic:**
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    - Mars atmospheric density and wind knowledge and modeling, including predictability needed.
    - Approach and atmospheric navigation and trajectory control
    - Hazard detection and avoidance
    - Proof testing of aeroassist sub-systems and integrated aeroassist system required for more demanding missions

Advanced Communications

Critical Elements to Test

- **RF, laser, & optical voice, video, data communications and inertial/relative navigation technologies**
  - Electronic components (reliability, radiation & thermal tolerance)
  - Electrical power requirements and sources
  - Data rate & bandwidth
  - Encryption and other IT/communications security technologies
- **Applicability of different types of communications technologies to specific mission ops requirements**
  - Earth to spacecraft, spacecraft to spacecraft, spacecraft to surface
  - Surface asset to surface asset (crewed, tended, or untended)
  - EVA crew to EVA crew, EVA crew to rover/habitat/untended asset
  - Earth to surface habitat/asset/EVA crew, etc.
  - Navigation & Comm relay systems (space or surface-based), etc.

Testing Venues & Benefits

- **Earth-based facilities**
  - Laboratory testing of reliability, radiation, and thermal tolerance, and performance testing
  - Field tests for surface to surface comm & relay systems in Moon/Mars analog terrain, and performance testing
- **Near-Earth Flight Tests**
  - ISS as a spacecraft to spacecraft, spacecraft to Earth, or communications/navigation relay systems test platform
- **Lunar Tests**
  - Routine operation of applicable comm systems on surface (line-of-sight & over- the-horizon, environmental tolerance, etc.)
  - Testing of navigation systems (space and surface-based, inertial/relative) for spacecraft and rovers
- **Mars Robotic Missions –** Same as lunar

Testing Approach & Support Needed

- **Earth**
  - Laboratories and other facilities capable of testing communications systems and navigation systems performance end-to-end
  - Laboratories and other facilities capable of performing simulated environmental stress testing/reliability testing on integrated communications and navigation systems hardware & software
  - Outdoor field sites for testing communications systems in realistic settings of terrain and moving vehicles.
- **Near-Earth**
  - Launch complete communications systems to the ISS for testing with Shuttle, Earth (MCC), or other spacecraft.
- **Lunar**
  - Test technologies for navigating on the lunar surface without a strong global magnetic field. Requires deployment of space-based or surface-based navigational assets (inertial and/or relative).
  - Test over-the-horizon and line-of-sight communications technologies on the lunar surface. Requires bringing a variety of such systems to the Moon.
- **Mars Robotic**
  - Test technologies for navigating on the surface of Mars without a strong global magnetic field, and with the possibility of wind-blown dust covering ones tracks. Requires deployment of space based or surface based navigational assets (inertial and/or relative).
  - Test spacecraft navigation systems at Mars. Requires deployment of space or surface-based assets, or technologies to use Mars' moons, Mars itself, or other bodies, for navigation (inertial and/or relative).

Advanced Automated Rendezvous & Capture

Critical Elements to Test

- **Single-sensor technology for long, medium, and close range pursuit of both unaugmented and cooperative spacecraft**
- **Advanced androgynous mating adapter**
- **Navigation and proximity operations with little direct Earth support**
- **Image recognition systems**
- **Intelligent flight software**

Testing Venues & Benefits

- **Earth-based facilities**
  - Ground-based testing of actual flight hardware in simulated real “flight” conditions provides opportunity to model expected as well as unexpected failure modes
- **LEO / ISS**
  - Demonstration of key AAR&C technologies at ISS provides actual routine flight performance data necessary for future applications
- **Near-Earth Flight Tests**
  - AAR&C tests in near-earth can be used to determine system responses to induced and indigenous faults at remote distances
- **Mars Robotic Missions**
  - None identified.

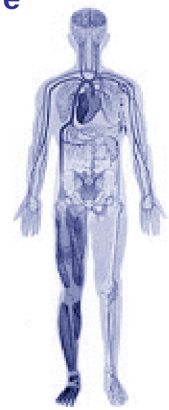
Testing Approach & Support Needed

- **Earth**
  - Laboratories and simulators utilized to determine single-sensor and flight software performance in flight-like conditions.
  - Simulations of distant, remote AAR&C operations conducted
- **LEO / ISS**
  - Single launch, dual spacecraft, mission approach for demonstrating AAR&C technology system performance
  - Demonstration of AAR&C technologies performed in LEO/Near-Earth prior to utilizing at ISS.
  - Routine operational use of AAR&C at ISS will develop in-depth operational performance data necessary for future missions
- **Near-Earth**
  - AAR&C technologies demonstrated in near-earth space robotically prior to utilization on human missions.
- **Mars Robotic**
  - None identified.

Crew Health Systems

Critical Elements to Test

- **Radiation environment and protection strategies**
- **Long-duration performance of countermeasure equipment and protocols**
- **Medical diagnosis and treatment equipment**
- **Artificial-g techniques and protocols**
- **Food - nutrition and long-term storage**



Testing Venues & Benefits

- **Earth-based facilities**
  - Ground testing with appropriate simulators provides necessary training & experience before committing crew to missions in space.
  - Allows both individual component and system level testing
- **Near-Earth Flight Tests**
  - Artificial-g testing important for crew and equipment testing.
  - Planetary g levels can be generated to test habitats, equipment, EVA, crew health, integrated spacecraft, and control strategies.
- **Lunar Tests**
  - Evaluate radiation shielding strategy and neurovestibular issues
  - Opportunities for Bioastronautics research in lieu of ISS
- **Mars Robotic Missions**
  - Key to providing environmental hazard data

Testing Approach & Support Needed

- **Earth**
  - Simulators to test countermeasure equipment
  - Radiation biology and shielding tests to determine risk levels
  - KC-135 flight tests at various gravity levels

- **All Human Space Venues**
  - All items mentioned will not only be sent for testing, but must also meet the requirements for crew health support. As such, it is not acceptable to send them ‘untested.’ Rather, they will need to be tested and verified pre-mission for at least their mission requirements. Verifying their ability to go beyond those requirements and fulfill additional or more stringent requirements for a Mars mission is the real goal.

- **Near-Earth**
  - ISS research as established in Critical Path Research Program
  - Artificial-g program recommended, especially if used for MTV.

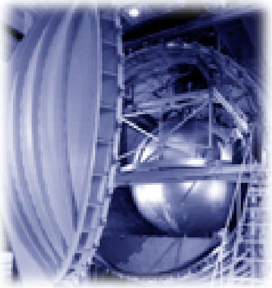
- **Lunar**
  - Validate efficacy and performance of countermeasure equipment
  - Validate and demonstrate medical equipment
  - Validate food systems and habitat human factors on a planet.

- **Mars Robotic**
  - Mars robotic missions are key to providing Martian environmental data (dust composition, radiation, terrain, hazards)

Cryogenic Fluid Management

Critical Elements to Test

- **Long-term pressure control with flight type system**
- **Zero-boiloff control with integrated vehicle concept**
- **0-g & Low-g liquid acquisition and mass gauging data**
- **Cryocooler performance & life in integrated tank**
- **0-g & Low-g propellant transfer**
- **Variable g (1-g to 0-g to 1/3 or 1/6-g) thermal management**



Testing Venues & Benefits

- **Earth-based facilities**
  - Component as well as system level tests can be conducted in Earth-based simulators (chambers) to verify system performance
  - Long-duration Mars surface simulation with dust
- **Near-Earth Flight Tests**
  - Zero-g testing is critical to test and validate liquid acquisition and distribution as well as mass gauging and pressure control technologies
  - Flight test of integrated systems reduces potential Mars mission risk
- **Lunar and Mars Robotic Tests**
  - Not required for system certification, however validation of low-g and dust on system thermal management performance (tanks and radiators) is highly desired to minimize conservatism

Testing Approach & Support Needed

- **Earth**
  - Earth-based testing is required for all cryogenic systems
  - Although storage system components can be tested separately, an integrated system level test is required to verify system performance and math models
  - Most Earth-based testing can be conducted in existing facilities. Long-duration Mars surface simulation with dust is not currently available (upgrades possible)
- **Near-Earth**
  - Zero-g flight test of liquid acquisition, mass gauging, and pressure control technologies desired to minimize design conservatism
  - Long-duration test of integrated performance further reduces potential Mars mission risk
  - A subscale cryogenic fluid management test, integrated with other systems, is highly desirable prior to human flight.
    - Lack of low-g data creates significant accumulative uncertainty for liquid acquisition, mass gauging, pressure control, and zero boil-off technologies.
    - Long-duration testing with integrated systems would further reduce potential Mars mission risk
- **Lunar**
  - Not required for certification. However demonstrations to validate low-g and dust on system thermal management performance (tanks and radiators) is highly desired
- **Mars Robotic**
  - Not required for certification. However demonstrations to validate low-g and dust on system thermal management performance (tanks and radiators) is highly desired

EVA Systems

Critical Elements to Test

- **Space suit mobility & dexterity performance**
- **EVA communications / information systems**
- **Life support system component operation**
- **Space suit thermal protection & operation**
- **Dust protection and radiation protection**
- **EVA traverse mapping & route planning**
- **Surface mobility systems “trafficability”**
- **EVA system maintenance strategies**

Testing Venues & Benefits

- **Earth-based facilities**
  - Certification in ground-based simulators required before use
  - Both simulators and field tests allow “build a little; test a little” to provide greater insight to “go/no go” technical decisions
- **Near-Earth Flight Tests**
  - None identified
- **Lunar Tests**
  - Lunar surface tests can establish EVA systems functional performance capabilities in a similar environment
  - May prove useful for long-term “dry run” rehearsals and “what if” scenarios
- **Mars Robotic Missions**
  - Key to providing martian environmental and hazard data

Testing Approach & Support Needed

- **Earth**
  - High-fidelity simulators and chambers
  - Analog ground-based (field) testing
  - KC-135 flight tests at various gravity levels
  - Integrated systems tests of leading candidates to “down-select”

- **Near-Earth**
  - No apparent benefits considering the vast operational and unique environmental differences between LEO and planetary surfaces.

- **Lunar**
  - Surface EVA in greater numbers & durations for system validation
  - Validate EVA traverse mapping & route planning techniques
  - Lunar surface conditions similar, but not truly “Mars-like”

- **Mars Robotic**
  - Mars robotic missions are key to providing martian environmental data (dust composition, thermal, radiation, terrain, hazards)

Integrated Testing

Critical Elements to Test

- **Integration of most mission elements for vehicles, habitats, & surface operations – *"Fly the Mission on the Ground"***
  - **Life support, medical, mission operations, Integrated controls, EVA, rovers, robotics, …**
- **Focus for R&D**
- **Low risk, low cost**
- **Develop new management techniques**
- **International, commercial, academic partnering**
- **Education & public outreach**

Testing Venues & Benefits

- **Earth-based facilities**
  - Provides continual focus for R&D programs
  - Validate technologies in integrated mode
  - Best way to identify integration challenges of complex systems & long duration operations
  - Low risk, low cost
  - Allows for development of improved management techniques while training personnel needed for future missions
  - Processes for international, commercial, & academic partnering can be developed
  - Tremendous education tool
  - On-going engagement of public
- **Near-Earth Flight Tests**
  - Artificial gravity vehicles; hypogravity test platforms
- **Lunar System Tests**
- **Mars Robotic Missions**

Testing Approach & Support Needed

- **Earth**
  - High-fidelity, mission-level, long-duration testing with humans in the loop can be accomplished in atmospherically sealed modules
  - Multiple simulators – transit vehicle, landing/ascent vehicle, planetary habitat, planetary surface operations (EVA, robotics), rovers, mission control
  - Can use prototype technologies (lower cost than flight or flight-like equipment)
  - Can evaluate multiple candidate technologies concurrently; can transfer hardware in and out easily to make adjustments without stopping test (airlock)
  - Data for complex modeling can be collected to minimize crew time requirements
  - Maintainability issues can be addressed
  - Crew autonomy can be evaluated
  - Develop improved management techniques for large, complex programs (missions) with international, commercial, & academic partners
  - Integrate with other test beds & analog sites around the world
  - Engage the public world wide
  - Equivalent of flight experiments can be conducted – easy access
  - Implement a methodical & sustained public outreach plan with visitor's center to engage the public
  - Develop & continually use metrics to assess progress in all areas
- **Near-Earth**
  - Testing & validation of artificial gravity transit vehicles would mean that ground testing can be used to validate technologies for direct use in transit vehicles
- **Lunar**
  - Validation in hypogravity & vacuum environments can be accomplished
- **Mars Robotic**
  - Robotic missions to assess Mars environment, conduct early experiments, & to pre-deploy equipment for human missions

Integrated Testing – Mars Ascent

Critical Elements to Test

- **Long-duration radiation hardening of spacecraft components**
- **Mars surface environment affects**
- **Long-duration dormancy of primary vehicle systems**
- **Propellant management and conditioning**
- **Blast debris during ascent**

Testing Venues & Benefits

- **Earth-based facilities**
  - Radiation testing of electronics and spacecraft components tested in ground facilities mitigates the risk of deep-space radiation
  - Ground based simulators (chambers) utilized to test the environmental affects (temperature, dust, atmosphere)
  - Long-duration dormancy tests in Mars-analog field sites
- **Low-Earth Orbit**
  - Not applicable
- **Near-Earth and Lunar System Tests**
  - Missions to the lunar surface can serve as proto-tests of Mars mission hardware and operational techniques including long-duration dormancy and liftoff debris mitigation
- **Mars Robotic Missions**
  - Robotic missions, though not at a large scale, can demonstrate some critical elements including radiation hardening, long-duration dormancy, and ascent techniques.

Testing Approach & Support Needed

- **Earth**
  - Mars analog simulators (chambers) used to simulate surface conditions, including atmosphere, temperature, and dust, for long durations
  - Beam-line tests to certify and understand radiation effects and radiation mitigation techniques
  - Long-duration exposure test both in chambers and Earth field sites to understand component dormancy and environmental issues
  - Ascent simulations in Earth-based facilities
- **Low-Earth Orbit**
  - Not applicable
- **Near-Earth and Lunar**
  - Lunar missions provide operational performance data of radiation hardened electronics
  - Operational and system performance during staged ascent from the lunar surface including subsystem performance and debris mitigation
  - Extended surface stays will provide additional dormancy issues to mitigate future Mars mission risks
- **Mars Robotic**
  - Large-scale sample return mission provides an opportunity to observe and measure the performance of launch system and ascent propulsion technologies in the actual Martian environment

Integrated Vehicle Health Management

Critical Elements to Test

- **Identification of system failure modes**
- **Model Based Reasoning techniques**
- **Computing systems and requirements**
- **Software verification and validation**

Testing Venues & Benefits

- **Earth-based facilities**
  - Ground-based testing of actual flight hardware in simulated real “flight” conditions provides opportunity to model expected as well as unexpected failure modes
- **Near-Earth Flight Tests**
  - IVHM tests in near-earth can be used to determine system responses to induced and indigenous faults while close to Earth
- **Mars Robotic Missions**
  - Robotic missions can demonstrate some IVHM techniques prior to human missions

Testing Approach & Support Needed

- **Earth**
  - Ground based testing of actual flight hardware, including simulated cooling, power supply effects etc. Emphasis not on design errors so much as real world effects not taken into account.
  - Development of Model Based Reasoning techniques as currently implemented require a substantial effort during design. This is because of the need for a lot of human interaction during the design process to set appropriate threshold levels and identify failure modes.
  - IVHM requires substantial computational power, thus higher computational power increases the reasoning speed and the scope of problems that IVHM can deal with.
  - Ground-based software verification and validation for MBR and Neural Net software is essential.

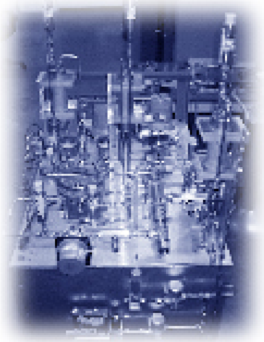
- **Near-Earth & Lunar**
  - Space based testing will require a high bandwidth data connection to the ground, so as to allow ground based computation to back up the space based computing. And the usual, design specific, requirements on power, volume, etc. The environment should match as closely as possible (radiation, gravity, vacuum, vibration) but the location would have to be close enough to earth for reasonable communication bandwidth.
  - LEO missions can substitute reasonably well for the Mars transits

- **Mars Robotic**
  - IVHM concepts integrated with robotic mission avionics suites implemented within system resources and capabilities

In-Situ Resource Utilization

Critical Elements to Test

- **All ISRU subsystems and components:**
  - Atmospheric acquisition
  - Chemical reactors
  - Gas and water separation
  - Water electrolysis
  - CO_2 electrolysis
  - Phase separation
  - Product storage
  - Environmental (dust) effects
  - Advanced health monitoring



Testing Venues & Benefits

- **Earth-based facilities**
  - Earth-based analogs and simulators are essential for testing, performance characterization, and environmental operation simulation
  - KC-135 flight tests of lower gravity environments necessary for gravity sensitive processes
  - Simulation of martian environment, especially dust, is essential
- **Lunar Tests**
  - Lunar surface tests can demonstrate performance in actual space environments especially water processes that may be used on Mars
- **Mars Robotic Missions can demonstrate**
  - Robotic missions can demonstrate many ISRU components and processes prior to use with human systems

Testing Approach & Support Needed

- **Earth**
  - Long-duration Earth-based simulations and analogs would be performed in laboratories, mission environment (vacuum) simulation chambers, mission analog complexes, and field trials
  - Long-duration Mars surface simulation with dust is not currently available (upgrades possible)
- **Near-Earth**
  - Fluid and thermal experiments and lab facilities on the ISS to perform basic research, especially zero-g and partial-g phenomenon
- **Lunar**
  - Science instruments and sampling systems design to provide engineering and resource availability data (i.e. prospector data) as well as potential ISRU precursor missions, such as lunar ice excavation and separation
  - Partial-g processes and techniques should be tested
- **Mars Robotic**
  - A wide range of testing can be conducted on robotic missions:
    - Standalone ISRU component testing
    - ISRU concepts which extend or enhance robotic mission return (e.g. ISRU hopper or rover with fuel cell resupply)
    - Missions which are enabled via ISRU concepts (e.g. propellant production for large-scale sample return missions)

Life Support System

Critical Elements to Test

- **Model validation of integrated life support system**
- **System performance characterization**
- **Crew interaction**

Testing Venues & Benefits

- **Earth-based facilities**
  - Certification in ground-based simulators required before use in space
  - Ground-based testing allows crew interaction as well as "build a little; test a little" to provide greater insight to "go/no go" technical decisions
- **Near-Earth Flight Tests**
  - ISS provides an ideal location to test advanced life support concepts while improving ISS efficiency
  - ISS provide a venue for long-duration system testing
- **Lunar System Tests**
  - Provides a venue to test system performance in a low-gravity environment
- **Mars Robotic Missions**
  - Can test limited system performance that is applicable

Testing Approach & Support Needed

- **Earth**
  - Various tests can be performed from the component to system level
  - Chamber and integrated tests with human subjects (providing not only metabolic loads, but operational interactions), mission-scale power, and appropriate volume constraints
  - Tests should include longer duration simulations to adequately model future Mars missions
  - Tests of differing configurations and technologies to determine optimum performance
  - Test data provides valuable data for math model validation
- **Near-Earth**
  - Tests of advanced life support systems at ISS should be used as much as possible to gather data about human accommodations and life support systems and the crew's interactions with them
- **Lunar**
  - System performance in a similar, though not truly "Mars like" planetary environments (low-gravity, dust) will provide additional risk mitigation data
- **Mars Robotic**
  - Robotic missions can provide data on system performance in the martian environment, such as thermal control and gas venting.

Life Support System – Air Revitalization

Critical Elements to Test

- **Long-duration testing with humans in the loop to understand optimal system performance and crew operation**
- **Integrated testing of multiple systems**
  - Trace contaminant control
  - Software integration
  - Oxygen generation
  - CO_2 removal

Testing Venues & Benefits

- **Earth-based facilities**
  - Allows integrated systems testing with less risk and cost
  - Allows evaluation of components, systems for future down-selection
  - Allows for contingency and operational planning
- **Near-Earth Flight Tests**
  - Allows for critical micro-gravity validation of systems on an integrated level
  - Provides greater confidence and evaluation of design
- **Lunar System Tests**
  - Allows for long-duration validation in a more relevant environment
- **Mars Robotic Missions**
  - Obtaining Mars environmental data (presence of water, O_2, N_2) is vital

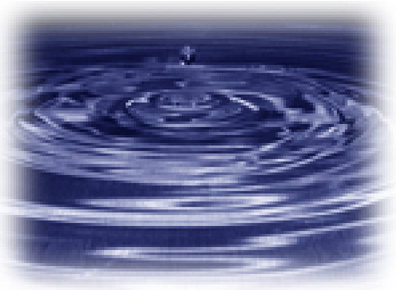
Testing Approach & Support Needed

- **Earth**
  - Various tests can be performed from the component to system level
  - Chamber and integrated tests with human subjects (providing not only metabolic loads, but operational interactions), mission-scale power, and appropriate volume constraints
  - Tests should include longer duration simulations to adequately model future Mars missions
  - Tests of differing configurations and technologies to determine optimum performance
  - Test data provides valuable data for math model validation
- **Near-Earth**
  - Tests of advanced life support systems at ISS should be used as much as possible to gather data about human accommodations and life support systems and the crew's interactions with them
- **Lunar**
  - System performance in a similar, though not truly "Mars like" planetary environments (low-gravity, dust) will provide additional risk mitigation data
- **Mars Robotic**
  - Mars environmental data needed.

Life Support Systems – Water Recovery

Critical Elements to Test

- **Multi-phase flow technologies for use in a micro-gravity environment**
- **Integrated advanced water recovery system performance**



Testing Venues & Benefits

- **Earth-based facilities**
  - Earth-based analogs and simulators are essential for testing, performance characterization, and environmental operation simulation
- **Near-Earth Flight Tests**
  - Flight tests in micro-gravity will provide data to validate multi-phase flow math models. Can be conducted as free-flyer or on ISS
  - ISS provides an excellent venue for demonstrating advanced water recovery technologies
- **Mars Robotic Missions**
  - Not applicable

Testing Approach & Support Needed

- **Earth**
  - End-to-end integrated life support system tests for long-durations including crew interactions
  - Integration with all other life support systems is critical for testing with representative loading and contamination levels
  - Testing should be closed-loop to mitigate issues arising from the associated environment
  - Further, extended testing of at least 90 days is required to mitigate issues associated with integrated testing
- **Near-Earth**
  - Testing on ISS could consist of flight experiments of an integrated water system. It would be necessary to interface with the existing water recovery system on ISS
  - A minimum of one “Express Rack” would be required to complete the necessary testing. Size would vary depending on scale selected for experiment
- **Lunar**
  - In order to test water recovery systems the lunar test bed should have the capability of a closed-loop environment with human-generated waste streams
  - Operational experience on full-scale systems could be collected and evaluated prior to system deployment on a Mars mission
- **Mars Robotic**
  - Not applicable

Life Support Systems – Plant Growth

Critical Elements to Test

- **Long-term sustainability / reliability of crop production systems**
- **Autonomous environmental monitoring**
- **Thermal protection and management**
- **Inflatable structure technologies**
- **Low-pressure growth systems**
- **Plant light systems**

Testing Venues & Benefits

- **Earth-based facilities**
  - Earth based simulations could cover much of initial assessments, whether in laboratory or field settings,
  - Lunar orbit/surface or Mars transit for more accurate testing
  - High elevation sites (e.g., ALMA telescope site in Chile)
- **Near-Earth Flight Tests**
  - Earth Orbital Mission (ISS) operations required for more realistic and transit for worst case testing
  - Lunar tests to better simulate deep-space conditions
- **Mars Robotic Missions**
  - Robotic missions key to providing Mars environmental data
  - Robotic missions can demonstrate some technologies such as gas separation and compressors

Testing Approach & Support Needed

- **Earth**
  - Use of laboratory setting (plant growth chambers) and large scale closed environment facilities
  - Laboratory or field settings with cold temperature and high UV for solar collector/conduit, inflatable structure, and low pressure tests
  - Lab testing using soil simulates in growth chambers develop simulants based on surface or sample return data
  - Autonomous monitoring / control: initial tests in lab, hyperbaric chambers, test plant chamber ops on orbit (ISS)
- **Near-Earth**
  - ISS plant growth facilities with continuous sustained production
- **Lunar**
  - Lunar surface plant growth facilities with continuous sustained production
  - Demonstration of advanced light collection/distribution technologies and advanced thermal control
- **Mars Robotic**
  - Instrumentation to provide key Mars environmental data

Life Support Systems – Waste Management

Critical Elements to Test

- **Fecal processing, storage and disposal**
- **Waste CO_2 and nutrient recovery**
- **Waste drying and water recovery**
- **Gravity dependent phenomenon**
- **Integrated LSS testing**
- **Waste sterilization**
- **Waste compaction**

Testing Venues & Benefits

- **Earth-based facilities**
  - Earth-based testing facilities are critical to the development and validation of advanced life support system technologies prior to use
- **Near-Earth Flight Tests**
  - Testing of the advanced waste management systems will require micro-gravity testing before they can be considered reliable enough for a Mars mission
- **Mars Robotic Missions can demonstrate**
  - Not applicable

Testing Approach & Support Needed

- **Earth**
  - Earth based testing can be conducted on a stand alone basis in laboratories on advanced prototypes as well as in integrated tests in relevant environments including the other subsystems with which the waste subsystems must interchange material or energy. Typically a test will include the need to provide representative waste, volume up to about 8 cubic meters, energy varying from 100 watts to several kW, and provision for handling exit products including gases, water, and solids
- **Near-Earth**
  - Microgravity or Lunar hypogravity testing should be conducted with advanced prototypes. In some cases only particularly sensitive parts of the subsystem may need testing in microgravity. Test requirements will generally be less than for earth based testing. Typically the test will require representative waste input, volume up to about 1 cubic meter, energy up to about 1 kW, and provision for handling exit products including gases, water, and solids.
- **Lunar**
  - See near-earth above.
- **Mars Robotic**
  - Not applicable

Operations – Automation Technologies

Critical Elements to Test

- **Hardware, software, and mission control systems**
- **System performance and planning**
  - Normal operation and planning
  - Fault detection a reconfiguration
  - Trajectory and navigation
  - Trends and predictions
  - Displays and alarms

Testing Venues & Benefits

- **Earth-based facilities**
  - Earth-based testing (simulators and analogs) of advanced automated operational concepts is vital to reduce further exploration risks
  - Can repeatedly test automated systems management technologies against proven, deterministic, mission operations procedures and flight rules, including malfunction procedures that are used for currently operational vehicles
- **Near-Earth Flight Tests**
  - Extending testing locales to ISS and eventually lunar operations can further reduce potential long-duration Mars mission risks
- **Mars Robotic Missions**
  - Limited applicability due to mission resources

Testing Approach & Support Needed

- **Earth**
  - In simulators, the automation technology would consist of a software load that would monitor data from specified simulated vehicle systems, evaluate system health and trends, predict future health status, issue commands, and perform system configuration tasks according to deterministic rules.
  - Trajectory, and GN&C automation software would operate with simulated state vector, accelerometer, and attitude data as inputs. The automation software can be adapted to monitor and command any kind of system that can be electronically commanded and that outputs commands and/or performance data.
  - Automation software loaded on a laptop computer can be used to monitor and command operational hardware that is deployed to analog sites for field-testing.
  - Iron Bird testing could be much more extensive, on the order of simulator testing, but using real spacecraft systems for a much higher fidelity integrated test of automation technology
- **Near-Earth**
  - Automation technologies may be tested aboard the ISS by monitoring an actual system in parallel with operational ISS systems and the MCC.
- **Lunar**
  - Automation technologies technologies for Mars missions can be conducted on the Moon. A lunar habitat, occupied for 30 to 90 days at a time, allows automation technologies to be used and tested over a long period of time, under actual operational conditions, in an environment where their performance is not critical to mission success or crew safety, as it would be during a human mission to Mars.
- **Mars Robotic**
  - Limited applicability due to mission resources

Operations – Dust Mitigation

Critical Elements to Test

- **All components and systems exposed to planetary surface dust**
  - Electronic components
  - EVA systems and rovers
  - Lander and surface systems
- **Operational procedures**
  - EVA to IVA dust management
- **Cleaning and filtering**

Testing Venues & Benefits

- **Earth-based facilities**
  - Environmental simulators (wind, dust, vacuum), full-scale mockups
  - Field tests including simulated environments and terrain
- **Near-Earth Flight Tests**
  - Not applicable
- **Lunar Tests**
  - Routine operation of surface systems to determine dust effects
  - Demonstrate and perfect dust mitigation for low-g environments
- **Mars Robotic Missions**
  - Mars surface and atmospheric environmental data
  - Routine operation of surface systems to determine dust effects
  - Demonstrate and perfect dust mitigation for low-g environments

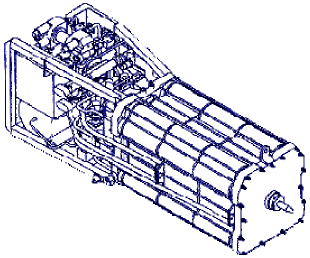
Testing Approach & Support Needed

- **Earth**
  - Reduces cost and provides greater maturity of operational techniques for dust mitigation and system design
  - Provides low-cost methods of testing multiple planetary analogs representing various potential landing sites
  - Provides the capability to test the many components and systems that will be exposed to planetary dust
  - Allows the testing of near-actual planetary environments including martin wind (although can not adequately simulate dust suspension due to higher gravity)
- **Near-Earth**
  - Not applicable
- **Lunar**
  - Although the lunar surface environment is not truly “Mars like,” lunar surface missions can serve as a test bed for future Mars dust mitigation procedures and techniques
  - Lunar surface operation will provide valuable data on component performance in dusty environments
- **Mars Robotic**
  - Robotic missions can test dust mitigation techniques and component performance in the actual dust environment
  - Will provide improved Mars atmospheric knowledge and modeling, including predictability
  - Dust mitigation technologies, such as electrostatic sensors and discharge techniques, should be tested on robotic missions

Power Systems – Fuel Cells

Critical Elements to Test

- **Fuel Cell Power Plant**
  - Stack and component life
  - Gravity-independent operation of components
- **Power System**
  - Integrated performance



Testing Venues & Benefits

- **Earth-based facilities**
  - Integrated / regenerative testing in relevant environments and operational conditions provides system verification
  - Both simulators and field tests allow “build a little; test a little” to provide greater insight to “go/no go” technical decisions
- **Near-Earth Flight Tests**
  - Testing in LEO and Near-Earth provides operational data on gravity independence performance
- **Lunar Tests**
  - Provides data on long-term system performance in planetary environments that are similar, though not actually “Mars like”
- **Mars Robotic Missions**
  - None identified

Testing Approach & Support Needed

- **Earth**
  - Component and integrated system ground-based testing (performance and life testing)
  - Gravity-independence tested via various orientations
  - Performance during field testing (surface rovers)
- **Near-Earth**
  - Integrated flight test for micro-gravity and gravity independence
- **Lunar**
  - Testing in multiple operational conditions including orbital (zero-g), entry & descent, and surface (partial-g)
  - Operational testing in similar modes (rovers)
- **Mars Robotic**
  - None identified

Power Systems – Surface Solar

Critical Elements to Test

- **Environmental affects on solar power system performance**
  - Dust mitigation
  - Atmospheric discharge
- **System performance during changes in environmental conditions**

Testing Venues & Benefits

- **Earth-based facilities**
  - Earth based testing is essential in verifying long life operation of array and energy storage operations
- **Near-Earth Flight Tests**
  - None identified
- **Lunar Surface Tests**
  - None identified
- **Mars Robotic Missions can demonstrate**
  - A flight experiment of the array is required to fully understand and assess the interaction of both the static and dynamic aspects of the environment on long term (Martian year) operation issues

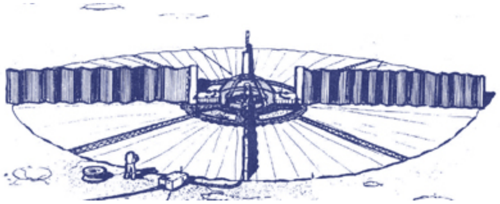
Testing Approach & Support Needed

- **Earth**
  - Earth based testing should establish component and system performance, life, establish operational characteristics and inter-component dynamics such as the array, energy storage and power management systems can be determined in laboratory breadboard testing.
  - Earth based testing of exposed voltage components must be tested in a relevant environment (large bell jar or small vacuum chamber).
  - High voltage/insulation experiments on cables and electrical components should be done in a simulated Mars atmosphere
  - Array/energy storage integration does not require a simulated environment for test components.
- **Near-Earth**
  - Not applicable
- **Lunar**
  - Not applicable
- **Mars Robotic**
  - Flight demonstrate an array module of the anticipated flight hardware size should be evaluated on the Martian surface outfitted with the most feasible dust mitigation techniques as a definitive evaluation of solar power issues on Mars.
  - Small scale tests should be done on near term Mars missions to determine optimal dust mitigation techniques.

Power Systems – Surface Nuclear

Critical Elements to Test

- **Radiation and thermal effects on materials**
- **Power system design and thermal characterization (level, gradients, stress)**
- **Transient responses (startup and shutdown)**
- **System level performance**



Testing Venues & Benefits

- **Earth-based facilities**
  - Earth-based testing in simulators allows independent testing of reactor, power conversion, heat rejection, & power distribution
  - Radiation effects can be tested in DOE and university labs
  - Mars environmental effects tested in chambers
- **Near-Earth Flight Tests**
  - Not applicable
- **Lunar Surface Tests**
  - Characterization of system performance in planetary, although not truly “Mars Like” environments
- **Mars Robotic Missions can demonstrate**
  - Large-scale robotic missions can demonstrate nuclear power use

Testing Approach & Support Needed

- **Earth**
  - Component and system performance, life, establish operational characteristics and inter-component dynamics such as the reactor and conversion dynamic response to flow, power and temperature variations.
  - Testing of all nuclear systems is required to varying degrees for launch and operational safety.

- **Near-Earth**
  - Not applicable

- **Lunar**
  - Lunar surface missions can be utilized to further verify systems prior to committing to a human Mars mission. A nuclear power system can be delivered to a planetary location and tested as its own demonstration. When success has been determined, other missions can be sent to that locale to take advantage of a pre-deployed power system.

- **Mars Robotic**
  - Large-scale robotic missions can demonstrate nuclear power components and systems operational characteristics

Propulsion – Advanced Chemical

Critical Elements to Test

- **Main engines & attitude control system (ACS) thrusters**
- **Propellant management components (isolation valves, couplings, etc.)**
- **ACS feedsystem**
- **Integrated Main/ACS system**
- **Mission environments of concern:**
  - Long-duration quiescence
  - “Fire-in-hole” ascent stage
  - Landing exhaust/dust damage

Testing Venues & Benefits

- **Earth-based facilities**
  - Component as well as system level tests can be conducted in Earth-based simulators (chambers) to verify system performance
  - Long-duration lunar/Mars surface simulation with dust required to understand impact on internal softgoods, turbomachinery, and injectors
- **Near-Earth and Lunar Flight Tests**
  - Not required for system certification, however validation of low-g and dust on system performance and landing exhaust characterization is highly desired to minimize conservatism
- **Mars Robotic Missions**
  - Not required for system certification, however validation of low-g and dust on system performance and landing exhaust characterization is highly desired to minimize conservatism

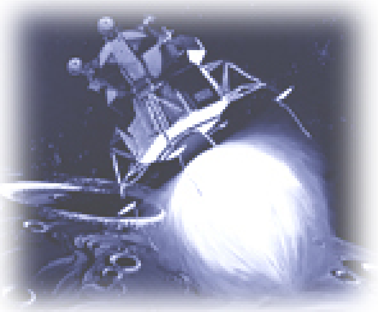
Testing Approach & Support Needed

- **Earth**
  - Sea-level and attitude chamber testing of engines and systems using existing facilities
  - Cold flow and hot-fire testing of ACS and integrated main/ACS systems at sea-level and simulated mission environments
  - Simulated exhaust/plume surface testing
  - Simulated “Fire-in-hole” ascent stage testing
  - Long-term quiescent testing leading to hot-fire (not know if simulation capability currently exists)
- **Near-Earth**
  - Not required
- **Lunar**
  - Not required for system certification, however validation of low-g and dust on system performance and landing exhaust characterization is highly desired to minimize conservatism
- **Mars Robotic**
  - Not required for system certification, however validation of low-g and dust on system performance and landing exhaust characterization is highly desired to minimize conservatism

Propulsion – Rocket Exhaust Cratering

Critical Elements to Test

- **Physical dynamic phenomena**
  - Physics and kinematics
  - Surface bearing capacity
  - Influence of carbon dioxide and water ice
- **Software and math models**



Testing Venues & Benefits

- **Earth-based facilities**
  - Fundamental research in ground-based facilities provides necessary understanding of the vehicle/surface landing physics
  - Ground facilities can be used to simulate a variety of surface models and landing conditions
  - Detailed understanding of this phenomenon is vital to vehicle design
- **Near-Earth and Lunar Flight Tests**
  - Not applicable due to different environmental conditions
- **Mars Robotic Missions**
  - Can only be tested on very large robotic landers utilizing terminal landing descent techniques
  - Can characterize Martian subsurface and provide some surface erosion data during landings

Testing Approach & Support Needed

- **Earth**
  - Ground-based research on basic cratering phenomena including various engine types and surface (regolith) models with differing surface and subsurface conditions
  - Development of physical math models from a variety of engine firing tests and ground models
- **Near-Earth**
  - Not applicable
- **Lunar**
  - Not applicable due to different environmental conditions
- **Mars Robotic**
  - Can investigate composition and mechanical properties of Martian near subsurface including ices
  - Can only be tested on very large robotic landers utilizing terminal landing descent techniques
  - Unmanned cargo missions which land prior to the human mission to certify and determine level of exhaust cratering
  - Instrumentation for the surface and sub-surface environmental characterization of Mars is vital

Propulsion – Solar Electric

Critical Elements to Test

- **Electric thruster performance**
  - Efficiency at high power levels
  - Lifetime and degradation
- **Solar power generation**
  - Efficiency and degradation
  - Deployment and control
  - Power distribution

Testing Venues & Benefits

- **Earth-based facilities**
  - Long-duration high-power EP thruster tests in vacuum chambers provides valuable system performance data
  - Power generation and degradation tests partially tested
  - Sub-scale deployment tests can be conducted in ground facilities
- **Near-Earth Flight Tests**
  - In-space performance of EP systems, deployment, radiation damage, and lifetime tests can be demonstrated
- **Earth to Moon Flight Tests**
  - In-space performance of SEP cargo vehicle can be demonstrated
- **Mars Robotic Missions can demonstrate**
  - Not applicable

Testing Approach & Support Needed

- **Earth**
  - Long-duration test of high-power EP thrusters. Long-duration tests become a pacing item.
  - Laboratory tests of solar cell concepts.
  - Radiation testing to simulate Van Allen radiation and deep space damage.
  - Sub-scale deployment and / or construction tests

- **Near-Earth**
  - Deployment and/or construction tests of sub-scale to large-scale SEP systems is required
  - Maneuvering and control of large scale structures demonstrated
  - Long-duration tests of thrusters, power generation, and power distribution systems in the deep-space (beyond Earth's magnetosphere) demonstrated

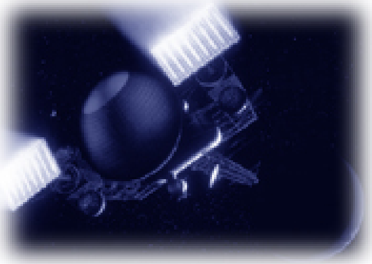
- **Lunar**
  - Full-scale operational tests of SEP systems beyond low-Earth orbit demonstrated in actual operation

- **Mars Robotic**
  - Not applicable

Propulsion – Nuclear Electric

Critical Elements to Test

- **Nuclear Reactor**
  - Lifetime
  - Power conversion
  - Two-phase flow
  - Thermal control
  - Thrusters
- **Mission Concepts**
  - Deployment/assembly
  - Steering
  - Rendezvous



Testing Venues & Benefits

- **Earth-based facilities**
  - Ground testing is necessary due to the advanced technology and high power requirements
  - Simulation of power conversion and reactor dynamics under normal and transient conditions.
  - Ground testing allows simulation of anomalous conditions
- **Near-Earth Flight Tests**
  - In-space performance of EP systems, deployment, radiation damage, and lifetime tests can be demonstrated
- **Earth to Moon Flight Tests**
  - In-space performance of NEP cargo vehicle can be demonstrated
- **Mars Robotic Missions can demonstrate**
  - Not applicable

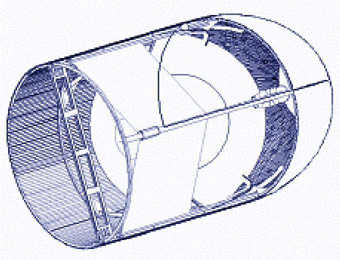
Testing Approach & Support Needed

- **Earth**
  - Ground testing of 500-1000 kWe thruster concepts. Note that effluent throughput will require upgrades to the pumping capacity of existing vacuum chambers.
  - Long-duration tests in ground chambers
  - Reactor subsystems including fuel characterization, tested in an appropriate DOE lab.
  - Ground based non-nuclear thermal tests of power conversion system
  - Sub-scale deployment tests in ground-based simulators
- **Near-Earth**
  - Two-phase flow experiment for simulated reactor/conversion system must be done in space and early in the development. Dedicated free-flyer may be required due to safety issues.
  - Deployment / assembly tests in LEO needed prior to final design of human vehicle.
- **Lunar**
  - Complete sub-scale system (100’s kWe) test prior to human mission
- **Mars Robotic**
  - Not applicable

Structures and Materials

Critical Elements to Test

- **Radiation shielding**
  - Vehicles, habitats, EVA crew, robotics, electronic systems
- **Construction / deployment of vehicle components**
- **Long-duration exposure of materials to the deep-space environment**
- **Meteroid / debris shielding**
  - Vehicles, possibly surface habitats



Testing Venues & Benefits

- **Earth-based facilities**
  - Ground-based simulators (chambers, vibration labs, etc.) and analogs necessary to understand system performance & reduce risk

- **Near-Earth Flight Tests**
  - Long-term exposure of systems to the deep-space environment, including radiation, to reduce risk
  - Deployment and construction techniques in LEO demonstrate and validate advanced vehicle concepts

- **Mars Robotic Missions**
  - Determination of the deep-space and Mars environment is vital

Testing Approach & Support Needed

- **Earth**
  - Ground-based testing of structures behavior and predictability in the various operating environments
  - Sub-scale deployment tests of vehicle and system components

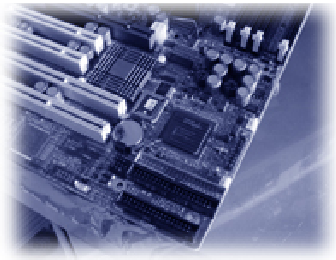
- **Near-Earth**
  - Full-scale deployment tests of vehicle and system components
  - Material behavior in deep-space environment
- **Lunar**
  - Material behavior in deep-space environment

- **Mars Robotic**
  - Material behavior in deep-space environment, including Mars surface conditions

Supportability

Critical Elements to Test

- **Concepts for effective supportability**
  - Maintenance
  - Repair
  - Integrated logistics support
  - Crew autonomy and training concepts
- **Component level repair**
- **Fabrication concepts**



Testing Venues & Benefits

- **Earth-based facilities**
  - Simulators and analogs where hardware performance and operational techniques can be tested
  - Test repeatability of hardware performance, maintenance procedures, and operational concepts is necessary prior to commitment to long-duration Mars missions
- **Near-Earth Flight Tests**
  - Concept can be tested to a limited extent on ISS
  - Long-duration stays on lunar surface more applicable
- **Mars Robotic Missions can demonstrate**
  - Not applicable – requires crew

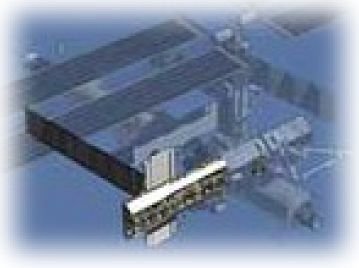
Testing Approach & Support Needed

- **Earth**
  - Advanced support concepts benefit most from testing crew, hardware, and operational support techniques together
  - Simulations of hardware failure and crew recovery techniques, including reconfiguration, component level repair, and just in time training
  - Long-term simulations for preventative maintenance strategies and repairs
- **Near-Earth**
  - Wide-scale implementation on ISS not possible due to hardware maturity and cost
  - Supportability concepts can be tested in LEO (ISS) for selected pre-planned hardware systems
- **Lunar**
  - Systems must be designed with supportability in mind
  - Supportability concepts can be tested on lunar missions, especially on missions of extended duration
- **Mars Robotic**
  - Not applicable – requires crew

Thermal Control Systems

Critical Elements to Test

- **Two-phase thermal control systems**
- **Radiators**
- **Heat pumps**



Testing Venues & Benefits

- **Earth-based facilities**
  - Earth-based simulators and vacuum chambers
  - Mars environmental chambers
- **Near-Earth Flight Tests**
  - Zero-g flight tests to determine gravity sensitive phenomena
- **Mars Robotic Missions**
  - Thermal system performance on martian surface including CO_2 and optical properties due to dust degradation

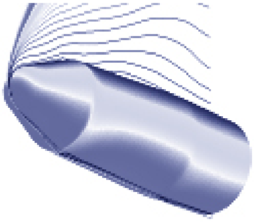
Testing Approach & Support Needed

- **Earth**
  - All radiator testing could be performed in Earth-based simulators
  - Mars environmental chambers would provide data to examine long-term performance in dusty environment with similar atmosphere chemical composition
  - Two-phase systems can, for the most part, be adequately tested on Earth
- **Near-Earth**
  - Flight tests, especially of two-phase systems, provides data on gravity sensitive performance (heat transfer, pressure drops, stability)
- **Lunar**
  - Provides data on long-term performance in planetary environments that are similar, though not actually “Mars like”
- **Mars Robotic**
  - Provides data on long-term performance in actual Mars operational environment

Thermal Protection Systems

Critical Elements to Test

- **Convective/Radiative heating environment**
  - – Vehicle shape and entry velocity dependent
- **Thermal Protection System Materials**
  - – Development, characterization, catalytic effects
- **Thermal Protection System Design**
  - – Selection and vehicle location
- **Operating Environment**
  - – Exposure, duration



Testing Venues & Benefits

- **Earth-based facilities**
  - Arc jet and radiant test facilities are necessary for certification of new TPS materials
  - Arc jet and radiant test facilities can simulate many, but not all entry variables simultaneously
  - New TPS material tests used to develop analytical models and perform ground validation
- **Near-Earth Flight Tests**
  - Flight tests required to simulate actual flight environments
- **Mars Robotic Missions can demonstrate**
  - Actual aeroshell and TPS performance in the martian atmosphere

Testing Approach & Support Needed

- **Earth**
  - Arc jet tests of coupons and systems
  - Radiant tests of coupons and systems
  - Impact tests of coupons and systems
  - Vacuum chambers for long-duration exposure tests

- **Near-Earth & Lunar**
  - Near-Earth tests can be used to increase the convective/radiative heating, pressure, and enthalpy
  - Flight tests provide additional model and system verification.
  - Lunar return speeds would provide both radiative and convective heating components plus all other induced environment components

- **Mars Robotic**
  - TPS performance in the actual martian atmosphere during actual flight conditions

Previously Identified Risks

Source	Risk ID	Description	L	C	Risk Score
Mars Hazards 3	1001	Close approach to Venus for gravitational boost places crew in closer proximity to the Sun which could result in Injury or death of the crew depending on the size and shielding within the spacecraft.	4	5	20
Mars Hazards 25	1002	Radiation hazard from solar and galactic radiation could result in possible crew death or injury from irradiation	4	5	20
RLL-PRP-03	1003	Dust generated during normal ops could cause critical failures (for example dust in thruster engines, EVA suit; filtration system).	3	5	15
RLL-PRG-09	1004	A massive solar flare while the crew is on the Mars surface may subject the crew to a critical radiation dose, resulting in crew illness or death and other long term health problems	3	5	15
Mars Hazards 22	1005	Meteoroid or orbital debris collision with spacecraft during the mission; could result in possible loss of crew and vehicle	3	5	15
Mars Hazards 1	1006	Chemical or oxidation effects of Martian soil on surface systems could result in possible damage to ascent or surface habitat resulting in crew death or injury	3	5	15
Test-01	1028	Failure of the ascent system during surface stay may not perform when needed during ascent could result in loss of crew	3	5	15
Gateway 3	1007	There is little or no data on LDE (long duration exposure) for materials in the Mars environment; the premature degradation of polymer/composites (which may be used for inflatable structures) could lead to early end of life.	3	4	12
RLL-PRG-08	1008	The build up of dust on the Mars surface habitat over multiple missions may cause critical system failure(s) during a mission.	3	4	12
RLL-ECS-01	1009	Given dust may be transferred into the Mars lander or habitat; could have adverse effect on the landers critical life support systems.	3	4	12
Mars Hazards 2	1010	Close approach to Venus for gravitational boost may result in planetary collision; could result in Injury or death of the crew	2	5	10
Gateway 33	1011	EVA suit failure could lead to inability to perform additional EVAs; leads to mission failure. Possible loss of EVA crew member	2	5	10
Gateway 37	1012	Unable to communicate between the Mars Lander and the Mars Transport Vehicle could lead to Docking failure, vehicle damage or loss of life	2	5	10
Mars Hazards 29	1013	Given unknown surface conditions (weather); there is a possibility that critical systems may not be able to withstand the environment.	3	3	9

Previously Identified Risks

Source	Risk ID	Description	L	C	Risk Score
Gateway 42	1014	Given inadequate design of fault detection and recovery system (IVHM); may lead to inadequate spares planning.	2	4	8
Gateway 26	1015	Critical subsystem failure could result in loss of mission (e.g. propulsion, GNC, ECLSS…)	2	4	8
Blueprint N-7	1016	Safety from environmental conditions could lead to an EVA suit design that is not capable of the range of necessary operations.	3	2	6
Blueprint N-6	1017	Given launch and orbital safety issues associated with nuclear propulsion technology and the lack of experience in actual nuclear launches; the processes may not be in place for timely launches of a Mars nuclear propulsion vehicle.	3	2	6
Gateway 18	1018	Given transit time required by electric propulsion to spiral out; critical systems will require longer system design lifetimes.	2	3	6
Gateway 36	1019	Given the use of autonomous robotic capabilities; there is a possibility that critical operations may not be completed.	2	3	6
Gateway 28	1020	Critical failure of crew exercise equipment could lead to crew health degradation	3	2	6
Mars Hazards 5	1021	Given biological contamination of descent, surface, or ascent vehicle from Martian surface; could result in failure of life support, crew illness/injury/death, damage to ascent vehicle, or return of contamination to Earth.	1	5	5
Gateway 27	1022	Given a toxic chemical release in the crew cabin; could lead to crew illness, injury, or death	1	5	5
BluePrint 27	1023	Given a mission to Mars requires multiple critical maneuvers; there is the possibility the vehicle may deviate from the planned path increasing travel time, propellant, or loss of vehicle.	1	5	5
Mars Hazards 8	1024	Excessive time exposure of crew to zero-g could result in injury or death of the crew due to large gravitational forces on degraded bone mass of the crew during Earth return.	1	5	5
Mars Hazards 26	1025	Static discharge between Martian surface and spacecraft during descent and landing could result in potential damage to the descent, ascent, or surface vehicles	1	4	4
Mars Hazards 23	1026	Outgassing of materials during long term low pressure operations could result in physiological effects on the crew.	1	3	3
RLL-STR-02	1027	Failure of landing systems due to off nominal landing conditions could result in delay or loss of mission objective.	1	3	3