TRANSPORTATION: DESTINATION MARS

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As the agency space transportation lead center, Marshall Space Flight Center has been conducting transportation assessments for future robotic and human Mars missions to identify critical technologies. Five human Mars options are currently under assessment with each option including all transportation requirements from Earth to Mars and return. The primary difference for each option is the propulsion source from Earth to Mars. In case any of the options require heavy launch capability that is not currently projected as available, an in-house study has been initiated to determine the most cost-effective means of providing such launch capability. This assessment is only considering launch architectures that support the overall human Mars mission cost goal of $25B. The guidelines for the launch capability study included delivery of 80 metric ton (176 KLB) payloads, 23 feet diameter x 92 feet long, to 220 nmi orbits at 28.5 degrees. The launch vehicle concept of the study was designated "Magnum" to differentiate from prior heavy launch vehicle assessments. This assessment along with the assessment of options for all transportation phases of a Mars mission are ongoing.

The Marshall Exploration Transportation Office (RA50), under Mr. Bill Eoff, is responsible for managing the Mars Transportation Study (MTS) in response to the Integrated Mars Mission Study co-chaired by Mr. Doug Cooke, Johnson Space Center and Mr. Norm Haynes, Jet Propulsion Laboratory. Ames Research Center, Kennedy Space Center, Langley Research Center, Lewis Research Center and Stennis Space Center also participate in the study.

Acronyms

AGS  Advanced Grid Stiffened (Composite) Shroud
AR&C  Automatic Rendezvous & Capture
ASTP  Advanced Space Transportation Program
DDT&E  Design, Development, Test & Evaluation
DRM  (Human Mars) Design Reference Mission
EELV  (USA) Evolved Expendable Launch Vehicle
ETO  Exploration Transportation Office
ETO  Earth to Orbit
ETP  Exploration Transportation Program
HEELV  (TRW) Highly Evolved Expendable Launch Vehicle
HLV  Heavy Lift Vehicle
HMM  Human Mars Mission
IMLEO  Initial Mass to Low Earth Orbit
ISPP  In-Situ Propellant Production
LCE  (TRW) Low Cost Engine
LFBB  (Shuttle) Liquid Fly Back Boosters
MLV  Magnum Launch Vehicle
MT  Metric Tons
RLV  Reusable Launch Vehicle
SDV  Shuttle Derived Vehicle
SPS  Solar Power Satellite
SSP  Space Solar Power Program
STP  Space Transportation Programs
TBC  Turbine Based Combined Cycle
TMI  Trans-Mars Insertion
TSTO  Two Stage To Orbit
Von Braun proposed a human Mars mission in his 1953 book, the “Mars Project,” with ten ships, a crew of seventy and 5.3 million metric tons of fuel.

Exploration Transportation

Exploration Transportation Focus:
Mars Exploration
- Human Mars Space Transportation Systems
- 2005 Robotic Mars Sample Return Prop System
- Technology Dev & Demos

Other Assignments:
- Launch Vehicle Assessments for Space Solar Power

Affordable Earth-to-Orbit Transportation
Advanced Interplanetary Propulsion
In-Situ Resource Utilization/Cryogenic Fluid Management

Space Solar Power
Reusable TSTO
2005 Robotic Mars Sample Return
Why Invest in Transportation Technologies?

- Transportation Historically Accounts for >50% of Exploration Mission Costs.
- Space Transportation Costs Must Be Reduced to Make Exploration Affordable.
- Transportation Technology Investments Are Required to Reduce Costs.
Human Mars Mission

Transportation Architecture Options

- Earth-to-Orbit
  - Shuttle Derived HLV
  - Energia Derived HLV
  - New HLV
  - Shuttle/RLV

- Trans Mars Injection
  - Chemical Prop
  - Nuclear Thermal
  - Nuclear Electric
  - Solar Electric

- Mars Orbit Capture
  - Aeroassist
  - Chemical
  - Nuclear
  - Solar Electric

Transportation Decision Criteria
- Cost
- Technology Dev Tools
- DDT&E & Adv Dev
- Mass to LEO/Br 
- Cost Sharing
- Life Cycle Costs
- Human Factors
  - Trip Time
  - Stay Time
  - Radiation
  - Zero-G Exposure
  - Maximum G’s
- Risk
- Mission Performance
- Programmatic
- Mission Acceptance
- Transfer
- Propulsion Potential
- Other

Earth Entry
- Direct
- Rendezvous

Earth Capture
- Aeroassist
- Chemical Prop
- Nuclear Thermal
- Nuclear Electric
- Solar Thermal

Trans Earth Injection
- Chemical
- Nuclear Thermal
- Nuclear Electric
- Solar Electric
- Solar Thermal

Human Mars Payload Requirements

DESIGN REFERENCE MISSION
- P/L Diameter: 7.5 m/24.8 ft
- P/L Length: 27.7 m/91.4 ft
- P/L weight: 80 MT/176 Klb
- Assembly Orbit: 407 km/220 nmi
- 28.5 degrees
- Launch Rate: 6/year

HMM ETO Costs Driven by:
- Mass Required in Earth Orbit
- Launch Costs

IMLEO (Initial Mass to LEO) Launch Vehicle Payload

<table>
<thead>
<tr>
<th>IMLEO (Initial Mass to LEO)</th>
<th>Launch Vehicle Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td>89° 90-Day Study</td>
<td>850 MT</td>
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<tr>
<td>93°/94° DRM</td>
<td>850 MT</td>
</tr>
<tr>
<td>96° DRM</td>
<td>660 MT</td>
</tr>
<tr>
<td>97° DRM</td>
<td>431 MT</td>
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</tbody>
</table>

200-300 MT

Affordable Launch Costs

- Mars Aerocapture
- Earth Return
- Surface Habitats
- Crew Ascent Vehicle
Affordable Earth-to-Orbit Transportation

- Need: Minimize Total Transportation Costs Including In-Space Assembly and Checkout.
- Exploration ETO Could Be Accomplished With RLV/Shuttle; However, Costs of Launch/In-Space Assembly and Checkout Would Be Prohibitive (30+ Launches and Associated Assembly/Checkout Per Human Landing).
- Approach: Each Mars Payload Launched In Two 80 Metric Ton Pieces.
  - Pieces Automatically Assembled On-Orbit.
  - Design Reference Mission Requires 6 to 7 Launches of 80 MT Vehicle for First Humans to Mars.
    - Two Payloads (4 ETO Launches) Required During the First Opportunity (Human Support Cargo/ISRU)
    - One Payload (2 ETO Launches) Required During the Second Opportunity (Humans).
- Cost Bogey for ETO: $3B to $6B for First Human Landing
  - Technology Investment
  - DDT&E
  - Flight Hardware and Integration
  - Launch Facilities and Operations

Magnum Concept

Typical Configuration
- 80 MT (176 KLB) P/L
- 220 NMI/28.5 Degrees
- P/L: 25 ft Dia X 92 ft

Launch Pad (Shuttle)
Advanced Interplanetary Propulsion

- Needs:
  - Minimize Total Transportation Costs
  - Develop Affordable Option for Non-Nuclear In-Space Transportation

- Approach:
  - Parallel Nuclear Thermal and Solar Electric Technologies for Trans-Mars Injection (TMI).
    - Downselect by End of 2001
    - Nuclear Thermal Focused on Fuels Improvements, Components, and Test Capability.
    - Solar Electric Focused on High Power Thruster, Components, and Test Capability.
  - Decent/Ascent Focused on Research to Support Use of In-Situ Resource Products.

- Cost Bogey for TIM: <$3B for First Human Landing
  - Technology Investment
  - DDT&E
  - Flight Hardware and Integration
  - Launch Processing
Solar Electric Transfer Vehicle Concepts

Electric Propulsion with Chemical TMI Stage

LOX/LH2 Stage Performs Transfer from EPO to TMI

Chemical TMI Burn

Earth

Mars Transfer Orbit

Elliptical Parking Orbit (EPO)

Chem Transfer

Electric Propulsion System Performs Transfer from LEO to EPO

Mars Aerocapture

Aerobrake System Captures into Mars Orbit

Thin Film Amorphous Silicon Inflatable Arrays

Concentrator Multi-Band Gap Blanket Deployed Arrays
Electric Propulsion Technology for TMI

Small Russian Hall Thrusters
(1.5 to 4.5 Kw)

High Power Electric Propulsion
for Exploration
(50 to 100 Kw)

- High Power Hall Thrusters
  - 25 Kw Russian Thruster Tested and Evaluated
  - 50 Kw Breadboard Using American Technologies
  - 100 Kw Prototype unit
- Power Processing Technologies
  - Light Weight
  - Efficient
- Tankage and Feed System Technologies

Trans-Mars Insertion Option

Nuclear Thermal Propulsion Technology

- Fuel Development, Test and Validation for High Performance Bimodal Operation
- Effluent Treatment for Environmentally Acceptable Ground Test Capability
- Low Cost Component Technologies
- Materials Technologies
- Health Management and Instrumentation Technologies
Mars Exploration Program
Aeroassist Benefits & Requirements

Direct Entry and Aerocapture

**Requirements & Goals**
- Fast human transit drivesentry speeds
- 15% mass fractions
- Minimal EVA Assy
- L/D for precision landing
- Biconic "new" shape

- Cargo/Human entry: 5.7 to 8.7 Km/sec
- Astronaut return entry: 12.8 to 14.1 Km/sec

- Aeroassist significantly reduces system complexity and mass of propulsion systems.

- Reductions in mass of vehicles → Reduced launch requirements or direct increase in payload e.g... 40% reductions in IMLEO for Human mission assuming chemical propulsion.

- Aerocapture at Mars gives options for precision landing with reduced entry errors, entry in daylight conditions, or entry after an unexpected dust storm.
Aeroassist Technology
Investment Returns

Aerothermodynamics: Prediction of flowfield surrounding entry vehicle to determine aerodynamic forces and surface heating conditions.
Impact: Reduce uncertainties -> smaller safety factors -> mass & cost decrease

TPS: Protective material system surrounding entry vehicle, designed to maintain specified spacecraft structure and payload temperatures.
Impact: Lightweight TPS -> Smaller launch vehicle & useful payload mass increase

GN&C: Actively control vehicle attitude and trajectory during entry
Impact: Enables precision landing and aerocapture missions

Vehicle Design: Optimized integration of entry vehicle systems to meet mission requirements
Impact: Drives technology focus & assures project goals are met. Allows design problems to surface before Phase C/D

Investment in Aeroassist Technology will enable exciting planetary missions, allow for larger payloads, and use smaller launch vehicles. It will enable HEDS exploration of Planetary Bodies with Atmosphere.
“Better, Faster Cheaper”

Comparison of Mars Entry Vehicles

<table>
<thead>
<tr>
<th></th>
<th>Viking</th>
<th>Pathfinder</th>
<th>Mars 2001</th>
<th>HEDS Biconic</th>
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<tbody>
<tr>
<td>$V_{\text{rel}}$ (km/s)</td>
<td>4.5</td>
<td>7.65</td>
<td>6.52</td>
<td>5.7 - 8.4</td>
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<tr>
<td>Diameter (m)</td>
<td>3.5</td>
<td>2.65</td>
<td>2.4</td>
<td>8.6</td>
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<td>$m_0$ (kg)</td>
<td>981</td>
<td>603</td>
<td>450</td>
<td>65000</td>
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<tr>
<td>$Q_o$ (J/cm$^2$)*</td>
<td>$\sim$1000</td>
<td>$\sim$4000</td>
<td>$\sim$7000</td>
<td>50000 (est)</td>
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<tr>
<td>$q_{\text{max}}$ (W/cm$^2$) *</td>
<td>25</td>
<td>100</td>
<td>60</td>
<td>1000 (est)</td>
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</table>

* non-ablating conditions

Concerned NASA technologist
In-Situ Resource Utilization

- Needs:
  - Minimize Total Transportation Costs
  - Develop Affordable Options for In-Situ Propellant Production (ISPP) from Mars Resources

- HEDS Approach:
  - Integrated Technology Program Addressing Needs of Human Missions
  - Phased Precursor Demonstrations of ISPP on Robotic Missions (Under Review)
    - 2001: Component Experiments
    - 2003: Small Oxygen Production Capability
    - 2005: BYOP Mars Sample Return Using Cryogenic Oxygen (Fuel is TBD)
    - 2007: Mars Sample Return Using ISPP to Provide Ascent Stage Propellants

Cryogenic Fluid Management

- Needs:
  - Minimize Total Transportation Costs
  - Cryogenic Fluid Storage for Long Periods In-Space and on the Martian Surface
  - ISPP Product Liquification, Transfer, and Storage
  - Minimum Propellant Boiloff Losses (Goal is Zero Boiloff)

- HEDS Approach:
  - Integrated Technology Program Addressing Needs of Human Missions as Part of ASTP CFM Program (STT Project)
  - Phased Precursor Demonstrations of Mars Surface Liquification, Transfer and Storage on Robotic Missions
    - 2003: Small Oxygen Production Capability
    - 2005: BYOP Mars Sample Return Using Cryogenic Oxygen (Fuel is TBD)
    - 2007: Mars Sample Return Using ISPP to Provide Ascent Stage Propellants

(Note: JPL Carrying Parallel Code S Funded Propulsion Technology Development for Hypergolic Propellant; Downselect in 2000)
Cryo Fluid Management

Mars Human Mission Cryogen Storage Requirements

<table>
<thead>
<tr>
<th>Mission Phase</th>
<th>Liquid Propellant</th>
<th>Quantity (Mg/m³)</th>
<th>Temperature</th>
<th>Days of Operation</th>
<th>Operating Environments</th>
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<tbody>
<tr>
<td>TMI Descent</td>
<td>H₂</td>
<td>60/850</td>
<td>20</td>
<td>150</td>
<td>Earth launch, 0-g, TMI burn</td>
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<td>ISRU seed</td>
<td>O₂, CH₄</td>
<td>16/14, 4.6/11</td>
<td>90</td>
<td>500</td>
<td>Earth launch, TMI burn, 0-g, aerocapture, descent</td>
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<tr>
<td>ISRU Ascent</td>
<td>O₂, CH₄</td>
<td>30.5/27, 7.6/18</td>
<td>90</td>
<td>1200</td>
<td>Mars surface</td>
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<tr>
<td>Ascent</td>
<td>O₂, CH₄</td>
<td>30.5/27, 7.6/18</td>
<td>90</td>
<td>1200</td>
<td>Mars surface, ascent</td>
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<tr>
<td>TEI</td>
<td>O₂, CH₄</td>
<td>25/22, 7.2/17</td>
<td>90</td>
<td>1700</td>
<td>Earth launch, TMI burn, 0-g, aerocapture, TEI burn</td>
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Transportation Technology Challenges

Affordable Earth-to-Orbit Transportation
- Low Cost Technologies Scaled to Large Launcher
  - Tanks & Structures
  - Propulsion Systems
  - Shrouds
  - Upper Stages
- Accommodate large-volume payload requirements
- Minimum on-orbit assembly costs
- Minimum impact to launch facilities

Cryogenic Fluids Management
- Long-Term (1700 days) Cryogenic Fluid Storage
- Cryogenic Liquefaction of In-Situ Propellants
- Cryogenic Refrigeration
- Zero-G Fluid Management

Aeroassist
- Earth/Mars Orbital Insertion & Direct Entry
- Advanced Thermal Protection Systems
- Mars Atmospheric Modeling
- Guidance & Navigation for Precision Landing & Aerocapture

Advanced Interplanetary Propulsion
- All Chemical Propulsion Option
- Solar Electric Propulsion Option
- Nuclear-Thermal Option
- Ascent & Descent Propulsion

In-Situ Resource Utilization
- Propellant Production from Mars Atmosphere
- Human Mars Ascent Propellant
- Mars Sample Return Using In-Situ Resources
- Lunar Demonstration from Soil
Exploration Transportation Technology Definition

Transportation Summary

- Human Exploration Is a Key Part of the NASA Strategic Plan
- Transportation Technology Development Is Required for Affordable Human Exploration
- Transportation Technologies Defined by Multi-Center Teams of Technical Experts
  - Anchored by Transportation Architecture Systems Analyses
  - Requirements and Goals Established to Guide Technology Definition
- Exploration Transportation Technology Update to be Performed as a Part of Budget Submission