TAPER:
Technology Advancing Phobos Exploration & Return
Inspiration

“He who receives an idea from me, receives instruction himself without lessening mine; as he who lights his taper at mine, receives light without darkening me.”
-Thomas Jefferson
Presentation Roadmap

1. Execution & Administration (Chris Nie)
2. Science (Abigail Fraeman)
3. Engineering
   1. Mission Profile, Launch Dates, and Trajectory (Natasha Bosanac)
   2. Spacecraft Design & Layout (Frans Ebersohn)
   3. Propulsion Systems & Launch Capability Requirements (Frans Ebersohn)
4. Human Factors (Stefanie Gonzalez)
5. Conclusion (Nick Sweet)
TAPER - The Road Map to Mars

Technology Advancing Phobos Exploration and Return (TAPER) is a concept program that aims to bridge the policy, technology, and science gaps for manned exploration of Mars by sending a crew to a Martian moon.
**KEY ENABLING CAPABILITIES**

- Satellite size decrease and capability increase
- Heavy lift launch vehicles
- Composite propellant tanks
- Zero boil-off technology

- High resolution topography, gravitational field, radiation, thermal, mineralogical and chemical composition mapping of Phobos.
- Examine the geotechnical and mechanical properties of the regolith.
- Examine the dust and regolith content.
- Search for subsurface ice/volatile products

**Precursor Missions**

- Phobos

**Robotic Characterisation Operations - Phobos**

**Extended Mars Operations**

- Deep Space Exploration Vehicles

- Manned Mission

- Mars Surface ISRU
- Mars Sample Return
- Manned Mars Exploration
Mission Overview

Mission Statement
The mission of TAPER 1 is to send an international crew of four to Phobos and return them safely with surface samples to serve as precursor to the human exploration of Mars.

Objectives
• Demonstrate the ability to send humans to the martian system and return them safely with samples of the environment;
• Assess the feasibility of Phobos as resources for future missions to the martian surface;
• Investigate the origin and evolution of the moons to better understand the martian system;
• Understand the current environment of Phobos in the context of the martian system to support architecture for future manned Mars missions.
• Establish infrastructure on Phobos to support future manned exploration of both Phobos and Mars.
Mission Timelines

Opposition Class Mission

LEO Technology Demonstration using the International Space Station: January 2015

Nominal Precursor Mission: October 2024 - July 2026

Contingent Precursor Mission: August 2026 - May 2028

Nominal TAPER Mission: March 2033 - July 2034

Contingent TAPER Mission: August 2035 - October 2036
Mission Architecture
Mission Phasing

- **Phase I:**
  - Launch and transit of cargo to Low Earth Orbit (LEO)
- **Phase II:**
  - LEO Assembly of transit stage
- **Phase III:**
  - Interplanetary transfer to Mars vicinity
  - Experimentation
- **Phase IV:**
  - Martian and Phobos orbit injection
  - PSE undock and landing on Phobos
  - Surface operations (detailed later)
- **Phase V:**
  - Interplanetary transfer to Earth vicinity
  - Sample down select
  - Experimentation

Mission Phasing Diagram:

- Phase I: Cargo Launch Approx: T-30 to T-1
- Phase II: LEO Assembly T+0 to T+2
- Phase III: Phobos Transit T+3 to T+183
- Phase IV: Phobos Vicinity T+184 to T+207
- Phase V: Earth Return T+208 to T+441
Science
Why Phobos?
Strategic Knowledge Gaps

1. Map the global topography of Phobos.
2. Measure the gravitational field in the local vicinity of Phobos.
3. Assess the radiation properties in the local vicinity of Phobos.
4. Map and assess the mechanical properties of the regolith on Phobos.
5. Examine the mechanical and electrostatic properties of the dust and regolith on the surface of Phobos.
6. Search for subsurface ice and other volatile products.
7. Map the thermal environment of Phobos.
8. Map the global mineralogical and chemical composition of Phobos.

Can be addressed by NASA Discovery class mission(s)
Science Objectives for Surface Operations

1. Investigate the origin and evolution of the moons to better understand the Martian system
   • Identify diverse suite of rocks and regolith to be collected and returned for detailed laboratory investigation
   • Determine composition in situ of rocks and regolith from diverse and well characterized locations
   • Constrain internal structure of Phobos
   • Characterize Phobos regolith and processes that may have modified it over time
Science Objectives for Surface Operations

1. Investigate the origin and evolution of the moons to better understand the Martian system

2. Assess availability of in situ resources for possible future use in manned Mars missions
   - Determine if the volatile content of the moon's surface and subsurface
   - Detect and quantify any mineable material including magnesium, methane, ammonia, clays, REE
Science Objectives for Surface Operations

1. Investigate the origin and evolution of the moons to better understand the Martian system
2. Assess availability of in situ resources for possible future use in manned Mars missions
3. Understand the current environment of Phobos in the context of the Martian system to support architecture for future manned Mars missions
   • Characterize effects of space weathering on the Phobos' regolith
   • Understand how radiation is attenuated and blocked on the surface over time
   • Quantify amount of dust fall and frequency of micrometeorite impacts on Phobos
<table>
<thead>
<tr>
<th>Science Related Mission Objectives</th>
<th>Measurement Objectives</th>
<th>Measurement Requirements</th>
<th>Instrument Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investigate the origin and evolution of the moons to better understand the Martian system</td>
<td>Identify diverse suite of rocks and regolith to be collected and returned for detailed laboratory investigation</td>
<td>Rock and soil samples must be collected from at least two locations on Phobos (red and blue units), preferably three</td>
<td>Returned samples to be analyzed by techniques on Earth including XRD, isoptoic/age dating analyses, etc.</td>
</tr>
<tr>
<td></td>
<td>Determine composition in situ of rocks and regolith from diverse and well characterized locations</td>
<td>Rock and soil samples must be investigated from at least two locations on Phobos (red and blue units), preferably three</td>
<td>Raman/LIBS, Visible/Near infrared spectrometer measurements; Multispectral camera to identify spectrally unique areas and provide context</td>
</tr>
<tr>
<td></td>
<td>Constrain internal structure of Phobos</td>
<td>Seismic measurements locations across Phobos</td>
<td>Deployable Seismometers</td>
</tr>
<tr>
<td></td>
<td>Characterize Phobos regolith and processes that may have modified it over time</td>
<td>In situ science to characterize grain size/distribution/roundness; investigation of returned core samples</td>
<td>Hand lense, corer and scoop to bring back regolith samples</td>
</tr>
<tr>
<td>Assess availability of in situ resources for possible future use in manned Mars missions</td>
<td>Determine the volatile content of the moon’s surface and subsurface</td>
<td>Measure regolith water content in situ, collect sample cores from any areas indentified by precursor as potential for having subsurface water</td>
<td>Raman/LIBS, VNIR spectrometer, Neutron spectrometer, drill for areas identified by precursor mission as potential for subsurface ice; deep drill if indicated necessary by precursor science</td>
</tr>
<tr>
<td></td>
<td>Detect and quantify any mineable material including magnesium, methane, ammonia, clays, REE</td>
<td>Understand composition of surface</td>
<td>Raman/LIBS, APXS, Visible/Near infrared spectrometer measurements</td>
</tr>
<tr>
<td>Understand the current environment of Phobos in the context of the Martian system to support architecture for future manned Mars missions</td>
<td>Characterize effects of space weathering on the Phobos’ regolith</td>
<td>Collect core samples from at least three locations on each of two sites</td>
<td>Returned samples: XRD, isoptoic and age dating analysis, GCMS, etc.</td>
</tr>
<tr>
<td></td>
<td>Understand how radiation is attenuated and blocked on the surface over time</td>
<td>Measure fluxes and energies of particles received at Phobos surface</td>
<td>Plasma wave detector; energetic particle detector for high and low energy particles</td>
</tr>
<tr>
<td></td>
<td>Quantify amount of dust fall and frequency of micrometeorite impacts on Phobos</td>
<td>Measure dust fall on Phobos</td>
<td>Dust detector</td>
</tr>
</tbody>
</table>
## Landing Sites

<table>
<thead>
<tr>
<th>Site Identifier</th>
<th>Site Location</th>
<th>Coordinates</th>
<th>Distance from previous site [km]</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>Stickney crater</td>
<td>50 deg W, 0 deg N</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>Blue spectral unit</td>
<td>30 deg W, 15 deg N</td>
<td>6</td>
</tr>
<tr>
<td>C</td>
<td>Red spectral unit</td>
<td>15 deg E, 45 deg N</td>
<td>11</td>
</tr>
<tr>
<td>D</td>
<td>Mars Visible</td>
<td>28 deg W, 60 deg N</td>
<td>9</td>
</tr>
</tbody>
</table>
Science Payload: *In Situ* Science

Sample collection equipment

Mobile Science Platforms "Phobots"

Seismic Array with ChipSats

Space Weather Stations

Mass margin left for new instruments based on precursor science results
<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Heritage</th>
<th>Qty</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface science equipment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample collection equipment</td>
<td></td>
<td>1</td>
<td>425</td>
</tr>
<tr>
<td>Robonants</td>
<td></td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>Tongs, rake, dust scooper, hammer, hand lens, documentation camera</td>
<td></td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>Sample boxes, cores, bags</td>
<td></td>
<td>1</td>
<td>200</td>
</tr>
<tr>
<td><strong>Mobile Science Platforms (Typical payload below)</strong></td>
<td></td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Raman/LIBS Spectrometer</td>
<td>JPL Raman/LIBS in development</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Multispectral imaging system</td>
<td>Rosetta Landing Imaging System (ROLIS)</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Neutron spectrometer</td>
<td>Dynamic Albedo of Neutrons (DAN)</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Visible/Near-Infrared Spectrometer</td>
<td>Comet Infrared and Visible Analyzer System (CIVA)</td>
<td>1</td>
<td>0.75</td>
</tr>
<tr>
<td>Chasis + communications</td>
<td></td>
<td>1</td>
<td>2.75</td>
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<tr>
<td><strong>Seismic network stations</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small networks deployed towards landing</td>
<td>JPL in development</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td><strong>Space weather stations</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma Wave System</td>
<td>FPMS</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Micrometeorite Detector</td>
<td>METEOR</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>Dust Particle Detector</td>
<td>DIAMOND</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Structure + comm system</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td><strong>Margin for additional instruments necessary by precursor science</strong></td>
<td></td>
<td></td>
<td>300</td>
</tr>
<tr>
<td><strong>Total + 20% margin</strong></td>
<td></td>
<td>1005</td>
<td></td>
</tr>
</tbody>
</table>
Sample Collection Strategy

Samples will be collected from each of the 3 EVA sites.

Artists conception of GLACIER, a possible precursor to types of cold storage required for samples possibly containing volatile material.

<table>
<thead>
<tr>
<th>Required collected qty per EVA site:</th>
<th>Rock samples</th>
<th>Core samples</th>
<th>Soil scoops</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>

| Number of EVA sites:               | 3            | 3            | 3           |

| Minimum mass per single sample (kg): | 0.2 | 1.5 | 0.1 |

| Total mass (kg) for all samples:    | 18  | 45  | 1.5 |

| Total mass + margin for 10% E/PO, 20% international cooperation, 20% target of opportunity: | 27  | 67.5 | 2.25 |
Surface Operations

- $T_s +1$
  - T&L: Site A
- $T_s +2$ to $+8$
  - Begin drilling
  - Collect samples
- $T_s +9$ to $+10$
  - Collect samples
- $T_s +11$
  - T&L: Site B
- $T_s +13$ to $+14$
  - Exp. install
  - Coring

$T_s \sim MD-232$
Surface Operations

- $T_s + 15$
  - T&L: Site C
  - $T_s + 16$ to $+18$
    - Exp. install
    - Coring

- $T_s + 19$
  - T&L: Site D

- $T_s + 20$ to $+23$
  - Secure PSE Exp. install

- $T_s + 24$
  - Depart Phobos
  - Dock with DSV

$T_s \sim$ MD-232
Science Payload: Additional Science

<table>
<thead>
<tr>
<th>Orbital Remote Sensing Instruments</th>
<th>Heritage</th>
<th>Mass (kg)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High resolution multispectral imaging</td>
<td>Dawn framing camera</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Radar</td>
<td>Sharad</td>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>Middle energy range particle detector</td>
<td>MARIE</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Low energy range particle detector</td>
<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>High energy range particle detector</td>
<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Cubesats sent to Deimos (x 5)</td>
<td></td>
<td>3</td>
<td>N/A</td>
</tr>
<tr>
<td>Dedicated instrument for</td>
<td></td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Total + 20% margin</td>
<td></td>
<td>69.6</td>
<td>97.2</td>
</tr>
</tbody>
</table>

Science in Transit

- Compositional and isotopic analysis of samples for triage
- Radiation experiments
  - New-LIFE
  - Dosimeters
  - Additional experiments designed to test the effects of long duration spaceflight on humans are described in section on human factors
- Provide outreach opportunity for the general scientific community to propose experiments and develop instrumentation for observations of Earth as an exoplanet
Engineering
Engineering Requirements

Top Level Requirements derived from Objectives
The crew shall remain safe for the mission duration.
The crew shall travel to Phobos and return.
The crew shall land on the surface of Phobos.
The crew shall obtain samples from Phobos.
The mission shall satisfy the science goals
The mission shall demonstrate selected technologies
The mission shall comply relevant legal and Planetary Protection requirements.

Subsystem level requirements
> Trajectory design, spacecraft design, propulsion system, human factors, power, communications, thermal control, AODCS & GNC
Mission Profile, Launch Dates, and Trajectory
Selection of Crew Launch Year

Selected Crew Launch Year: 2033
Backup Crew Launch Year: 2035

[Hopkins, 2013]
2033 Crew Earth Departure
Selection of Departure Date and TOF

TOF : 180 days
Earth Departure: 7\textsuperscript{th} April 2033
Mars Arrival: 6\textsuperscript{th} October 2033
Crew Launch: 6\textsuperscript{th} April 2033
Earth Departure Window (ΔV<6.8 km/s):
1\textsuperscript{st} April 2033 to 2\textsuperscript{nd} May 2033
Crew Return Leg (2033 Launch)
Mars Departure $\Delta V$

- Mars Departure: 2\textsuperscript{nd} November 2033
- Earth Arrival: 6\textsuperscript{th} July 2034
- $\Delta V$: 350 km/s
- $V_a$: 20 km/s
- TOF: 246 days
2035 Crew Earth Departure
Selection of Departure Date and TOF

- TOF: 180 days
- Earth Departure: 14th August 2035
- Mars Arrival: 10th February 2036
- Crew Backup Launch: 13th August 2035
- Earth Departure Window: 6th August 2035 to 20th August 2035

\[ \Delta V \text{ km/s} \]
Crew Return Leg (2035 Launch)
Mars Departure Delta V

TOF: 233 days
Mars Departure: 11th March 2036
Earth Arrival: 30th October 2036
Crew Outbound Trajectory Overview

**Launch from Earth**
- Date: 6 April 2033
- ΔV = 3.7 km/s performed at periapsis

**Interplanetary Trajectory**
- Begin: 7 April 2033
- End: 6 October 2033
- C3 = 8.4 km²/s²
- Right Ascension = 269 deg
- Declination = -56 deg

**Trans-Mars Injection from 300km LEO**
- Date: 7 April 2033
- ΔV = 3.7 km/s performed at periapsis

**Plane Change & Insertion into High Mars Orbit**
- Date: 6 October 2033
- ΔV = 2.36 km/s, at crossing of Phobos orbit plane

**Raise Periapsis:**
- Date: 6 October 2033, ΔV = 0.10 km/s, at apoapsis

**Enter Phobos Orbit:**
- Date: 7 October 2033, ΔV = 0.57 km/s, at periapsis
- Maintain: ΔV ~ 0.10 km/s

**Enter Phobos L_1 Lyapunov Orbit**
- Begin: 7 October 2033
- End: 1 November 2033
[Landau & Strange, 2013]

**Phobos Orbit**
- Periapsis: 9376 km
- Apoapsis: 37000 km
- Inclination=0 deg

**High Mars Orbit**
- Periapsis: 300km
- Apoapsis: 28.5 degree inclination

**All maneuvers are impulsive**

---

Team Explorer
TAPER

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Crew Inbound Trajectory Overview

**Phobos L₁ Lyapunov Orbit**
Begin: 7 October 2033  End: 1 November 2033

**Raise Apoapsis:**
Date: 1 November 2033, ΔV = 0.57 km/s, periapsis

**Lower Periapsis, Insertion into High Mars Orbit:**
Date: 2 November 2033, ΔV = 0.07 km/s, apoapsis

**Trans-Earth Injection**
Date: 4 November 2033, ΔV = 6.03 km/s

**Interplanetary Trajectory**
Begin: 4 November 2033

**Direct Earth Entry**
Date: 6 July 2034  Entry velocity ~ 11.3 km/s

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**High Mars Orbit**
Periapsis: 9376 km. Apoapsis: 37000 km  Inclination=0 deg

C₃ = 8.4 km²/s²  Right Ascension = 269 deg  Declination = -56 deg

**LEO**
300km Altitude, 28.5 degree inclination

**Earth**

**All maneuvers are impulsive**

Total Time of Flight: 456 days.  Total ΔV = 13.5 km/s
Crew Outbound Trajectory
Interplanetary Transfer

1. Earth LEO departure: April 7th 2033
2. Mars Arrival: October 6th 2033
3. Mars Departure: November 2nd 2033
4. Earth Arrival: July 6th 2034
Crew Outbound Trajectory

Mars-Phobos Vicinity

- Insertion to Interplanetary Transfer
- High Mars Orbit Insertion
- Insertion into Mars-Phobos $L_1$ Lyapunov
- Phobos
- Deimos
Crew Outbound Trajectory

Mars-Phobos Vicinity
Spacecraft Design & Layout
Vehicle Stack

- Bigelow Deep Space Habitat (DSH)
- Nuclear Thermal Rocket (NTR)
- NTR Hydrogen Fuel Tanks
- Dragon Crew Vehicle (CV)
- Phobos Surface Explorer (PSE)
Crewed Vehicles

Bigelow DSH

Dragon CV

PSE
PSE - Phobos Surface Explorer

- 2-Stage SEV - Habitable and Ascent
- Wet mass = ~17000 Kg
- Science Instruments = ~1000 Kg
Surface Exploration
Return to DSV
Propulsion Systems and Launch Capability Requirements
Launch Vehicle Choices

Falcon 9 (1)
• Crew Vehicle (10,100 kg)
• 10,450 kg to LEO
• Cost: $130-140M

Falcon 9 Heavy (1)
• DSH & PSE (17,000 kg)
• Cost: $80-125M

SLS (4)
• NTR Tanks and System
  ○ (246,000 kg over 4 launches)
• Cost: $2.5 billion
Mass Budget For Propulsion System Design

<table>
<thead>
<tr>
<th>Component</th>
<th>Notes</th>
<th>DSH (Outbound)</th>
<th>CV (Outbound)</th>
<th>PSE</th>
<th>PSEP (Ascent)</th>
<th>DSH (Inbound)</th>
<th>CV (Inbound)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECLSS</td>
<td>Food, Gases for Life Support, Water, Tanks, Life Support Hardware</td>
<td>8</td>
<td>2</td>
<td></td>
<td></td>
<td>8</td>
<td></td>
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<tr>
<td>Med</td>
<td>Centrifuge, Countermeasure, Excercise, Clinical medicine, rapid prototyper, small fridge</td>
<td>1</td>
<td></td>
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<td></td>
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<tr>
<td>Crew</td>
<td>Astronauts, clothes</td>
<td>0.6</td>
<td>0.6</td>
<td>0.3</td>
<td>0.3</td>
<td>0.6</td>
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<tr>
<td>Habitat Structure</td>
<td>Beds, Storage, equipment, structure</td>
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<td>Wet Mass</td>
<td>Avionics, Power, Environment Protection, Crew systems</td>
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<tr>
<td>Science Equipment</td>
<td>Science Equipment for Crew to use to/from Phobos</td>
<td>0.2</td>
<td>1</td>
<td>0.2</td>
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<td>3.7</td>
<td>0.9</td>
<td>75.4</td>
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<td>Dragon Capsule</td>
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<tr>
<td>Samples</td>
<td>Samples from Phobos</td>
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<td>PSE - Hab</td>
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<td>PSEP Structure</td>
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<td><strong>Total:</strong></td>
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<td><strong>209.8</strong></td>
<td><strong>10.1</strong></td>
<td><strong>13.07</strong></td>
<td><strong>3.7</strong></td>
<td><strong>101.2</strong></td>
<td><strong>10.6</strong></td>
</tr>
</tbody>
</table>

4 SLS Launches ~46 tons H2 each
Falcon Heavy ~39 tons
Falcon 9 ~10.1 tons

Units: Metric Tons
Propulsion Trade Study (1/2)

Propulsion systems considered:

- Chemical Propulsion: LOX/H2, LOX/CH4, N2O4/MMH [Humble, 1995]
- Electric Propulsion: Clusters of 50 kW Hall Thrusters [Strange et al., 2011]
- Nuclear Propulsion: NERVA Variant, Particle Bed Reactors [Humble, 1995]

Considered Multiple Flight and Rendezvous Scenarios, examples to follow
Propulsion Trade Study (2/2)

<table>
<thead>
<tr>
<th>Description</th>
<th>IMLEO (Metric tons)</th>
<th>Crew Time of Flight (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO Rendezvous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a.) NTR DSV departure from LEO</td>
<td>279</td>
<td>456</td>
</tr>
<tr>
<td>b.) Cluster of fourteen 50 kW Hall thrusters DSV departure from LEO</td>
<td>202</td>
<td>1076</td>
</tr>
<tr>
<td>HEO Rendezvous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a.) A NTR DSV is placed in HEO by cluster of six 50 kW Hall thrusters</td>
<td>297</td>
<td>456</td>
</tr>
<tr>
<td>which rendezvous with CV and then departs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cargo Rendezvous with DSV at Phobos</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a.) Cargo pre-placement at Phobos by cluster of six 50 kW Hall thrusters</td>
<td>276</td>
<td>456</td>
</tr>
<tr>
<td>and DSV departure with NTR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cargo and Fuel Rendezvous with DSV at Phobos</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a.) Cargo and fuel pre-placement at Phobos by cluster of six 50 kW Hall</td>
<td>248</td>
<td>456</td>
</tr>
<tr>
<td>thrusters and DSV departure with NTR</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Chosen:
- **LEO Rendezvous with Nuclear Thermal Propulsion**

Reasoning:
- Time constraints of opposition class mission limit efficiency improvements of EP
- Small mass of total system which is not necessary for DSV flight (human flight) limits efficiency improvements of
- Risks of fuel pre-placement outweigh by performance improvements
DSV Propulsion Stage

- Assumptions:
  - Zero-boil off for cryogens
  - Sufficient PBR technology
- NTR Particle Bed Reactor type
  - Chosen for high thrust/weight ratio

<table>
<thead>
<tr>
<th>Thrust (N)</th>
<th>ISP (sec)</th>
<th>Engine Dry Mass (tons)</th>
<th>Propellant Mass (tons)</th>
<th>Propellant Tank Mass (tons)</th>
<th>Propellant Tank Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>333000</td>
<td>900</td>
<td>3.925</td>
<td>235.4</td>
<td>10</td>
<td>3440</td>
</tr>
</tbody>
</table>

[Emrich, 2013]
PSE Propulsion Stage

- **PSE Descent Engine:**
  - LOX/Methane type engine for technology demonstration
  - Small RCS thrusters
  - ISP: 380 sec

- **PSEP Engine:**
  - N2O4/MMH
  - Reliability and ability to escape Phobos and explore the terrain
  - Based off Draco thrusters
  - ISP: 320 sec
Human Factors
Crew Selection

• **Optimal Size of Crew**
  - 4 astronauts, in their 40s, mixed gender
  - Roles: Chief commander, Geologist, Engineer, Flight Surgeon

• **Physiological Testing**

• **Psychological Testing**
  - Psychiatric Diagnostic & Statistical Manual IV
  - Neuroasthenia

• **Genetic Testing**
  - HRAD9 Gene - Increased Radiation Tolerance
  - Screened for future diseases

• **Final Selection**
  - Field Tests
  - Self-evaluation

[Seedhouse, 2012]
[Pandita, 2006]
Radiation Mitigation

• Dose shall not exceed 3% excess cancer mortality risk
• Assumptions:
  • Safe Haven
  • Shield sleeping quarters; water blanket
  • Five Dosimeter Monitor
• Vectran Material
  • Design thickness to 20 [g/cm^2]
• Passive and Active Shielding
• Future Technology Demonstration
  • Photobioreactor used for algae recycled biomass

[Turner, 2013] [Atwell, 2005]
Physiology in space

- Physiological deconditioning:
  - Bone loss
  - Muscle atrophy
  - Cardiovascular adaptation
  - Motion sickness

- Countermeasures:
  - Exercise: aerobic vs. resistance
  - Artificial gravity: short radius centrifuge
  - IVA wearable concepts:
    - Exoskeleton
    - Gravity Loading Countermeasure Suit

(Vico, www.humanspaceflight.esa.int)
(ESA, 2011)
(Waldie, 2011)
Clinical Medicine

- Advanced Research in Space Medicine I & II
  - Highest risk and incidence
    - Medical Packs
    - Extend shelf life
- Telemedicine
  - Tablet technology
  - Self-diagnosis
- 3D Metal Printing
  - Aluminum wrappers
- Surgical Suite
  - Inflatable sterile environment
  - Magnetic tray
  - Laminar flow

[Comet, 2003]
[Barrat, 2008]
Psychological Considerations

- Crew Selection
- Interpersonal Conflicts
  - Training on conflict resolution
- Sleep Deprivation
  - Medication
- Boredom
  - Tablet Technology: Reading, video games, and skill training
  - Outreach activities and science experiments
- Group Compatibility
  - Common Meal
- Pale Blue Dot Syndrome
  - Family Communication
  - Virtual Reality

[Clement, 2005]
[Pandita, 2006]
ECLSS

**AIR**
- CO$_2$ Removal:
  - 2 Electrochemical Depolarized Concentrator (EDC)
- O$_2$ Generation:
  - 3 Static Feed Water Electrolysis (SFWE)
  - 3 kg/day per unit
- 2 Trace Contaminant Control (TCC)
- Heat Exchangers (CHX)

**WATER**
- Regeneration by 2 VPCAR units
  - Waste water into potable water
  - 250 kg/day per unit
- Air Evaporator System (AES)
  - Recover residual H$_2$O

**FOOD**
- 1200 kg of dehydrated food
  - Maximum intake per person = 0.56 kg/d

**WASTE MANAGEMENT**
- CO$_2$ Reduction: 2 Sabatier Reactors
  - CO$_2$ + 4H$_2$ $\rightarrow$ CH$_4$ + 2H$_2$O
- CH$_4$ Reduction: 2 Pyrolysis units
  - CH$_4$ into C and H$_2$
ECLSS Architecture

(Image modified from Belz, 2010)
Deep Space Habitat ECLSS

Environmental Control and Life Support Systems (ECLSS) - Round trip 443 days

- O2 (Kg)
- CO2 (Kg)
- H2O (Kg)
- Food (Kg)
- N2 (Kg)
- H2 (Kg)
- WW (Kg)

Duration of the mission (days) vs Mass (Kg)
Habitability

Legend:
- Avionics, ECLSS, Stowage (60 m³)
- Crew Quarters (15 m³)
- Galley and Stowage (50 m³)
- Work Stations (73 m³)
- Hygiene (10 m³)
- Exercise/Centrifuge (30 m³)
Habitability

- Centrifuge
- Work Stations
- Hygiene

Legend:
- Avionics, ECLS (60 m²)
- Crew Quarters (15 m²)
- Galley and Stowage (50 m²)
- Work Stations (73 m²)
- Hygiene (20 m²)
- Exercise/Centrifuge (30 m²)
Habitability
Conclusion
Conclusions

• Our approach:
  • Stepping stone to Mars
  • Global context

• Risks are high for Mars missions
  • ...but gains are greater

• (So long as the gains are well-communicated)
“Ever since there have been people, there have been explorers, looking in places where other hadn't been before. Not everyone does it, but we are part of a species where some members of the species do—to the benefit of us all.”

- Neil de Grasse Tyson
References

B. Comet, Advanced Research in Space Medicine I and II for exploratory manned space missions. ISU-Strasbourg.
D. Landau and N. Strange, "Trajectory Design Techniques for Human Missions to Mars", Presented at the Caltech Space Challenge 2013
Acknowledgements

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Also: John Steeves, Heather Duckworth
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Dr. Louis J. Alpinieri
Dr. Hideo Ikawa
Mr. John K. Wimpress
John and Joy Caldwell, Caldwell Vineyard
Backup Slides
Example of Inbound/Outbound Daily Activities Crew Timeline

<table>
<thead>
<tr>
<th>06:00</th>
<th>12:00</th>
<th>18:00</th>
<th>24:00</th>
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<tbody>
<tr>
<td>Sleep</td>
<td>Meal</td>
<td>Exercise</td>
<td>Meal</td>
</tr>
<tr>
<td>Sleep</td>
<td>Meal</td>
<td>Exercise</td>
<td>Meal</td>
</tr>
<tr>
<td>Sleep</td>
<td>Meal</td>
<td>Engineering Project</td>
<td>Meal</td>
</tr>
<tr>
<td>Sleep</td>
<td>Meal</td>
<td>Engineering Project</td>
<td>Meal</td>
</tr>
<tr>
<td>Ground</td>
<td>Comm Band</td>
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<td>Comm Band</td>
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</table>
### Habitability

<table>
<thead>
<tr>
<th></th>
<th>Volume [m$^3$]</th>
<th>Qty.</th>
<th>Subtotal [m$^3$]</th>
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</thead>
<tbody>
<tr>
<td>Crew Quarters</td>
<td>5</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>Galley, Locker Access,</td>
<td>50</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>Operations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Science workstations</td>
<td>35</td>
<td>2</td>
<td>70</td>
</tr>
<tr>
<td>Hygiene and waste management</td>
<td>5</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Centrifuge/exercise</td>
<td>30</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>Translation paths</td>
<td>2.5</td>
<td>3</td>
<td>7.5</td>
</tr>
<tr>
<td><strong>Total Volume</strong></td>
<td><strong>180</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Total work = 13.6 hrs

- Scheduled work (6.5)
- MCC task list (0.7)
- Onboard task list (2.2)
- Exercise (2.5)
- Plan review (0.2)
- Meal (0.5)
- Pre-sleep (1.5)
- Post-sleep (1.5)
- Daily planning (0.5)
- Work preparation (1)

[Clement, 2012]
<table>
<thead>
<tr>
<th>#</th>
<th>Item</th>
<th>Risk and Mitigation Strategy</th>
<th>Impact</th>
<th>Prob.</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Risk</td>
<td>Loss of sample containment</td>
<td>3</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Strategy</td>
<td>System redundancy / multiple samples</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Risk</td>
<td>Phobots miss</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Strategy</td>
<td>Ensuring criteria for release</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Risk</td>
<td>Rover mobility failure</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Strategy</td>
<td>Robotic exploration capabilities</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Risk</td>
<td>Imperfect trajectory maneuvers</td>
<td>4</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Strategy</td>
<td>Ensuring sufficient margin in course planning</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Risk</td>
<td>Radiation and microgravity impacts on crew (chronic)</td>
<td>3</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Strategy</td>
<td>Shielding and countermeasures</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Risk</td>
<td>ECLSS failure</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Strategy</td>
<td>Redundancy</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Risk</td>
<td>Decompression sickness / EVA failures</td>
<td>5</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Strategy</td>
<td>Proper EVA protocol</td>
<td>5</td>
<td>2</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Risk</td>
<td>Medical emergencies</td>
<td>5</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Strategy</td>
<td>Crew training, medical supplies, and surgical suite</td>
<td>5</td>
<td>2</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Risk</td>
<td>Failed in space rendezvous (Earth proximity)</td>
<td>4</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Strategy</td>
<td>Abort capabilities to earth</td>
<td>4</td>
<td>2</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Risk</td>
<td>Structural failure of crew habitat</td>
<td>5</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Strategy</td>
<td>Prior demonstration of technology and testing</td>
<td>5</td>
<td>2</td>
<td>10</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Impact on Mission</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>Minor</td>
<td>Moderate</td>
<td>Critical</td>
<td>Catastrophic</td>
<td></td>
</tr>
<tr>
<td>No impact, No fix required</td>
<td>Minor impact, Fix required</td>
<td>Moderate impact, Fix required</td>
<td>Loss of Mission Objective</td>
<td>Loss of Vehicle or Crew Member</td>
<td></td>
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<tr>
<td>Probability of Occurrence</td>
<td>Extremely Unlikely</td>
<td>Seldom / Not Likely</td>
<td>Occasional / Potential</td>
<td>Likely</td>
<td>Frequent</td>
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</tbody>
</table>
# Risk Matrix

<table>
<thead>
<tr>
<th>Impact to Mission</th>
<th>None  (1)</th>
<th>Minor (2)</th>
<th>Moderate (3)</th>
<th>Critical (4)</th>
<th>Catastrophic (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequent (5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Likely (4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potential (3)</td>
<td></td>
<td></td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not likely (2)</td>
<td>2, 3</td>
<td></td>
<td>1</td>
<td>9</td>
<td>7, 8, 10</td>
</tr>
<tr>
<td>Extremely unlikely (1)</td>
<td></td>
<td></td>
<td></td>
<td>4,</td>
<td>6</td>
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