Progress Briefing
Research Contract 07600-041
(under Prime Contract NAS5-98051)
OTC-G096-PB-00-1

Prepared for:

Universities Space Research Association (USRA)
7 June 2000

By

Dr. Eric E. Rice
Orbital Technologies Corporation
Space Center, 1212 Fourier Drive
Madison, Wisconsin 53717
608-827-5000
www.orbitec.com
Email: ricee@orbitec.com
INTRODUCTION

• Background and Assumptions
• Advanced Concept Description
• SCO/GOX Hybrid Testing
• SCH₄/GOX Hybrid Testing
• Overall Study Approach
• Mission Identification
• Fuels/Oxidizers/Sources Considered
• Propellant Processing Scenarios
• Rocket Performance Calculations
• Traffic Model Data Sheet
• Phase I Scenarios
• Preliminary Cost-Benefit Analysis
• Phase I Conclusions
• Phase II Program
BACKGROUND AND ASSUMPTIONS

- **Purpose:** To Enable Cost-Effective, *In Situ* Production and Uses of Mars Atmospheric-Derived Oxidizers and Fuels and to Guide Technology Development and Unique Hardware Development, Advanced Concept Development and System Analysis Efforts

- Mars-produced Fuels and Oxidizers Will Enhance and/or Enable a Variety of Mars Exploration/Exploitation Missions by Providing a Very Cost-effective Supply of Propellants

- Most Cost-Effective Martian Resource Is the Atmosphere (95% CO₂), However, Mars Soil Can Also Provide other ISRU Species (Mg, Al, etc.) and Abundances (H₂O)

- Atmospheric CO₂ Can Be Easily Processed and Converted to CO, C and O₂

- Small Amount of H₂O Can Be Converted to H₂ and O₂, and N₂, and Ar Are Also Available from the Atmosphere -- with these Elements, There Are Many Propellant Combinations Possible
BACKGROUND AND ASSUMPTIONS (CONT.)

• Ground Transport Systems Include: Automated Unmanned Roving Vehicles, Personal Vehicles, Two-Person Unpressurized Rovers, Manned Pressurized Transport Rovers, and Larger Cargo Transports


• Auxiliary Power Systems Include: Brayton Cycle Turbines and Fuel Cells for Small Mars Outposts

• Implementation of this Architecture Will Also Greatly Support Logistics & Base Operations by Providing a Reliable and Simple Way to Store Solar or Nuclear Generated Energy
ADVANCED CONCEPT
DESCRIPTION

• It Is Believed That by Using the Baseline C/O System, in the Proper Fuel Form (CO Solid; C Solid) That Significant Economic Dividends Are Possible for Future Mars Base Activity

• The Production of O and CO through Solid State Electrolysis Appears to Be Well in Hand by Dr. Sridhar of the University of Arizona -- Hardware Is Now Being Prepared to Fly to Mars for an ISRU Demonstration

• ORBITEC Has Demonstrated Successful Hot Firings of Advanced Cryogenic Solid Hybrid Rocket Engines, Including: Solid CO, Solid H₂, Solid O₂, Solid CH₄, and Solid C₂H₂

• CO Gas Can Be Directly and Quickly Frozen to a Solid Hybrid Fuel Grain Below the Triple Point Temperature (68 K) by Using Cooled LOX (With the Low Pressure of the Mars Atmosphere (4.5 To 11.4 mm Hg, This Is Very Easy-@ 11.4 mm LOX Will Be at 63 K, and @6 mm LOX Will Be at 60 K) as the Freezing Fluid and Oxidizer in a Cryogenic Hybrid Engine

• Focusing on the Innovative and Revolutionary Use of Solid CO and C as Fuels with LOX in Hybrid Rockets and Power System Applications, but Have Broadened Scope to Include: SC/LOX, SCO/LOX, LCO/LOX, SCH₄/LOX, LCH₄/LOX, SC₂H₂/LOX, LH₂/SOX, LH₂/LOX, and other Secondary Derivative Propellants That May Have Significant Storability Advantages (e.g., H₂O₂/CH₃OH and H₂O₂)
ORBITEC Has Been Very Active in Developing Advanced Cryogenic Hybrid Rocket Technology and Has Been the Only Organization in the World that Has Test Fired Solid CO Hybrid

On January 29, 1998, ORBITEC Performed the First Ever Test Firing of a Solid CO/GOX Propellant Combination in the ORBITEC Mark-II Cryogenic Hybrid Rocket Engine

100 Grams of Solid CO Was Frozen Onto the Inside of the Cylindrical Chamber of the Engine and LHe was Used to Freeze and Cool the CO for the Test

The Freezing Pressure Was on the Order of 1 Torr and the Freezing Process Took 29 Minutes

Based on Previous Experience, We Estimate that the CO Was Approximately 10 K Just Prior to the Test Firing

Five Successful Tests Have Been Conducted to Date

Patent is Pending
VIDEO IMAGE OF A SOLID CO GRAIN FORMED IN THE MARK II ENGINE AND FIRING
PRESSURE-TIME AND O/F-TIME TRACES FOR SCO/GOX FIRINGS
## SCO/GOX HYBRID FIRING RESULTS

<table>
<thead>
<tr>
<th>Variable</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burn Time (s)</td>
<td>9.7</td>
<td>11.6</td>
<td>13.0</td>
<td>9.2</td>
<td>12.8</td>
</tr>
<tr>
<td>Initial SCO Temp. (K)</td>
<td>10-20</td>
<td>10-20</td>
<td>10-20</td>
<td>10-20</td>
<td>10-20</td>
</tr>
<tr>
<td>Main O₂ Flow (g/s)</td>
<td>6.0</td>
<td>6.0</td>
<td>4.0</td>
<td>10.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Avg. Reg. Rate (cm/s)</td>
<td>0.058</td>
<td>0.048</td>
<td>0.043</td>
<td>0.061</td>
<td>0.044</td>
</tr>
<tr>
<td>Avg. p_c (psi)</td>
<td>71</td>
<td>67</td>
<td>52</td>
<td>95</td>
<td>55</td>
</tr>
<tr>
<td>Avg. O/F</td>
<td>0.57</td>
<td>0.70</td>
<td>0.51</td>
<td>0.92</td>
<td>0.76</td>
</tr>
<tr>
<td>$C_{exp}^*$ (m/s)</td>
<td>1117</td>
<td>1176</td>
<td>1127</td>
<td>1166</td>
<td>1019</td>
</tr>
<tr>
<td>$C_{theo}^*$ (m/s)</td>
<td>1362</td>
<td>1352</td>
<td>1358</td>
<td>1325</td>
<td>1341</td>
</tr>
<tr>
<td>$C_{eff}^*$</td>
<td>82%</td>
<td>87%</td>
<td>83%</td>
<td>88%</td>
<td>76%</td>
</tr>
</tbody>
</table>

Note: Each SCO fuel grain had an initial mass of 100 g.
CONCLUSIONS REACHED FROM SCO/GOX TESTS

- SCO Can Be Easily Formed in a Solid Grain from the Gas Phase
- Grain Appears Structurally Sound
- No Indications of Grain Slipping During Burns Were Noticed
- SCO Burns Very Well with GOX – It Has Been One of the Smoothest Burning Cryogenic Solids That ORBITEC Has Tested
- Pressure Change with Time Was Primarily Due to the Increase in Area as the Grain Regressed; Some Contribution to the Increase in Grain Temperature Is Also Believed a Contributor
- Optimum O/F Ratio Was Easily Achieved the First Time Tried
- Tests Show Great Promise for the SCO/LOX Propellant Combination for Use as a Mars Sample Return and a Wide Variety of Mars Exploration Applications
ORBITEC Has Also Completed Work to Design, Build, and Test a Solid Methane/GOX Hybrid Rocket Engine

Total of 24 Successful Test Firings Were Performed

Largest SCH$_4$ Grain Fired Had a Mass of 120 g

Highest Steady Chamber Pressure Attained Was 240 Psia, and Highest Oxygen Mass Flow Rate Injected into the Engine Was 35 g/sec

Pressure Curves for SCH$_4$/GOX Firings, Showing Effect of Grain Size and Varying Oxygen Flow Rate
SUMMARY OF ORBITEC CRYOGENIC HYBRID REGRESSION RATE DATA

SOX/GH2: \( r = 0.24G_0^{0.77} \)
SOX/GH2 - A Control: \( r = 0.097G_0^{0.33} \)
SCH4/GOX: \( r = 0.29G_0^{0.77} \)
SCH4-7.5% Al/GOX: \( r = 0.17G_0^{0.89} \)
SCH4-15% Al/GOX, singlet injector
SCH4-15% Al/GOX, showerhead inj.
SCH4-30% Al/GOX, singlet injector
HTPB/GOX: \( r = 0.015G_0^{0.68} \)
Ref.: R.A. Fredrick

Average Oxygen or Hydrogen Mass Flux (g/cm² - sec)

Average Regression Rate (cm/sec)
OVERALL STUDY
APPROACH

**Fuel/Oxidizer Scenarios Defined**
1. Select Fuel/Oxidizer Combination
2. Determine Planetary Source
3. Develop Processing Scenario

**Vehicles/Systems Defined**
1. Space Transport
2. Ground Transport
3. Auxiliary Power
4. Other

**Mission Model Development**
1. Early Exploration
2. Low Exploitation
3. Medium Exploitation
4. High Exploitation

**Cost/Benefit Model Analysis**
1. Parametric Source Launch Cost
2. Recurring Cost
3. Recurring and Non-Recurring Cost

**Develop More Efficient Propellant Families**

**Assignment of Vehicles/Systems to Missions**

**Establishment of Vehicle/System Traffic/Use Model**

**Results Review & Sensitivity Study**
Consider Other Combinations to Lower Cost Further

**Final Recommendations for ISRU Fuel/Oxidizer Technology Development for Mars Exploration/Exploitation**
<table>
<thead>
<tr>
<th>MISSION IDENTIFICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Scientific Exploration &amp; Research</td>
</tr>
<tr>
<td>• Commercial Exploration</td>
</tr>
<tr>
<td>• Terraforming</td>
</tr>
<tr>
<td>• Infrastructure Construction</td>
</tr>
<tr>
<td>• Agriculture/Farming</td>
</tr>
<tr>
<td>• Manufacturing/Industrial Activities</td>
</tr>
<tr>
<td>• Resource Mining</td>
</tr>
<tr>
<td>• Weather/Environmental</td>
</tr>
<tr>
<td>• Communications Navigation Services</td>
</tr>
<tr>
<td>• Surveying/Mapping</td>
</tr>
<tr>
<td>• Personal Transportation</td>
</tr>
<tr>
<td>• Package/Mail Delivery/Package Delivery/Product Delivery/Food Delivery/Goods/Services/Cargo</td>
</tr>
<tr>
<td>• Government Activity/Law Enforcement/Emergency Rescue/Response</td>
</tr>
<tr>
<td>• Launch/Space Transport Satellite/Earth Cargo Launch/Space Transport</td>
</tr>
<tr>
<td>• Auxiliary Power/Emergency Power</td>
</tr>
<tr>
<td>• Live Support</td>
</tr>
<tr>
<td>• Waste/Trash Management</td>
</tr>
<tr>
<td>• Health Care/Maintenance</td>
</tr>
<tr>
<td>• Virtual Travel Market</td>
</tr>
</tbody>
</table>
## EXAMPLE OF MISSION DEFINITION

**Mission Category:** Scientific Exploration and Research

<table>
<thead>
<tr>
<th>Mission/Submission Scope?</th>
<th># of Crew/Robotic</th>
<th>Mission Duration</th>
<th>Distance from Base (km)</th>
<th>Travel Time</th>
<th>Payload Mass (kg)</th>
<th>Vehicle Type Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Past/Current Life on Mars – search for evidence of past life, geology of the planet, ice at poles or permafrost (tools, sample boxes, life support, rover, sample rocks/dust, measure seismic activity)</td>
<td>2/Robotic</td>
<td>1-5 days</td>
<td>4000 km</td>
<td>Minutes</td>
<td>300</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td>2/Robotic</td>
<td>1 day</td>
<td>500 km</td>
<td>Hours</td>
<td>300</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td>2/Robotic</td>
<td>3-7 days</td>
<td>10,000 km</td>
<td>Minutes</td>
<td>300</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td>Robotic</td>
<td>Infinite</td>
<td>Infinite</td>
<td>Minutes N/A</td>
<td>300</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td>Delivery Vehicle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Recovery Vehicle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sounding Rocket</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meteorology – study/characterize atmosphere, dust storms, other weather Phenomena (temperate, pressure, wind velocity, solar radiation, humidity)</td>
<td>Robotic</td>
<td>1 day</td>
<td>10,000 km</td>
<td>Minutes</td>
<td>10</td>
<td>Ballistic Flight Ballistic Flight</td>
</tr>
<tr>
<td></td>
<td>Robotic</td>
<td>1 day &lt; day</td>
<td>10,000 km ? altitude</td>
<td>Minutes</td>
<td>10</td>
<td>Ballistic Flight Ballistic Flight</td>
</tr>
<tr>
<td></td>
<td>Robotic</td>
<td></td>
<td></td>
<td>Minutes</td>
<td>2</td>
<td>Ballistic Flight Ballistic Flight</td>
</tr>
<tr>
<td></td>
<td>Ballistic Flight</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>Ballistic Flight Ballistic Flight</td>
</tr>
<tr>
<td></td>
<td>Ground</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>Ballistic Flight Ballistic Flight</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>Ballistic Flight Ballistic Flight</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>Ballistic Flight Ballistic Flight</td>
</tr>
<tr>
<td>Astronomy – any orbiting systems supplied from Earth</td>
<td>2/Robotic</td>
<td>1-5 days</td>
<td>4000 km</td>
<td>Minutes</td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td>2/Robotic</td>
<td>1 day</td>
<td>500 km</td>
<td>Hours</td>
<td>50</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td>2/Robotic</td>
<td>3-7 days</td>
<td>10,000 km</td>
<td>Minutes</td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td>Robotic</td>
<td></td>
<td></td>
<td>Minutes N/A</td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td>Ground</td>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td>Solar Monitoring – located at base, so no need for transport</td>
<td>2/Robotic</td>
<td>1-5 days</td>
<td>4000 km</td>
<td>Minutes</td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td>2/Robotic</td>
<td>1 day</td>
<td>500 km</td>
<td>Hours</td>
<td>50</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td>2/Robotic</td>
<td>3-7 days</td>
<td>10,000 km</td>
<td>Minutes</td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td>Robotic</td>
<td></td>
<td></td>
<td>Minutes N/A</td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td>Ground</td>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td>Other Science – study meteorites, characterize poles</td>
<td>2/Robotic</td>
<td>1-5 days</td>
<td>4000 km</td>
<td>Minutes</td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td>2/Robotic</td>
<td>1 day</td>
<td>500 km</td>
<td>Hours</td>
<td>50</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td>2/Robotic</td>
<td>3-7 days</td>
<td>10,000 km</td>
<td>Minutes</td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td>Robotic</td>
<td></td>
<td></td>
<td>Minutes N/A</td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td>Ground</td>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>Ballistic Flight Ground</td>
</tr>
<tr>
<td>Mars Moon Exploration (landing equipment, tools similar to the search for life/geology mission)</td>
<td>3/Robotic</td>
<td>1 week</td>
<td>Moon Orbits</td>
<td>Hours</td>
<td>100</td>
<td>Flight vehicle</td>
</tr>
<tr>
<td>Mission to Asteroid Belt</td>
<td>3/Robotic</td>
<td>Months</td>
<td>Asteroid Belt</td>
<td>Hours</td>
<td>100</td>
<td>Flight vehicle</td>
</tr>
</tbody>
</table>
## FUELS/OXIDERS/SOURCES CONSIDERED

<table>
<thead>
<tr>
<th>Fuel / Oxidizer</th>
<th>Source</th>
<th>Space Transport</th>
<th>Ground Transport</th>
<th>Aerocraft</th>
<th>Powered Balloon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Earth</td>
<td>Mars</td>
<td>Moon</td>
<td>Solid</td>
<td>Cryo - Hybrid</td>
</tr>
<tr>
<td>CO / O₂</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>C / O₂</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>CH₄ / O₂</td>
<td>✓H</td>
<td>✓</td>
<td>✓H</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>C₂H₂ / O₂</td>
<td>✓H</td>
<td>✓</td>
<td>✓H</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>CH₃OH / H₂O₂</td>
<td>✓H</td>
<td>✓</td>
<td>✓H</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>H₂ / O₂</td>
<td>✓H</td>
<td>✓</td>
<td>✓HO</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>CH₃OH / LOX</td>
<td>✓H</td>
<td>✓</td>
<td>✓H</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
PROPELLANT PROCESSING SCENARIOS

1. All Earth-Supplied H₂ and O₂
2. Earth-Supplied H₂; O₂ from the Mars Atmosphere
3. Moon-Supplied H₂; O₂ from Lunar H₂O
4. All Mars-Supplied H₂; O₂ from H₂O in the Atmosphere
5. CO and O₂ Made from the Mars Atmosphere
6. C₂H₂ Made from Earth-Supplied H₂; Mars C and O₂ from Mars Atmosphere
7. C and O₂ Made from the Mars Atmosphere
8. CH₄ Made from Earth-Supplied H₂; C and O₂ from Mars Atmosphere
9. CH₄ Made from Mars-Supplied H₂ (Atmospheric Water); C and O₂ from Mars Atmosphere
10. CH₃OH Made from Earth H₂; C from Mars Atmosphere; H₂O₂ from Earth H₂ and Mars O₂
11. CH₃OH Made from Mars C, H₂, O₂
12. H₂O₂ From Mars H₂O, O₂
CO/O₂ PRODUCTION PLANT

- Mass and Energy Requirements For Two Different Sizes of CO/O₂ Production Plants Were Developed
- Analysis for the Small Production Plant Assumes that the CO₂ Compressor and CO/CO₂ Separator Will Operate for One Cycle Per Day
- Analysis for the Large Plant Assume that the CO₂ Compressor and CO/CO₂ Separator Will Operate for 8 Cycles Per Day
- O₂ Generator in the Small Production Plant Would Operate for 7 Hours Each Day, While the Large Production Plant Would Operate 24 Hours Per Day

<table>
<thead>
<tr>
<th>Component</th>
<th>Small Mass (kg)</th>
<th>Plant 10 kg/day Energy (kW-hr)</th>
<th>Large Mass (kg)</th>
<th>Plant 1,000 kg/day Energy (kW-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ Compressor</td>
<td>120</td>
<td>24</td>
<td>1,500</td>
<td>2,400</td>
</tr>
<tr>
<td>Oxygen Generator</td>
<td>15</td>
<td>15</td>
<td>437</td>
<td>1,500</td>
</tr>
<tr>
<td>CO/CO₂ Separator</td>
<td>120</td>
<td>24</td>
<td>1,500</td>
<td>2,400</td>
</tr>
<tr>
<td>Support Equipment</td>
<td>75</td>
<td>-</td>
<td>950</td>
<td>-</td>
</tr>
<tr>
<td>TOTAL</td>
<td>330</td>
<td>63</td>
<td>4,387</td>
<td>6,300</td>
</tr>
</tbody>
</table>
PERFORMANCE CALCULATIONS FOR SELECTED PROPELLANTS

• CEA Code Used to Calculate the Propellant Performances

• Combinations Include:
  – SCO/LOX
  – C/LOX
  – SCH_4/LOX
  – SC_2H_2/LOX
  – LH_2/LOX
  – CH_3OH/H_2O_2
SCO/LOX

Specific Impulse (sec)

- 500 psia, 100:1 exp. to vac
- 100 psia, 20:1 exp. to vac
- 500 psia, 100:1 exp. to 10 torr
- 100 psia, 20:1 exp. to 10 torr
CARBON/LOX

Specific Impulse (sec)

O/F Ratio

- 500 psia, 100:1 exp. to vac
- 100 psia, 20:1 exp. to vac
- 500 psia, 100:1 exp. to 10 torr
- 100 psia, 20:1 exp. to 10 torr

Contract 07600-41/G-096
6/7/00
SCH$_4$/LOX

Specific Impulse (sec)

- 500 psia, 100:1 exp. to vac
- 100 psia, 20:1 exp. to vac
- 500 psia, 100:1 exp. to 10 torr
- 100 psia, 20:1 exp. to 10 torr

O/F Ratio

Specific Impulse (sec) vs. O/F Ratio graph with different conditions.
SC$_2$H$_2$/LOX

- 500 psia, 100:1 exp. to vac
- 100 psia, 20:1 exp. to vac
- 500 psia, 100:1 exp. to 10 torr
- 100 psia, 20:1 exp. to 10 torr

Specific Impulse (sec)

O/F Ratio

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5

310 320 330 340 350 360 370 380 390 400 410
LH$_2$/LOX

[Diagram showing specific impulse versus O/F ratio with different conditions indicated: 500 psia, 100:1 exp. to vac, 100 psia, 20:1 exp. to vac, 500 psia, 100:1 exp. to 10 torr, 100 psia, 20:1 exp. to 10 torr]
CH$_3$OH/H$_2$O$_2$

![Graph showing specific impulse (sec) vs O/F Ratio](image)
TRAFFIC MODEL DATA
SHEET EXAMPLE

[Note: each period represents 5 years]

<table>
<thead>
<tr>
<th>Mission Area</th>
<th>Solid CO/LOX</th>
<th>Propellant:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Total Period Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scientific Exploration &amp;Res</td>
<td>FV1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>FV2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>FV3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>FV4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>FV5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Totals:</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>GS1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>GS2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>GS3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>GS4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>GS5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Totals:</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
PHASE I
ANALYSIS SENARIOS
TO ASSESS COST/BENEFIT

• MAV Replacement for Mars Sample Return Mission

• Ballistic Surface Hopper, Assuming H₂/O₂, CO/O₂, CH₄/O₂, C/O₂ and Single Stage, 1000 Kg Payload, Fly to 500, 1000 Km Distances

• Rover/Transporter to 300 Km Distance Once Per Day, Using Fuel Cell or Brayton Cycle

• Outpost Chemical Power Using Fuel Cell or Brayton Cycle and H₂/O₂, CO/O₂, CH₄/O₂, CH₃OH/O₂
### MISSION CHARACTERISTICS AND ASSUMPTIONS

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>600 km</td>
</tr>
<tr>
<td>Orbit Type</td>
<td>Circular</td>
</tr>
<tr>
<td>Payload Mass</td>
<td>3.6 kg</td>
</tr>
<tr>
<td>Stage 1 Subsystem Mass</td>
<td>16.9 kg</td>
</tr>
<tr>
<td>Stage 2 Subsystem Mass</td>
<td>1.7 kg</td>
</tr>
<tr>
<td>Initial Launch Velocity</td>
<td>241 m/s</td>
</tr>
<tr>
<td>First Stage Delta-V</td>
<td>2382 m/s</td>
</tr>
<tr>
<td>Second Stage Delta-V</td>
<td>1514 m/s</td>
</tr>
<tr>
<td>Total Delta-V</td>
<td>4137 m/s</td>
</tr>
</tbody>
</table>
TSTO
MAV REPLACEMENT FOR MARS
SAMPLE RETURN MISSION
## TWO-STAGE TO ORBIT MARS ASCENT VEHICLE

<table>
<thead>
<tr>
<th>Propellant Combination</th>
<th>Propulsion System</th>
<th>Terrestrial Propellants</th>
<th>Propellant Mass (kg)</th>
<th>Dry Mass* (kg)</th>
<th>GLOW (kg)</th>
<th>ELM (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCO/LOX</td>
<td>Hybrid</td>
<td>-</td>
<td>107.2</td>
<td>50.9</td>
<td>161.7</td>
<td>50.9</td>
</tr>
<tr>
<td>SC/LOX</td>
<td>Hybrid</td>
<td>-</td>
<td>65.9</td>
<td>38.7</td>
<td>108.2</td>
<td>38.7</td>
</tr>
<tr>
<td>SC-H\textsubscript{2}/LOX**</td>
<td>Hybrid</td>
<td>C, H\textsubscript{2}</td>
<td>56.3</td>
<td>36.0</td>
<td>95.9</td>
<td>53.3</td>
</tr>
<tr>
<td>SC\textsubscript{2}H\textsubscript{2}/LOX</td>
<td>Hybrid</td>
<td>H\textsubscript{2}</td>
<td>40.4</td>
<td>31.0</td>
<td>75.0</td>
<td>32.1</td>
</tr>
<tr>
<td>HTPB/LOX</td>
<td>Hybrid</td>
<td>HTPB</td>
<td>48.2</td>
<td>33.5</td>
<td>85.3</td>
<td>47.3</td>
</tr>
<tr>
<td>LCH\textsubscript{4}/LOX</td>
<td>Bi-Propellant</td>
<td>H\textsubscript{2}</td>
<td>37.5</td>
<td>30.2</td>
<td>71.3</td>
<td>32.4</td>
</tr>
<tr>
<td>CTPB binder</td>
<td>Solid</td>
<td>Solid</td>
<td>81.3</td>
<td>40.7</td>
<td>125.6</td>
<td>122.0</td>
</tr>
</tbody>
</table>

*Dry mass does not include 3.6 kg payload
**SC with 5% H\textsubscript{2} additive by mass

Orbit: 600 km circular orbit, Payload: 3.6 kg
ISRU-BASED ONE-WAY BALLISTIC SURFACE HOPPER
CHARACTERISTICS OF
ONE-WAY HOPPER
MISSIONS WITH POWERED LANDINGS

<table>
<thead>
<tr>
<th>Propellant Combination</th>
<th>Propulsion System</th>
<th>Terrestrial Propellants</th>
<th>Distance (km)</th>
<th>Propellant Mass (kg)</th>
<th>Dry Mass (kg)</th>
<th>GLOW (kg)</th>
<th>ELM (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCO/LOX</td>
<td>Hybrid</td>
<td>-</td>
<td>500</td>
<td>4040</td>
<td>2320</td>
<td>6360</td>
<td>0</td>
</tr>
<tr>
<td>SC/LOX</td>
<td>Hybrid</td>
<td>-</td>
<td>500</td>
<td>3090</td>
<td>2220</td>
<td>5310</td>
<td>0</td>
</tr>
<tr>
<td>LCH4/LOX</td>
<td>Bi-Propellant</td>
<td>H2</td>
<td>500</td>
<td>2160</td>
<td>2110</td>
<td>4270</td>
<td>129</td>
</tr>
<tr>
<td>LH2/LOX</td>
<td>Bi-Propellant</td>
<td>H2, O2</td>
<td>500</td>
<td>1760</td>
<td>2070</td>
<td>3830</td>
<td>1760</td>
</tr>
<tr>
<td>SCO/LOX</td>
<td>Hybrid</td>
<td>-</td>
<td>1000</td>
<td>8250</td>
<td>2790</td>
<td>11,040</td>
<td>0</td>
</tr>
<tr>
<td>SC/LOX</td>
<td>Hybrid</td>
<td>-</td>
<td>1000</td>
<td>5770</td>
<td>2520</td>
<td>8290</td>
<td>0</td>
</tr>
<tr>
<td>LCH4/LOX</td>
<td>Bi-Propellant</td>
<td>H2</td>
<td>1000</td>
<td>3690</td>
<td>2280</td>
<td>5970</td>
<td>220</td>
</tr>
<tr>
<td>LH2/LOX</td>
<td>Bi-Propellant</td>
<td>H2, O2</td>
<td>1000</td>
<td>2900</td>
<td>2190</td>
<td>5090</td>
<td>2900</td>
</tr>
</tbody>
</table>

Payload = 1000 kg and is included in GLOW; 873 other non-propulsion mass included; vehicle structural mass fraction = 0.1
ISRU-POWERED ROVER/TRANSPORTER
FUEL NEEDS
FOR A 300 KM, TEN-HOUR TURBINE-POWERED, ROVER MISSION

• Rover Mass Kept Constant for all Fuels
• Turbine Efficiency of 65% for all Fuels
• 100 kg Mass Penalty Assessed for Exhaust Recovery System
• Payload of 1000 kg

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>H₂/O₂</th>
<th>CH₄/O₂</th>
<th>CO/O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Use, Exhaust</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recovered (kg)</td>
<td>113*</td>
<td>154 (13*)</td>
<td>249</td>
</tr>
<tr>
<td>Fuel Use, Exhaust</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not Recovered (kg)</td>
<td>104*</td>
<td>142 (12*)</td>
<td>223</td>
</tr>
</tbody>
</table>

*Mass Supplied from Earth or Moon as Hydrogen
FUEL REQUIREMENTS FOR POWER ASSUMING 70% OVERALL EFFICIENCY

![Graph showing fuel mass (kg/day) versus power requirements (kWh/day) for different fuel types: CO/O₂, CH₄/O₂, and H₂/O₂.]

- **CO/O₂**
- **CH₄/O₂**
- **H₂/O₂**

The graph illustrates the relationship between power requirements and fuel mass, with distinct lines for each fuel type.
# PRELIMINARY COST-BENEFIT COMPARISON OF ISRU PROPELLANTS

<table>
<thead>
<tr>
<th>Mission</th>
<th>ELM per Mission (kg)</th>
<th>ELM Cost ($M)</th>
<th>ISRU Savings per Mission ($M)</th>
<th>Missions per Year</th>
<th>ISRU Savings per Year ($M)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MAV Sample Return</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline Solid</td>
<td>122</td>
<td>1.22</td>
<td>----</td>
<td>1</td>
<td>----</td>
</tr>
<tr>
<td>SC:H₂/LOX Hybrid</td>
<td>32.1</td>
<td>0.32</td>
<td>0.90</td>
<td>1</td>
<td>0.90</td>
</tr>
<tr>
<td>LCH₄/LOX Bi-Prop</td>
<td>32.4</td>
<td>0.32</td>
<td>0.90</td>
<td>1</td>
<td>0.90</td>
</tr>
<tr>
<td>SC/LOX Hybrid</td>
<td>38.7</td>
<td>0.39</td>
<td>0.83</td>
<td>1</td>
<td>0.83</td>
</tr>
<tr>
<td>HTPB/LOX Hybrid</td>
<td>47.3</td>
<td>0.47</td>
<td>0.75</td>
<td>1</td>
<td>0.75</td>
</tr>
<tr>
<td>SCO/LOX Hybrid</td>
<td>50.9</td>
<td>0.51</td>
<td>0.71</td>
<td>1</td>
<td>0.71</td>
</tr>
<tr>
<td>SC-H₂/LOX Hybrid</td>
<td>53.3</td>
<td>0.53</td>
<td>0.69</td>
<td>1</td>
<td>0.69</td>
</tr>
<tr>
<td><strong>One Way Hopper (1000 km)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH₂/LOX Bi-Prop Baseline</td>
<td>2,900</td>
<td>29.0</td>
<td>----</td>
<td>10</td>
<td>----</td>
</tr>
<tr>
<td>LCH₄/LOX Bi-Prop</td>
<td>220</td>
<td>2.20</td>
<td>26.8</td>
<td>10</td>
<td>268</td>
</tr>
<tr>
<td>SC/LOX Hybrid</td>
<td>0</td>
<td>0</td>
<td>29.0</td>
<td>10</td>
<td>290</td>
</tr>
<tr>
<td>SCO/LOX Hybrid</td>
<td>0</td>
<td>0</td>
<td>29.0</td>
<td>10</td>
<td>290</td>
</tr>
<tr>
<td><strong>Turbine Powered Rover (300km)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH₂/LOX Turbine Baseline</td>
<td>113</td>
<td>1.13</td>
<td>----</td>
<td>100</td>
<td>----</td>
</tr>
<tr>
<td>LCH₄/LOX Turbine</td>
<td>7.7</td>
<td>0.08</td>
<td>1.05</td>
<td>100</td>
<td>105</td>
</tr>
<tr>
<td>SCO/LOX Turbine</td>
<td>0</td>
<td>0</td>
<td>1.13</td>
<td>100</td>
<td>113</td>
</tr>
<tr>
<td><strong>Outpost Auxiliary Power</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH₂/LOX Turbine Baseline</td>
<td>1400</td>
<td>14.00</td>
<td>----</td>
<td>50</td>
<td>----</td>
</tr>
<tr>
<td>LCH₄/LOX Turbine</td>
<td>100</td>
<td>1.00</td>
<td>13.00</td>
<td>50</td>
<td>650</td>
</tr>
<tr>
<td>LCO/LOX Turbine</td>
<td>0</td>
<td>0</td>
<td>14.00</td>
<td>50</td>
<td>700</td>
</tr>
</tbody>
</table>

Note: Processing equipment not amortized over ISRU derived propellant ELM, ELM ~ $10,000/kg, C and O₂ from Mars, H₂ from Earth
ISRU Will be a Significant Benefit to the Mars Program

- SCO/LOX Propellant System is likely good for Short Ballistic Hops and Wide Use in Ground Systems; Will Require Staging or Other Propellant Saving Measures for Large Orbital Operations
- Improving Mass Fraction Helps Lower Performance Systems
- Cryogenic Solid Grains Can Be Made and Stored in Mars Propellant Facilities
- CH₄/LOX Propellants Are Excellent for Large Orbital Operations
- Carbon/LOX and Acetylene/LOX Hybrids Also Are Excellent for More Demanding Missions
- H₂/O₂ Systems would be Best Suited for High-Performance Missions, If Mars Can Supply Water
- Large Cargo Transport Best Accommodated by Ground Transport Vehicles; Ballistic Rocket Flight Makes Sense for High Priority Missions
- O/F Choice Can Make a Significant Cost-Benefit Difference
- For Ground-based Systems, Hydrogen in the Exhaust Can and Should Be Recovered; CO₂ Can Be Released
- Consider Savings Attributed to Wings, Aeroshells, Parachutes, etc.
- Likely Need Nuclear Power Systems in Many Sizes
- The ISRU Analysis Approach is a Complex Problem
- Need to Do a Reasonable Concept Design on Vehicles and Process Equipment to Arrive at Correct Answer
PHASE II PROGRAM

- Schedule
- Study Ground Rules
- Tasks
- Progress
# PHASE II SCHEDULE

<table>
<thead>
<tr>
<th>Task Description</th>
<th>FY-2000</th>
<th>FY-2001</th>
<th>FY-2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Start</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 1. Review Overall Approach</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 2. Define Propellant Families</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 3. Define Vehicle/System Families</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 4. Develop Cost Data/Models</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 5. Develop Mission/Traffic Models</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 6. Assign Propellants/Vehicles</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 7. Cost Benefit Analysis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 8. Determine Best Architecture</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 9. Recommendation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 10. Reporting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Status Reports</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual Report</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Report</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Presentations</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **AM**: April, **M**: May, **J**: June, **J**: July, **A**: August, **S**: September, **O**: October, **N**: November, **D**: December, **J**: January, **F**: February, **M**: March, **A**: April, **J**: June, **A**: August, **S**: September, **O**: October, **N**: November, **D**: December.
CURRENT REQUIREMENT
/GROUND RULES

- Purpose of the Study Is to Assess Cost-Effective, In-situ Production and Use of Mars-Derived Oxidizers and Fuels to Guide Advanced Concept Development, System Analysis Efforts, and Technology and Unique Hardware Developments
- The Study Timeframe Includes the Early Manned Exploration Period and Extends 50 Years from the “End” of the Initial Human Mars Exploration Activity
- Missions to Be Used Are Those Defined by the Project Team
- Earth Launch Mass (ELM) Costs Will Be Parametrically Assessed at $10,000/kg, $1,000/kg, and $400/kg
- Human Activity Models Assumed for the 50-year Period of Assessment to Be 10,000 Humans for High, 1000 Humans for Medium and 100 Humans for Low
- Mission Vehicle Assignment and Mission Frequency Will Be Determined by Consensus of the Workshop Participants and the Project Team and Based Upon the Other Requirements and Guidelines
- All Cost Estimates Will Be in Year 2000 Dollars
- Ground Vehicles Are to Include: Automated Unmanned Roving Vehicles, Personal Vehicles, Two-Person Unpressurized Rovers, Manned Pressurized Transport Rovers, and Larger Cargo Transports
- Auxiliary Power Systems Are to Include: Brayton Turbines and Fuel Cells for Small Mars Outposts
- Only Propellants to Be Considered Are Those Derivable from Earth (Earth Deliveries), the Mars Atmosphere, or Water/Hydrogen Resources from the Moon
- Potential Propellant Candidates to Be Considered Include: CH₄/O₂, C/O₂, C₂H₂/O₂, CO/O₂, H₂O₂/CH₃OH, CH₃OH/LOX and H₂/O₂.
TASK 1. REVIEW OVERALL STUDY APPROACH

- Plan to Hold Approach Review through Workshop in Madison, June 21 - 22, 2000
- Invited Participants Include:
  - OSEAC Members - Eric Rice, Robert Gustafson, Mike Duke, Jerry Hanley, Doug O’Handley, Pete Priest
  - NIAC - Bob Cassanova
  - NASA - Bob Cataldo, Bill Larson, Diane Linne, Chris McKay, Dave McKay, Mike O’Neal, Bryan Palaszewski, Jerry Sanders, Tom Sullivan
  - Universities - George Miley, Leslie Gertsch, Richard Gertsch, KR Sridhar
  - Industry - Niklas Jarvstrat, Bill Siegfried
  - Others -

1.5 Day Agenda includes:
- Phase I Review
- Phase II Approach Review
- Technical Discussions
1. All Earth-Supplied H₂ and O₂
2. Earth-Supplied H₂; O₂ from the Mars Atmosphere
3. Moon-Supplied H₂; O₂ from Lunar H₂O
4. All Mars-Supplied H₂; O₂ from H₂O in the Atmosphere
5. CO and O₂ Made from the Mars Atmosphere
6. C₂H₂ Made from Earth-Supplied H₂; Mars C and O₂ from Mars Atmosphere
7. C and O₂ Made from the Mars Atmosphere
8. CH₄ Made from Earth-Supplied H₂; C and O₂ from Mars Atmosphere
9. CH₄ Made from Mars-Supplied H₂ (atmospheric water); C and O₂ from Mars Atmosphere
10. CH₃OH Made from Earth H₂; C from Mars; H₂O₂ from Earth H₂ and Mars O₂
11. CH₃OH Made from Mars C, H₂, O₂
12. H₂O₂ Made from Mars H₂O, O₂
## TASK 3. DEFINE VEHICLE/ SYSTEM FAMILY SCENARIOS

<table>
<thead>
<tr>
<th>Flight Vehicles</th>
<th>Ground Vehicles</th>
<th>Power Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAV's for Sample Return</td>
<td>Automated Rovers</td>
<td>Turbine</td>
</tr>
<tr>
<td>Ballistic Hoppers</td>
<td>Personal Closed Rovers</td>
<td>Fuel Cell</td>
</tr>
<tr>
<td>Surface to Orbit</td>
<td>2 - Person Open Rovers</td>
<td></td>
</tr>
<tr>
<td>Interplanetary</td>
<td>Multi-Person Closed Rovers</td>
<td></td>
</tr>
<tr>
<td>Powered Balloons</td>
<td>Large Cargo Transports</td>
<td></td>
</tr>
<tr>
<td>Winged Aerocraft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Rocket Backpacks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Rocket Platforms</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TASK 4. DEVELOP COST DATA/MODELS

- The Predicted Cost-Benefit of ISRU Propellants and Their Associated Production and Use Is Greatly Affected by the Earth Launch Mass (ELM) Cost or the Earth to Mars Surface Transport Cost
- The Latter is Much More Difficult to Estimate in the Future
- For ELM to Use Values of $10,000, $1,000 and $400 per kg
- As Part of the Cost-Benefit Analysis, Need to Understand Each Mission Scenario and How Much Mass is Required From Earth -- This Depends on the Missions that Are Defined, Their Frequency and Their Propellant Option
- Must Include Not Only ELM Propellant for Mars Delivery, But All of the Masses Associated with Storage, Processing, Upgrading/Refurbishment, Resupply, etc. of both Earth-Supplied and Mars-Supplied Propellants
- Must Also Consider the Different Recurring and Non-Recurring Costs of the Flight and Ground Systems that Are Designed for Each Propellant Use
- Will Estimate These Costs Using Aerospace CER’s or Other Software Models
TASK 5. DEVELOP MISSION AND TRAFFIC MODELS

- Traffic/Use Model Outlines How Often These Activities Take Place
- Four Different Levels of Human Presence on Mars Were Defined:
  - (1) Early Exploration (10 to 20 years),
  - (2) Low Presence (100 Permanent Inhabitants After 50 Years)
  - (3) Medium Presence (1,000 Permanent Inhabitants after 50 Years)
  - (4) High Presence (10,000 Permanent Inhabitant after 50 Years)
- 50-Year Clock Begins after the Initial Exploration Period is Over
- Once Defined Vehicles Are Assigned to the Given Missions, the Next Task is to Identify How Often the Mission Needs to Be Accomplished
- Data Needs for the Worksheet Include: Number of Crew, Robotic or Manned Mission, Distance from Base, Travel Time, Payload and Vehicle Type Required
TASK 6. ASSIGN PROPELLANTS/VEHICLES/SYSTEMS TO MISSIONS

- Once the Mission Data Are Developed, then Can Assign a Ground, Flight Vehicle or Power System that Can Satisfy the Specific Mission Need
- The Goal Would Be to Develop Only a Few Sets of Ground and Flight Vehicles that Can Satisfy all the Missions
TASK 7. COST/BENEFIT MODEL ANALYSIS/TRADES/SENSITIVITIES

- Once Cost-benefit Model Is Developed, Costs for Each Single Propellant Option Will Be Developed
- Groups or Families of Propellant Options Would Then Be Developed and Analyzed
- Expect that There May Be Significant Benefit in Selecting Both High and Low Performance Propellants for the Various Vehicles Considered
- Goal Is to Determine the Best Propellant Families to Satisfy the Lowest Cost for Exploration/Colonization Scenarios on Mars
TASK 8. DEVELOP THE MOST COST EFFECTIVE ARCHITECTURE

• As a Result of Conducting the Architecture Study and Looking at All the Predicted Costs, Issues and Sensitivities, We Will Recommend the Most Cost Effective Architecture

• A Separate System Definition Document Will Be Prepared for NIAC/NASA Use
TASK 9. PREPARE FINAL RECOMMENDATIONS

- ORBITEC Will Prepare Its Final Recommendations on The Results of the Study to NASA/NIAC
PHASE II PROGRESS

• Made All Arrangements for June 21-22, 2000 Workshop in Madison
• Sent Out Invitations to Prospective Participants
• Evaluating Cost Model Approaches
• Working on Propellant Family Definitions
• Prepared for the Annual Review
• Submitted 1st Progress Report