INTRODUCTION

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- **Background and Assumptions**
- **Advanced Concept Description**
- **SCO/GOX Hybrid Testing**
- **SCH_4/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**
- **Conclusions To Date**

BACKGROUND AND ASSUMPTIONS

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- 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% CO_2), However, Mars Soil Can Also Provide other ISRU Species (Mg, Al, etc.) and Abundances (H_2O)

- Atmospheric CO_2 Can Be Easily Processed and Converted to CO, C and O_2

- Small Amount of H_2O Can Be Converted to H_2 and O_2, and N_2, and Ar Are Also Available from the Atmosphere -- with these Elements, There Are Many Propellant Combinations Possible

BACKGROUND AND ASSUMPTIONS (CONT.)

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

- Flight Vehicles Include: Mars Sample Return Vehicles, Unmanned and Manned Surface-To-Surface “Ballistic Hoppers”, Surface-To-Orbit Vehicles, Interplanetary Transport Vehicles, Powered Balloons, Winged Aerocraft, Single-Person Rocket Backpacks, and Single-Person Rocket Platforms

- 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

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- **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 H_2, Solid O_2, Solid CH_4, and Solid C_2H_2**

- **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 <u>Solid</u> CO and C as Fuels with LOX in Hybrid Rockets and Power System Applications, but Have Broadened Scope to Include: SCH_4/LOX, LCH_4/LOX, SC_2H_2/LOX, LH_2/SOX, LH_2/LOX, SH_2-HEDM/LOX, Mg-Al/CO_2 and other Secondary Derivative Propellants That May Have Significant Storability Advantages (e.g., H_2O_2, CH_3OH)**

SCO/GOX HYBRID TESTING

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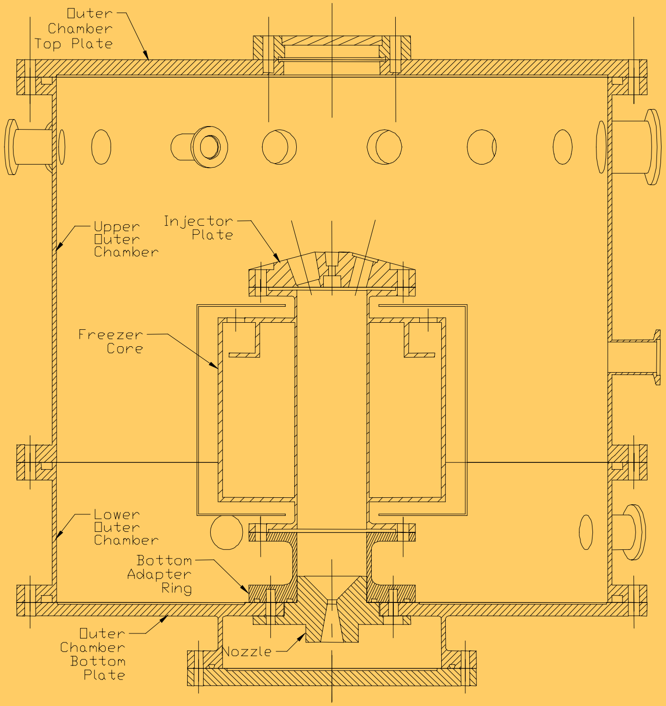
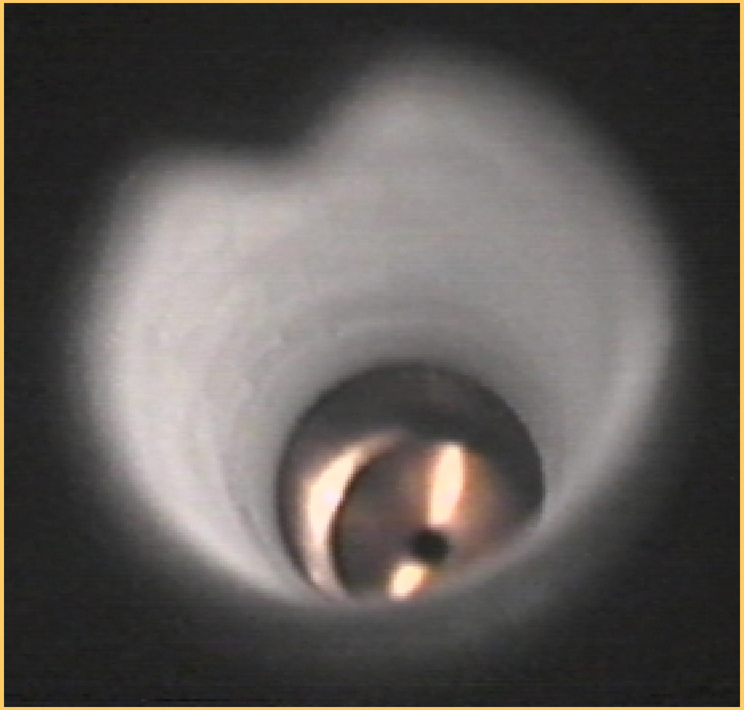
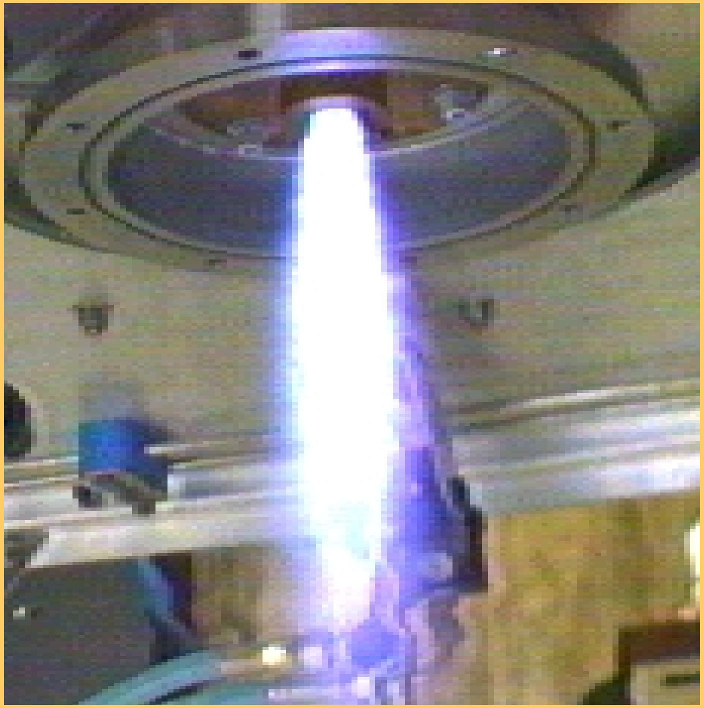
- **ORBITEC Has Been Very Active in Developing Advanced Cryogenic Hybrid Rocket Technology and Has Been the Only Organization in the World that Has Test Fired Solid CO Hybrid**
- **On January 29, 1998, ORBITEC Performed the First Ever Test Firing of a Solid CO/GOX Propellant Combination in the ORBITEC 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**
- **Three Tests Have Been Conducted to Date**

ORBITEC's Mark II Cryogenic Hybrid Rocket Engine



VIDEO IMAGE OF A SOLID CO GRAIN FORMED IN THE MARK II ENGINE AND FIRING





SCO/GOX HYBRID FIRING RESULTS

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Variable	Test 1	Test 2	Test 3
Burn Time (s)	9.72	11.61	12.95
Initial SCO Temp. (K)	10-20	10-20	10-20
Main O_2 Flow (g/s)	6.0	6.0	4.0
Initial O_2 Flux (g/cm^2-s)	0.48	0.48	0.32
Avg. O_2 Flux (g/cm^2-s)	0.39	0.39	0.26
Avg. reg. rate (cm/s)	0.058	0.048	0.043
Avg. p_c (psi)	70.9	67.3	51.5
Avg. O/F	0.57	0.70	0.51
C^*_{exp} (m/s)	1117.2	1172.1	1127
C^*_{theo} (m/s)	1342.6	1325.9	1332.8
C^*_{eff}	83.2%	88.4%	84.6%

SUMMARY OF ORBITEC CRYOGENIC HYBRID REGRESSION RATE DATA

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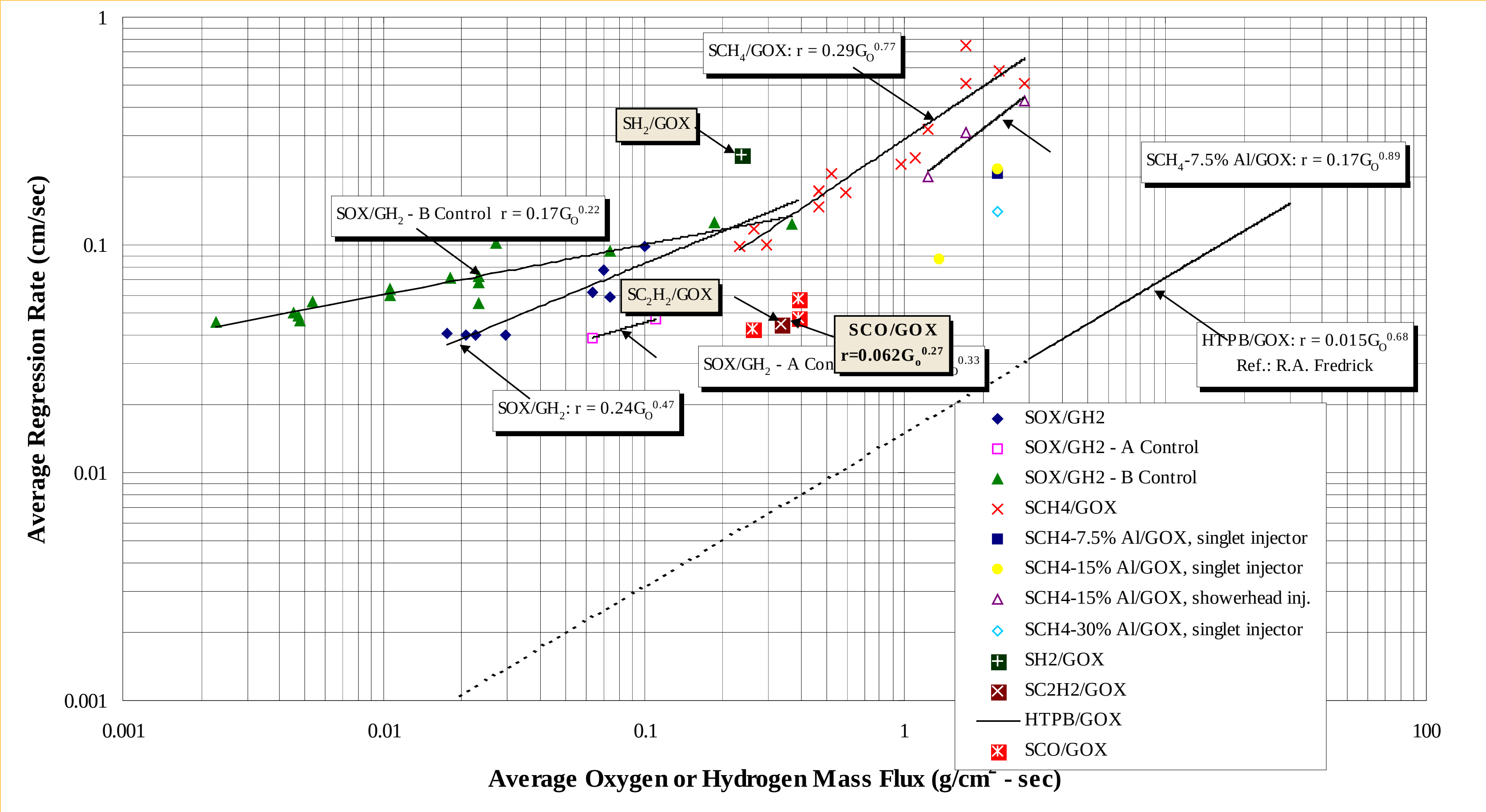

PRESSURE-TIME AND O/F-TIME TRACES FOR SCO/GOX FIRINGS

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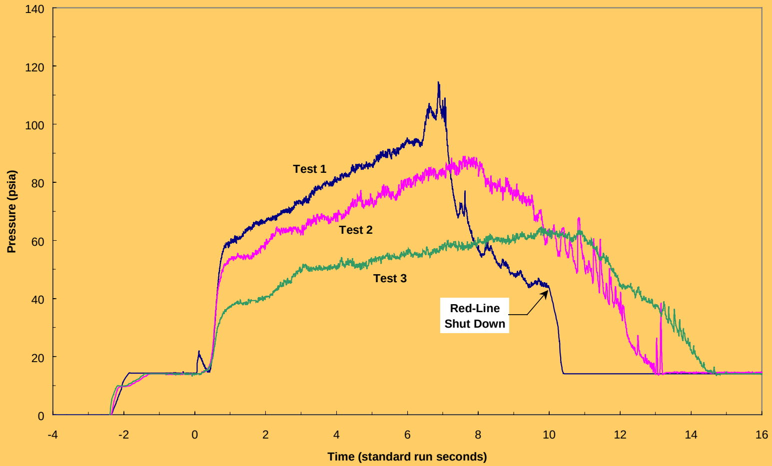

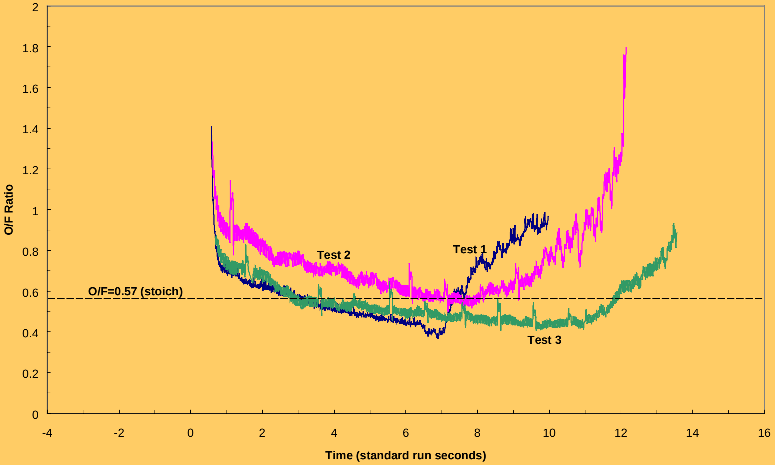

CONCLUSIONS REACHED FROM FIRST SCO/GOX TESTS

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- 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

SCH_4/GOX HYBRID PROPULSION TESTS

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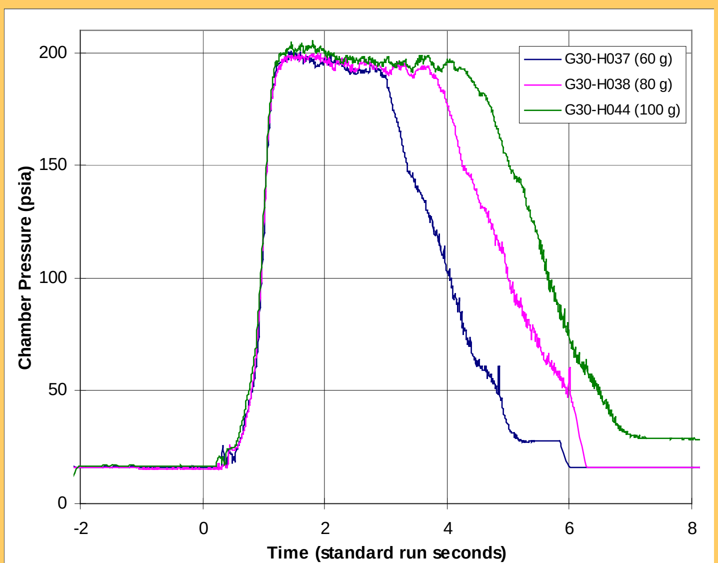
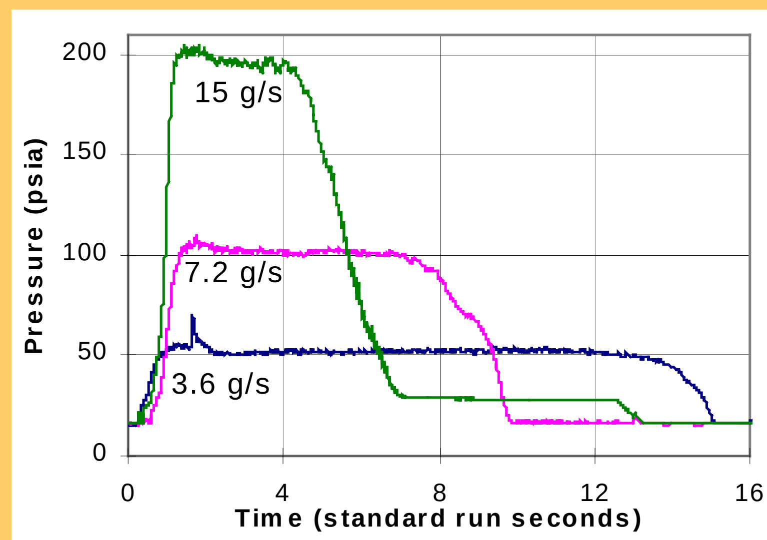
- ORBITEC Has Also Completed Work to Design, Build, and Test a Solid Methane/GOX Hybrid Rocket Engine
- Total of 24 Successful Test Firings Were Performed
- Largest SCH_4 Grain Fired Had a Mass of 120 g
- Highest Steady Chamber Pressure Attained Was 240 Psia, and Highest Oxygen Mass Flow Rate Injected into the Engine Was 35 g/sec





Pressure Curves for SCH_4/GOX Firings, Showing Effect of Grain Size and Varying Oxygen Flow Rate

OVERALL STUDY APPROACH

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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

Assignment of Vehicles/Systems to Missions

Establishment of Vehicle/System Traffic/Use Model

Cost/Benefit Model Analysis

1. Parametric Source Launch Cost
2. Recurring Cost
3. Recurring and Non-Recurring Cost

Results Review & Sensitivity Study

Consider Other Combinations to Lower Cost Further

Develop More Efficient Fuel/ Oxidizer Families

Final Recommendations for ISRU Fuel/Oxidizer Technology Development for Mars Exploration/Exploitation

MISSION IDENTIFICATION

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- **Scientific Exploration & Research**
- **Commercial Exploration**
- **Terraforming**
- **Infrastructure Construction**
- **Agriculture/Farming**
- **Manufacturing/Industrial Activities**
- **Resource Mining**
- **Weather/Environmental**
- **Communications Navigation Services**
- **Surveying/Mapping**
- **Personal Transportation**
- **Package/Mail Delivery/Package Delivery/Product Delivery/Food Delivery/Goods/Services/Cargo**
- **Government Activity/Law Enforcement/Emergency Rescue/Response**
- **Launch/Space Transport Satellite/Earth Cargo Launch/Space Transport**
- **Auxiliary Power/Emergency Power**
- **Live Support**
- **Waste/Trash Management**
- **Health Care/Maintenance**
- **Virtual Travel Market**

EXAMPLE OF MISSION DEFINITION

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Mission Category: Scientific Exploration and Research

Mission/Submission Scope?	# of Crew/ Robotic	Mission Duration	Distance from Base (km)	Travel Time	Payload Mass (kg)	Vehicle Type Required
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)	2/Robotic 2/Robotic 2/Robotic	1-5 days 1 day 3-7 days	4000 km 500 km 10,000 km	Minutes Hours Minutes	300 300 300	Ballistic Flight Ground Ballistic Flight
Meteorology – study/characterize atmosphere, dust storms, other weather Phenomena (temperate, pressure, wind velocity, solar radiation, humidity) Delivery Vehicle Recovery Vehicle Sounding Rocket	Robotic Robotic Robotic	1 day 1 day < day	10,000 km 10,000 km ? altitude	Minutes Minutes Minutes	10 10 2	Ballistic Flight Ballistic Flight Ballistic Flight
Astronomy – any orbiting systems supplied from Earth - any ground-based systems located at base, so no requirement for transport						
Solar Monitoring – located at base, so no need for transport						
Other Science – study meteorites, characterize poles	2/Robotic 2/Robotic 2/Robotic	1-5 days 1 day 3-7 days	4000 km 500 km 10,000 km	Minutes Hours Minutes	200 50 200	Ballistic Flight Ground Ballistic Flight
Mars Moon Exploration (landing equipment, tools similar to the search for life/geology mission)	3/Robotic	1 week	Moon Orbits	Hours	100	Flight vehicle
Mission to Asteroid Belt	3/Robotic	Months	Asteroid Belt	Hours	100	Flight vehicle

FUELS/OXIDERS/SOURCES CONSIDERED

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Fuel / Oxidizer	Source			Space Transport		Ground Transport		Aerocraft		Powered Balloon	
	Earth	Mars	Moon	Solid Cryo - Hybrid	Liquid Bi - Prop	Brayton	Fuel Cell	Brayton	Fuel Cell	Brayton	Fuel Cell
CO / O_2											
C / O_2											
CH_4 / O_2	H		H								
C_2H_2 / O_2	H		H								
CH_3OH / H_2O_2	H		H								
H_2 / O_2	H		HO	SOX							
$CO_2 / MgAl$				M							

PROPELLANT PROCESSING SCENARIOS

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1. All Earth-Supplied Hydrogen and Oxygen
2. Earth-Supplied Hydrogen, Oxygen from the Mars Atmosphere
3. Moon-Supplied Hydrogen and Oxygen
4. All Mars-Supplied Hydrogen and Oxygen from H_2O in the Atmosphere or Soil/Dust
5. Methane Made from Earth-Supplied Hydrogen, Carbon and Oxygen from Mars Atmosphere
6. Methane Made from Mars-Supplied Hydrogen, Carbon and Oxygen from Mars Atmosphere
7. CO and O Made from the Mars Atmosphere
8. C and O Made from the Mars Atmosphere
9. CO_2 from the Mars Atmosphere and Metal from Mars Regolith

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**
  - **Mg/CO_2**

SCO/LOX

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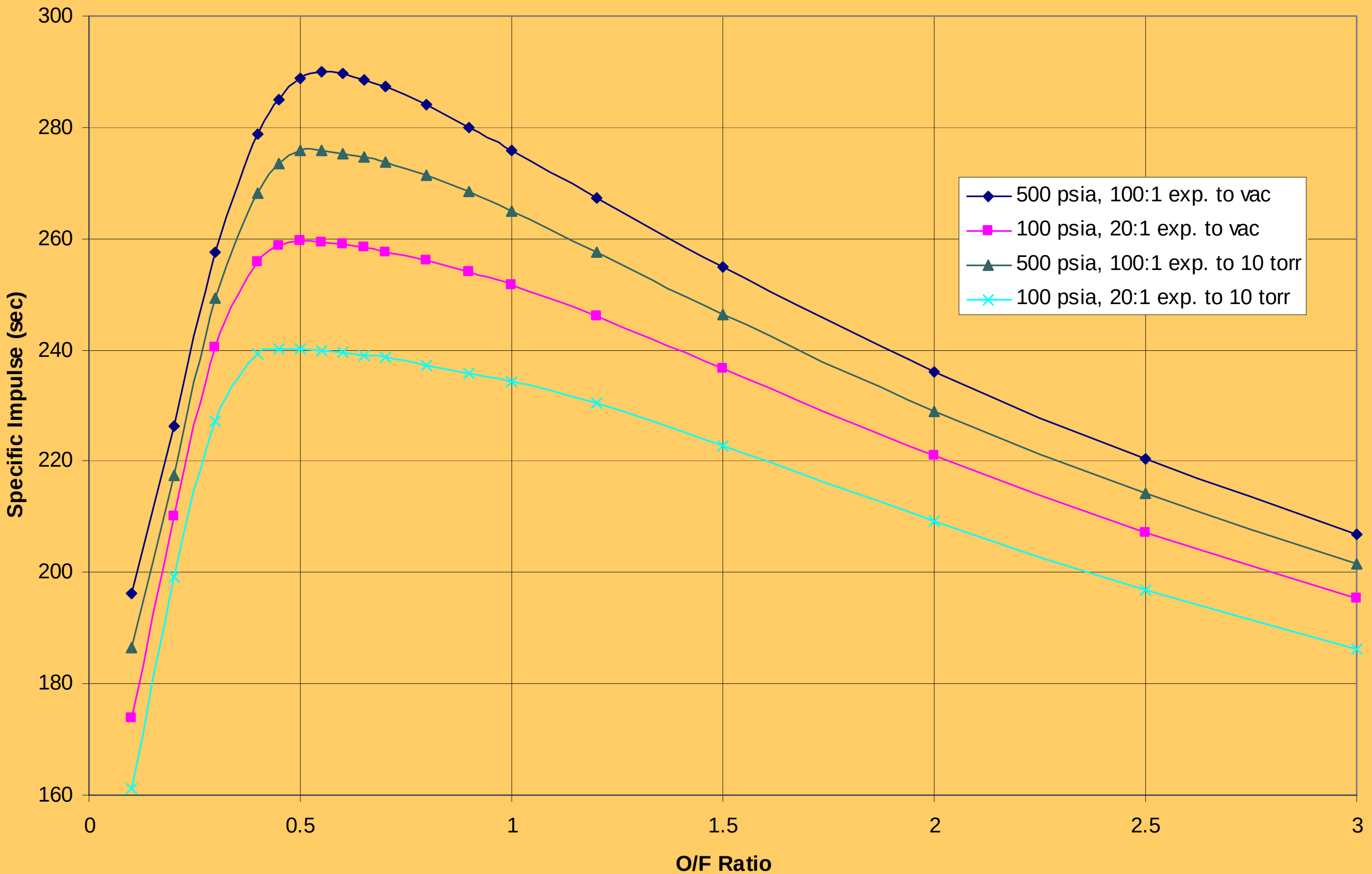

CARBON/LOX

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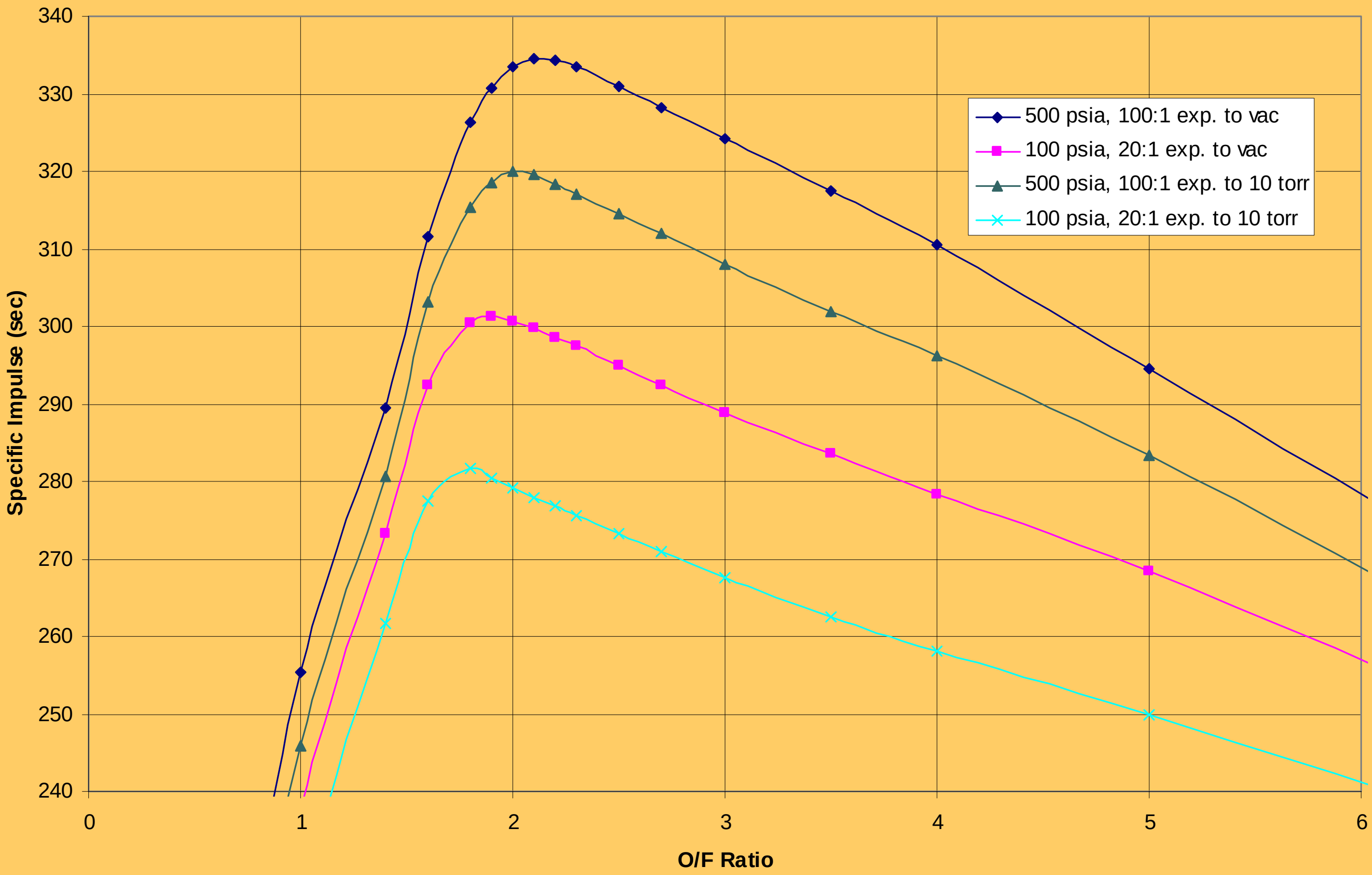

SCH_4/LOX

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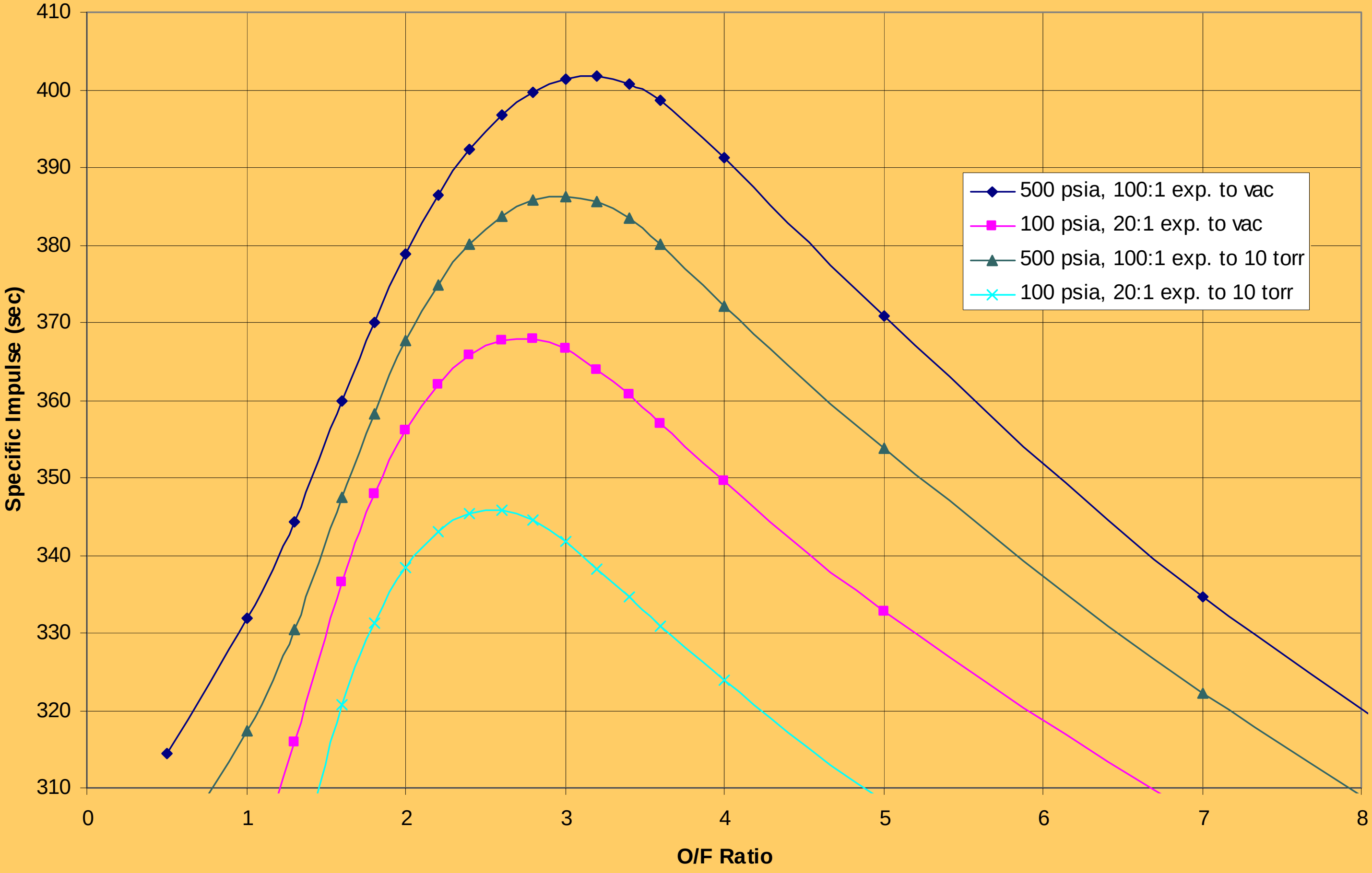

LH_2/LOX

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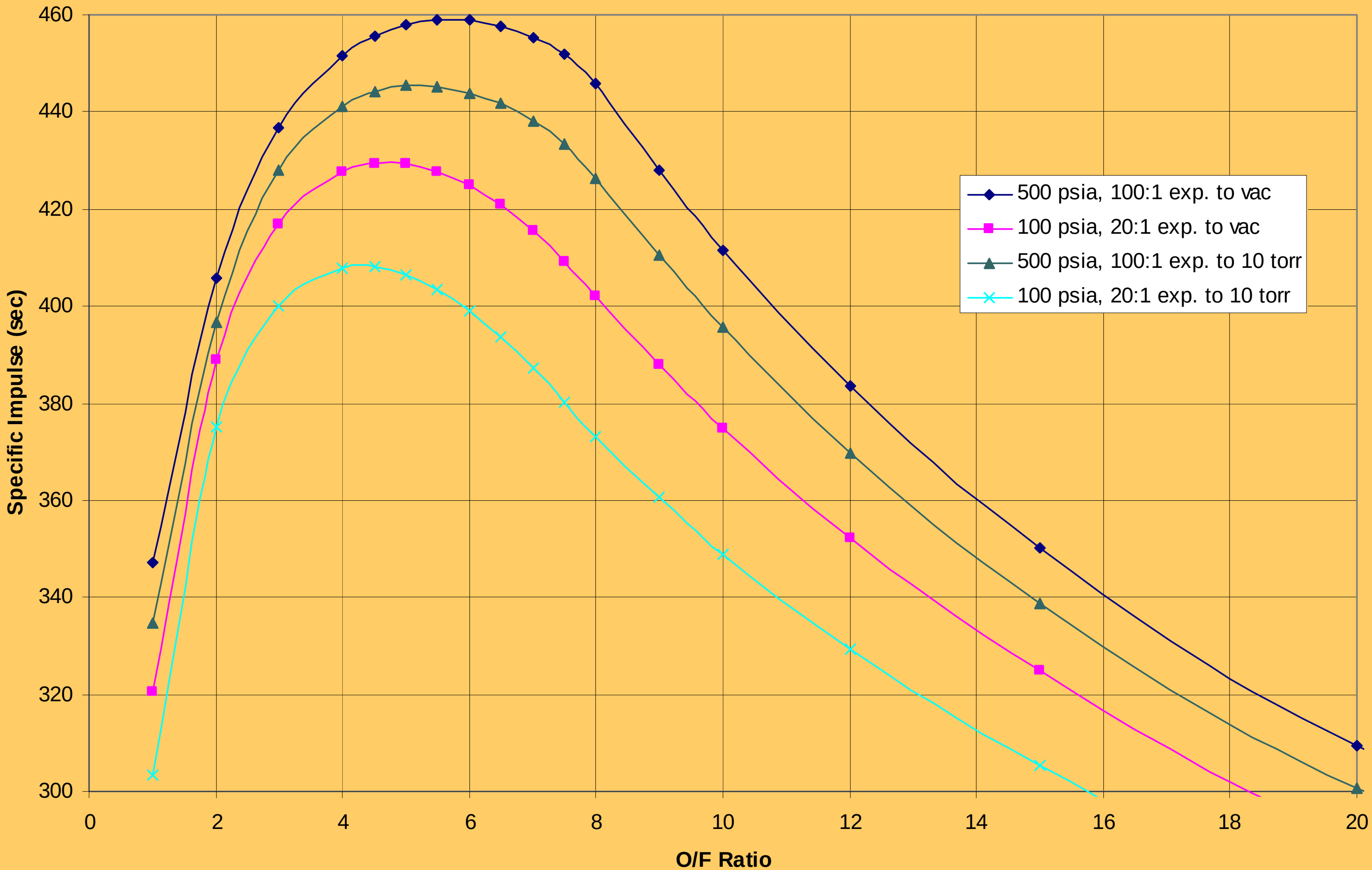

SC_2H_2/LOX

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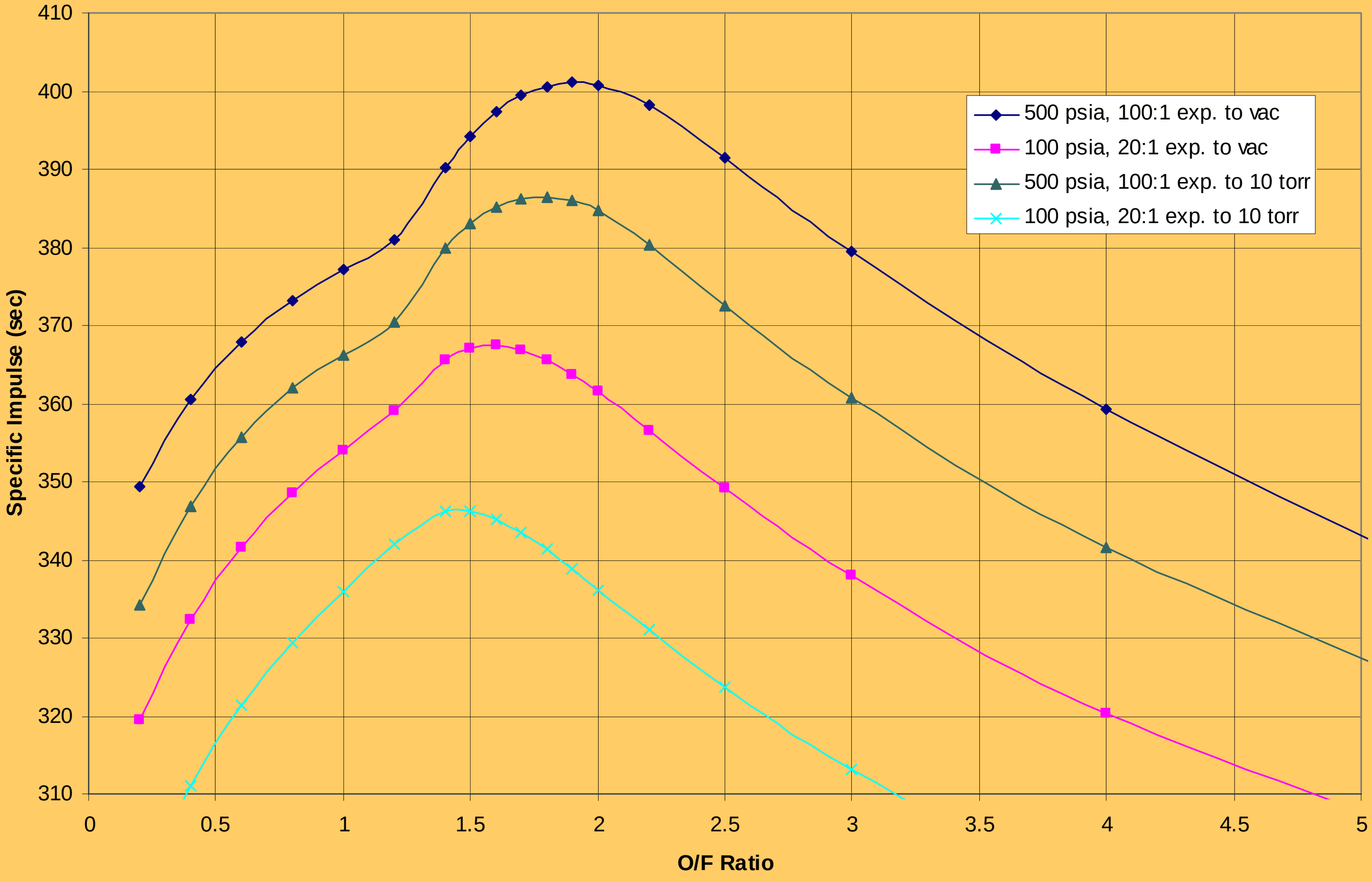

CH_3OH/H_2O_2

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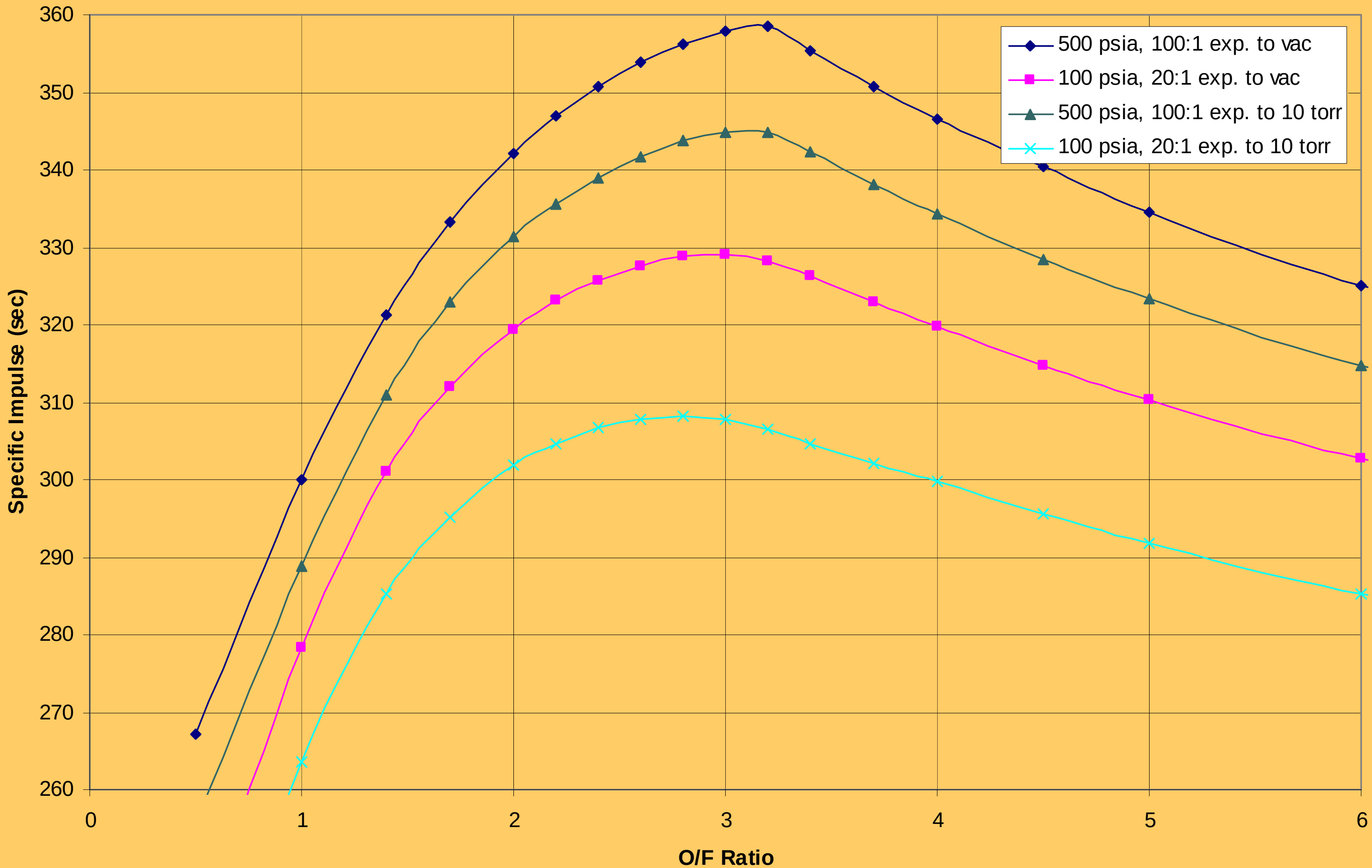

Mg/CO_2

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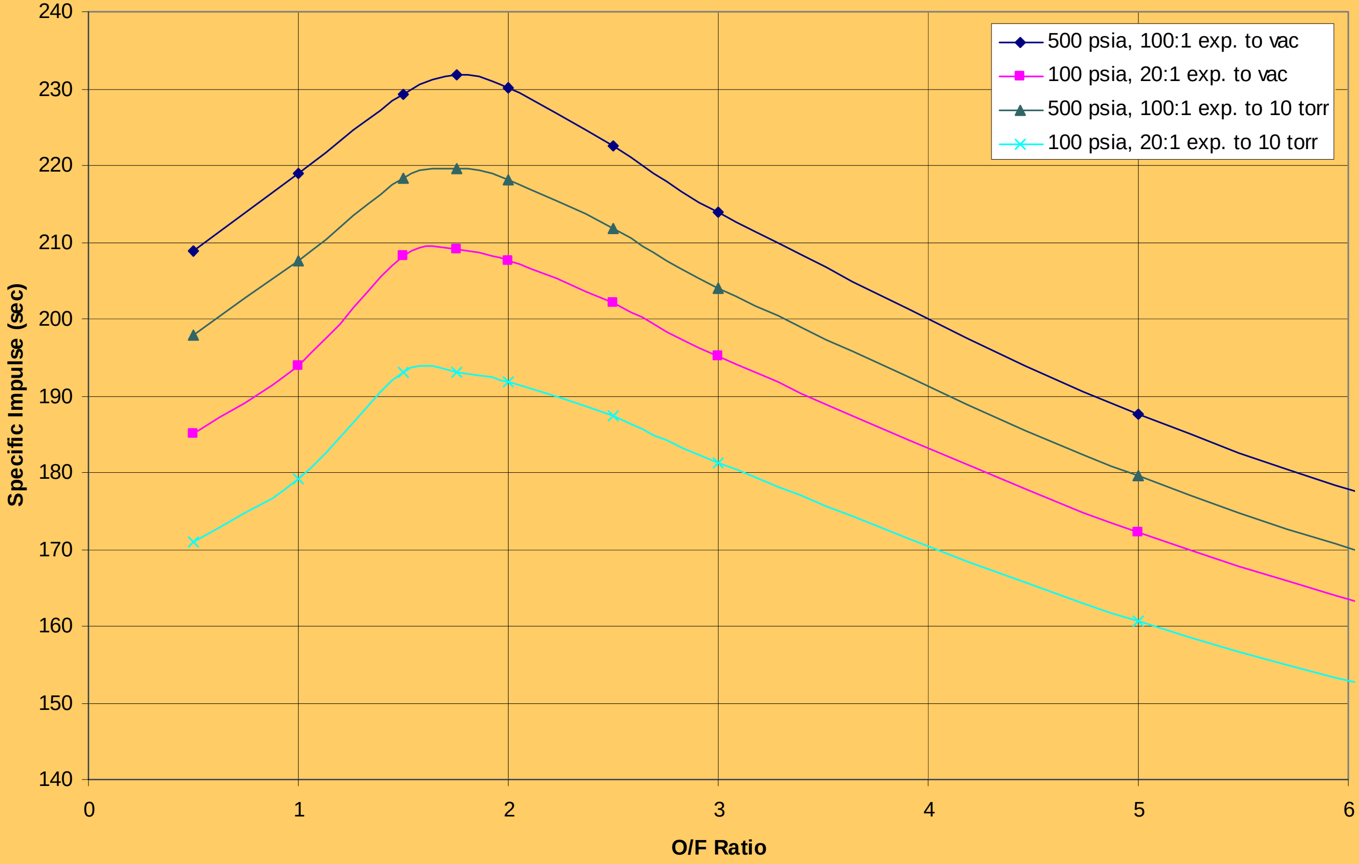

TRAFFIC MODEL DATA SHEET EXAMPLE

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[Note: each period represents 5 years]

Propellant: Solid CO/LOX

Mission Area	Time Period (low model)											Time Period (medium model)											Time Period (high model)											Total Period Su	
	1	2	3	4	5	6	7	8	9	10	Totals	1	2	3	4	5	6	7	8	9	10	Totals	1	2	3	4	5	6	7	8	9	10	Totals	Low	Medium
1 Scientific Exploration &Res																																			
FV1											0											0											0	0	0
FV2											0											0											0	0	0
FV3											0											0											0	0	0
FV4											0											0											0	0	0
FV5											0											0											0	0	0
Totals:	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GS1											0											0											0	0	0
GS2											0											0											0	0	0
GS3											0											0											0	0	0
GS4											0											0											0	0	0
GS5											0											0											0	0	0
Totals:	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

PHASE I
ANALYSIS SENARIOS
TO ASSESS COST/BENEFIT

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- **MAV Replacement for Mars Sample Return Mission**
- **Ballistic Surface Hopper, Assuming H/O, CO/O, CH_4/O, C/O and Single Stage, 1870 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 H/O, CO/O, CH_4/O, CH_3OH/O**

MAV REPLACEMENT FOR MARS SAMPLE RETURN MISSION

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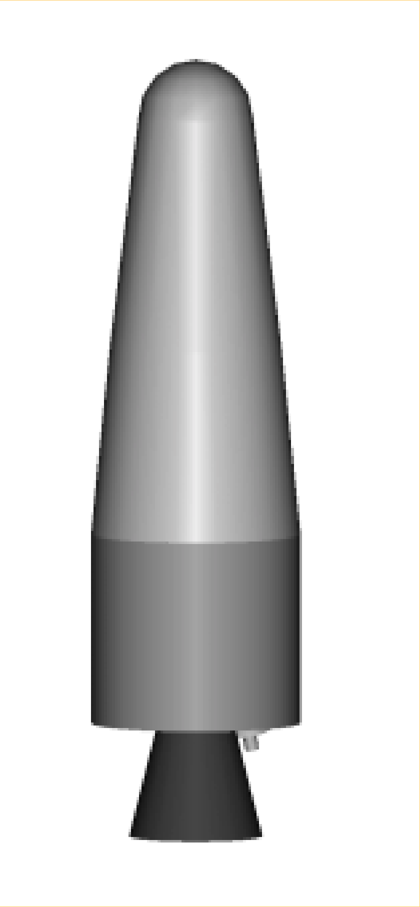

TWO-STAGE TO ORBIT MARS ASCENT VEHICLE

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Propellant Combination	Propulsion System	Terrestrial Propellants	Propellant Mass (kg)	Dry Mass* (kg)	GLOW (kg)	ELM (kg)
SCO/LOX	Hybrid	-	107.2	50.9	161.7	50.9
SC/LOX	Hybrid	-	65.9	38.7	108.2	38.7
$SC\text{-}H_2/LOX$**	Hybrid	C, H_2	56.3	36.0	95.9	53.3
SC_2H_2/LOX	Hybrid	H_2	40.4	31.0	75.0	32.1
HTPB/LOX	Hybrid	HTPB	48.2	33.5	85.3	47.3
LCH_4/LOX	Bi-Propellant	H_2	37.5	30.2	71.3	32.4
CTPB binder	Solid	Solid	81.3	40.7	125.6	122.0

Orbit: 600 km circular orbit, Payload: 3.6 kg

*Dry mass does not include 3.6 kg payload

**SC with 5% H_2 additive by mass

ISRU-BASED ONE-WAY BALLISTIC SURFACE HOPPER

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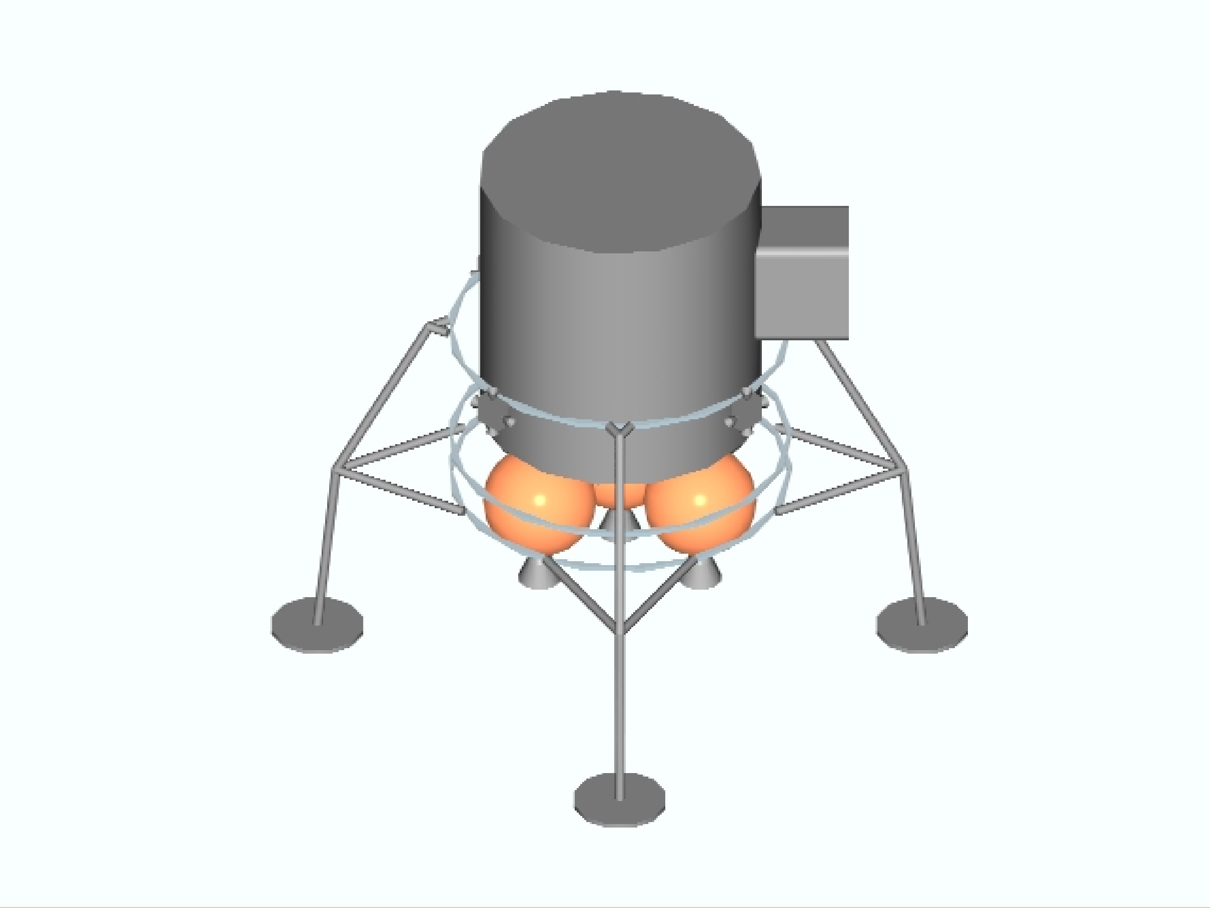

CHARACTERISTICS OF ONE-WAY HOPPER MISSIONS WITH POWERED LANDINGS

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Propellant Combination	Propulsion System	Terrestrial Propellants	Distance (km)	Propellant Mass (kg)	Dry Mass (kg)	GLOW (kg)	ELM (kg)
SCO/LOX	Hybrid	-	500	4040	2320	6360	0
SC/LOX	Hybrid	-	500	3090	2220	5310	0
LCH_4/LOX	Bi-Propellant	H_2	500	2160	2110	4270	129
LH_2/LOX	Bi-Propellant	H_2, O_2	500	1760	2070	3830	1760
SCO/LOX	Hybrid	-	1000	8250	2790	11,040	0
SC/LOX	Hybrid	-	1000	5770	2520	8290	0
LCH_4/LOX	Bi-Propellant	H_2	1000	3690	2280	5970	220
LH_2/LOX	Bi-Propellant	H_2, O_2	1000	2900	2190	5090	2900

Payload = 1870 kg and is included in GLOW, Vehicle Structural Mass Fraction = 0.1

ISRU-POWERED ROVER/ TRANSPORTER

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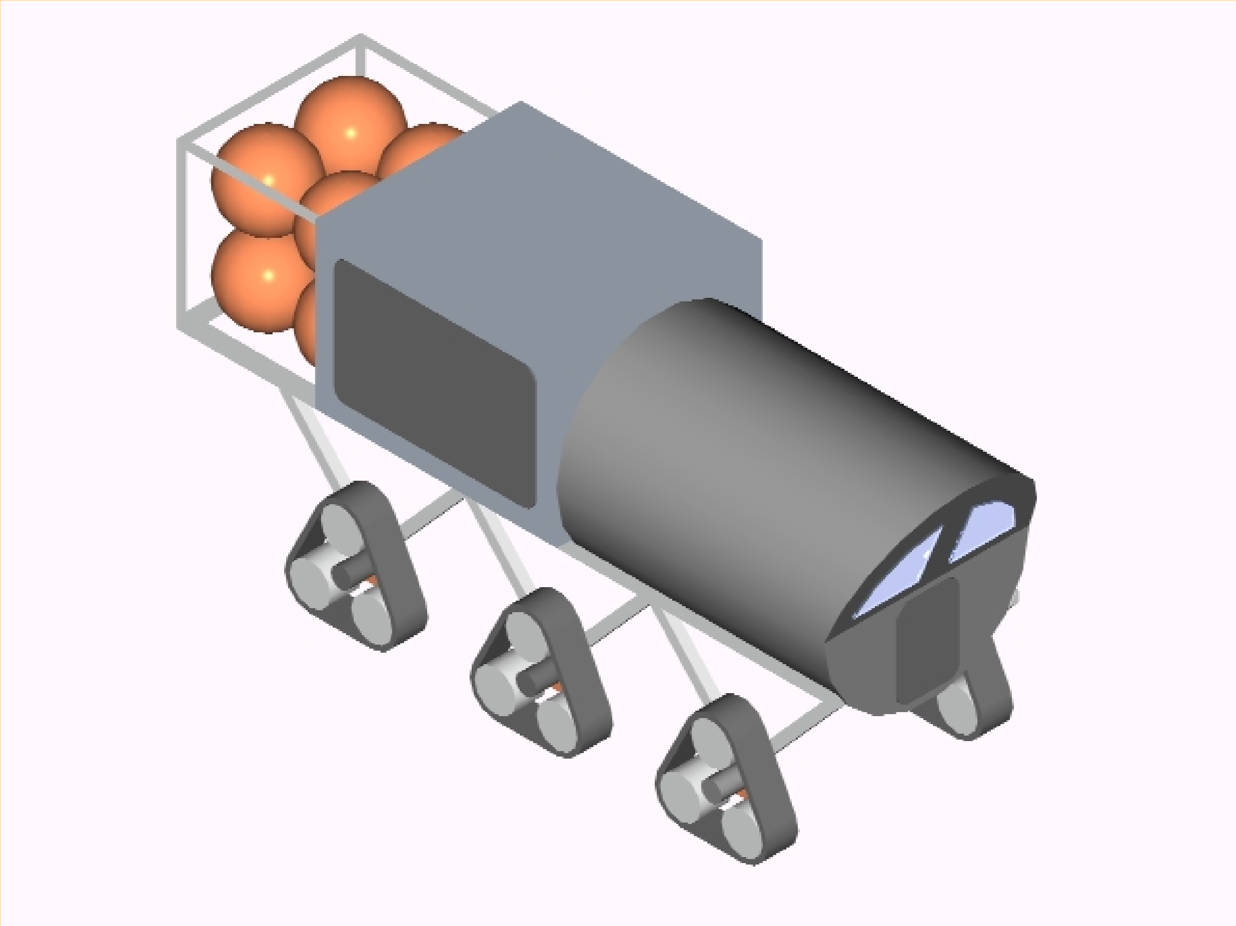

FUEL NEEDS FOR A 300 KM, TEN-HOUR TURBINE-POWERED, ROVER MISSION

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- 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

Fuel Type	H_2/O_2	CH_4/O_2	CO/O_2
Fuel Use, Exhaust Recovered (kg)	113*	154 (13*)	249
Fuel Use, Exhaust Not Recovered (kg)	104*	142 (12*)	223

*Mass Supplied from Earth or Moon as Hydrogen

FUEL REQUIREMENTS FOR POWER ASSUMING 70% OVERALL EFFICIENCY

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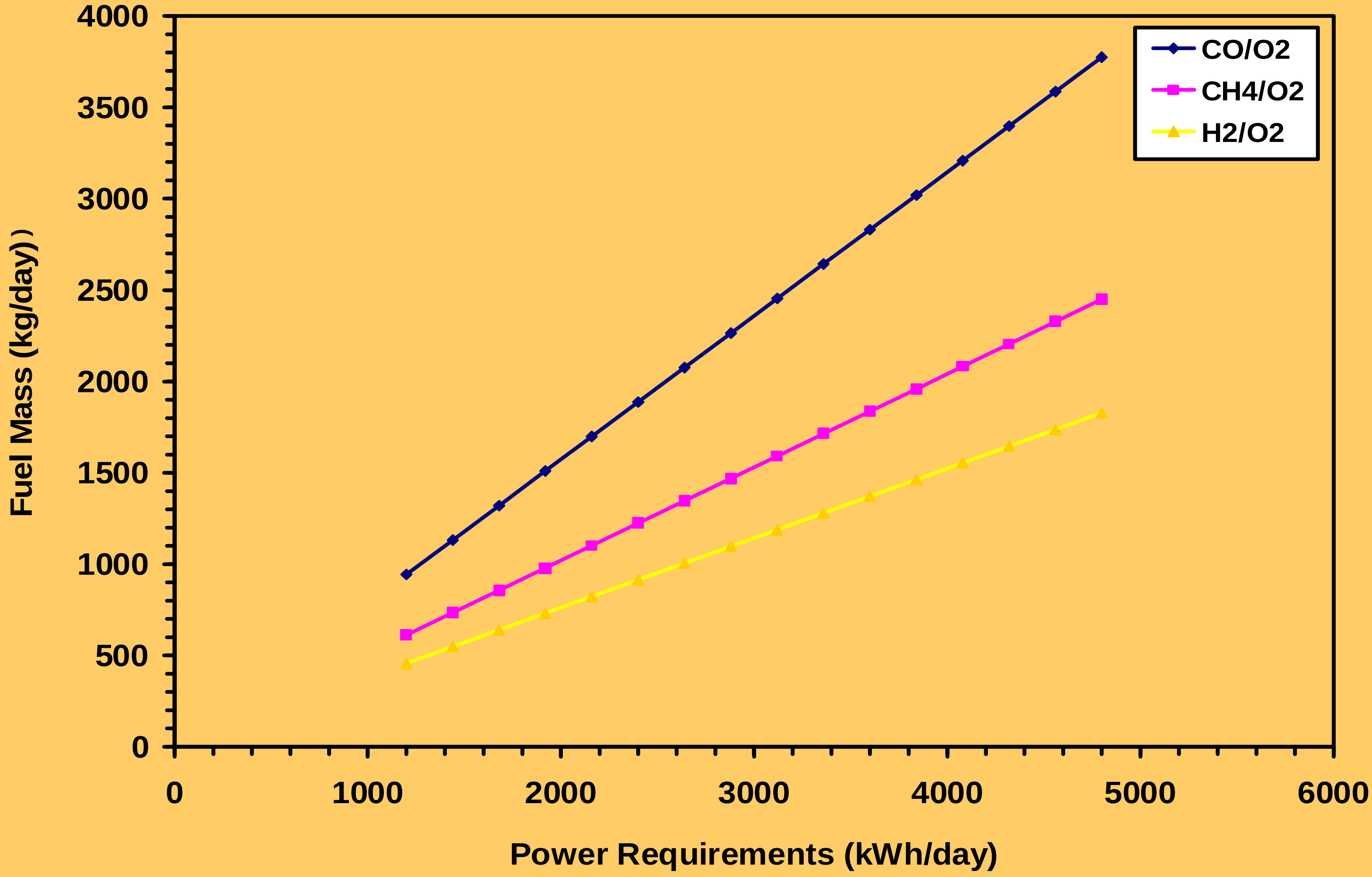

CONCLUSIONS TO DATE

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- 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
- CH_4/LOX Propellants Are Excellent for Large Orbital Operations
- Carbon/LOX and Acetylene/LOX Hybrids Also Are Excellent for More Demanding Missions
- H_2/O_2 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 or Metal Containing Exhaust Can and Should Be Recovered; CO_2 Can Be Released
- Consider Savings Attributed to Wings, Aeroshells, Parachutes, etc.
- Likely Need Nuclear Power Systems in Many Sizes
- The Analysis Approach is a Complex Problem
- Need to Do a Reasonable Concept Design on Vehicles and Process Equipment to Arrive at Correct Answer