ADVANCED SYSTEM CONCEPT FOR TOTAL ISRU-BASED PROPULSION AND POWER SYSTEMS FOR UNMANNED AND MANNED MARS EXPLORATION

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PRESENTATION OUTLINE

- Purpose and Background
- Advanced Concept Description
- Overall Study Approach
- Study Requirements & Ground Rules
- Propellant/Propulsion Scenarios
- Bases, Missions and Traffic Models
- Vehicle Systems Definitions
- Cost Models/Cost-Benefit Analysis
- Preliminary Results and Conclusions to Date

PURPOSE AND BACKGROUND

- Purpose: enable cost-effective, *in situ* production and uses of Mars derived oxidizers and fuels and to guide advanced concept development, system analysis efforts, and technology and unique hardware developments

- Promise: Mars-produced fuels and oxidizers will enhance and enable Mars exploration/exploitation missions by providing a very cost-effective propellant supply

- Most cost-effective Martian resource is the atmosphere (95% CO_2); however, Mars soil can also provide other ISRU species (Mg, Al, H_2O, etc.)

- Atmospheric CO_2 can be easily processed and converted to CO, C and O_2

- Small amount of Atmospheric H_2O can be converted to H_2 & O_2, and N_2 and Ar are also available from the atmosphere -- making many propellant combinations possible

- 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 SUMMARY

- **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 if Mars water is not readily available**

- **The production of O and CO through solid state electrolysis appears to be well in hand by UA**

- **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 - tested solid C, solid C_2H_4, solid C_6H_6**

- **CO gas directly frozen to a solid hybrid fuel grain below 68 K using sub-cooled LOX**

- **Focus on 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: SC/LOX, SCO/LOX, LCO/LOX, SCH_4/LOX, LCH_4/LOX, SC_2H_2/LOX, LC_2H_4/LOX, SC_2H_4/LOX, LH_2/SOX, LH_2/LOX**

OVERALL STUDY APPROACH

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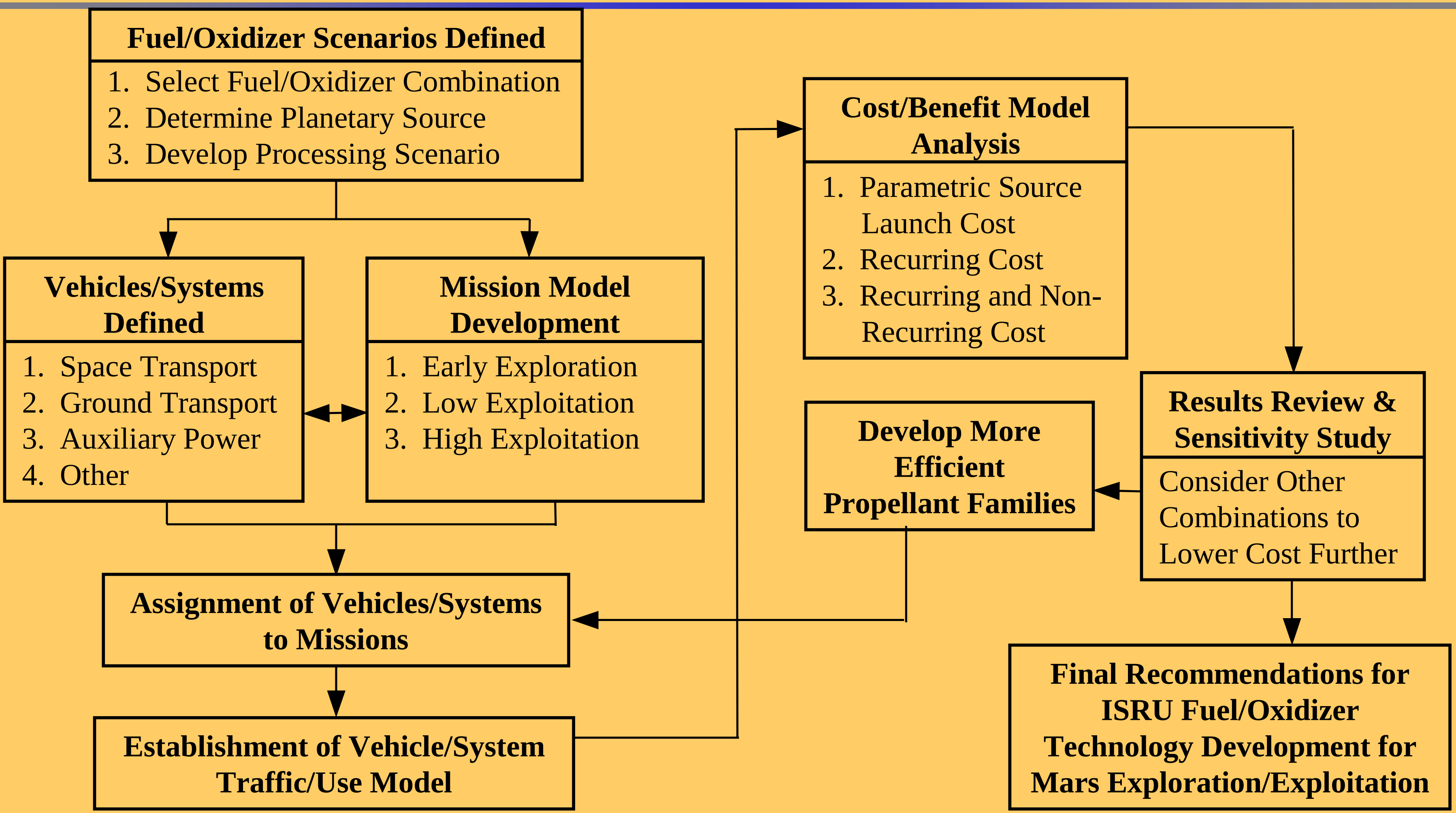

Fuel/Oxidizer Scenarios Defined

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. 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 Propellant Families

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

STUDY REQUIREMENTS AND GROUND RULES

- **Study purpose 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**
- **Study time frame includes the early manned exploration period (2020-2040) 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) to Mars orbit costs will be parametrically assessed at $5,000/kg (baseline) and $10,000/kg and $1,000/kg**
- **Human activity models assumed for the end of the 50-year period of assessment to be 10,000 humans for high and 100 humans for low**
- **Mission vehicle assignment and mission frequency will be determined by the project team**
- **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**
- **Flight vehicles are to 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 are to include: Brayton turbines and fuel cells for small Mars outposts**
- **Only propellants to be considered are those derivable from Earth (Earth deliveries), Mars resources, or water/hydrogen resources from the Moon**
- **Other lower-level requirements and ground rules are defined in each task**

PROPELLANT/PROPULSION SCENARIOS

- **Flight Vehicles**
- **Ground Vehicles**
- **Propellant Families and Sources**

DEFINITION OF PROPELLENT/ PROPULSION SCENARIOS TO BE CONSIDERED/ANALYZED (FOR FLIGHT VEHICLES)

1. LH_2/LOX bi-propellant liquid propulsion
2. LH_2/SOX cryogenic solid hybrid propulsion
3. SC/LOX vortex hybrid propulsion
4. LCO/LOX bi-propellant liquid propulsion
5. SCO/LOX cryogenic solid hybrid propulsion
6. SC_2H_2/LOX cryogenic solid hybrid propulsion
7. LC_2H_4/LOX bi-propellant liquid propulsion
8. SC_2H_4/LOX cryogenic solid hybrid propulsion
9. LCH_4/LOX bi-propellant liquid propulsion
10. SCH_4/LOX cryogenic solid hybrid propulsion

DEFINITION OF PROPELLENT/ PROPULSION SCENARIOS TO BE CONSIDERED/ANALYZED (FOR GROUND VEHICLES)

1. LH_2/LOX fuel cells
2. LH_2O_2 fuel cells
3. LCH_3OH/LH_2O_2 fuel cell/turbine
4. LCO/LOX fuel cell/turbine
5. LCH_4/LOX fuel cell/turbine

PROPELLANT FAMILIES AND SOURCES TO BE CONSIDERED/ANALYZED

H_2/O_2 or H_2O_2

All Earth or Moon-Supplied H_2 and O_2 (PF1)

Earth or Moon-Supplied H_2; O_2 from the Mars Atmospheric CO_2 (PF2)

All Mars Water-Supplied H_2 and O_2 (PF3)

C/O_2

Earth-Supplied C; O_2 from Mars Atmospheric CO_2 (PF4)

C and O_2 Made from the Mars Atmospheric CO_2 (PF5)

CO/O_2

CO and O_2 Made from the Mars Atmospheric CO_2 (PF6)

C_2H_2/O_2

C_2H_2 Made from Earth or Moon-Supplied H_2; Mars C and O_2 from Mars Atmosphere (PF7)

C_2H_2 Made from Mars-Supplied H_2; Mars C and O_2 from Mars Atmosphere (PF8)

C_2H_4/O_2

C_2H_4 Made from Earth or Moon-Supplied H_2; Mars C and O_2 from Mars Atmosphere (PF9)

C_2H_4 Made from Mars Supplied H_2; Mars C and O_2 from Mars Atmosphere (PF10)

PROPELLANT FAMILIES AND SOURCES TO BE CONSIDERED/ANALYZED (cont.)

CH_4/O_2

CH_4 Made from Earth or Moon-Supplied H_2; Mars C and O_2 from Mars Atmosphere (PF11)

CH_4 Made from Mars-Supplied Water; Mars C and O_2 from Mars Atmosphere; Mars O_2 from Mars Water (PF12)

CH_3OH/O_2

CH_3OH Made from Earth or Moon-Supplied H_2; Mars C and O_2 from Mars Atmosphere (PF13)

CH_3OH Made from Mars-Supplied Water; Mars C and O_2 from Mars Atmosphere; Mars O_2 from Mars Water (PF14)

CH_3OH/H_2O_2

CH_3OH Made from Earth or Moon-Supplied H_2; C and O_2 from Mars Atmosphere; H_2O_2 from Earth or Moon-Supplied H_2 and Mars O_2 from Mars Atmosphere (PF15)

CH_3OH Made from Mars-Supplied Water, C and O_2 from Mars Atmosphere; H_2O_2 from Mars Water (PF16)

BASES, MISSIONS AND TRAFFIC MODELS

- **Location of Mars bases**
- **Population growth models**
- **Mission Identification and definition**
- **Mission models**
- **Assignment of vehicles to missions**
- **Traffic models**
- **Infrastructure models**

LOCATION OF MARS BASES

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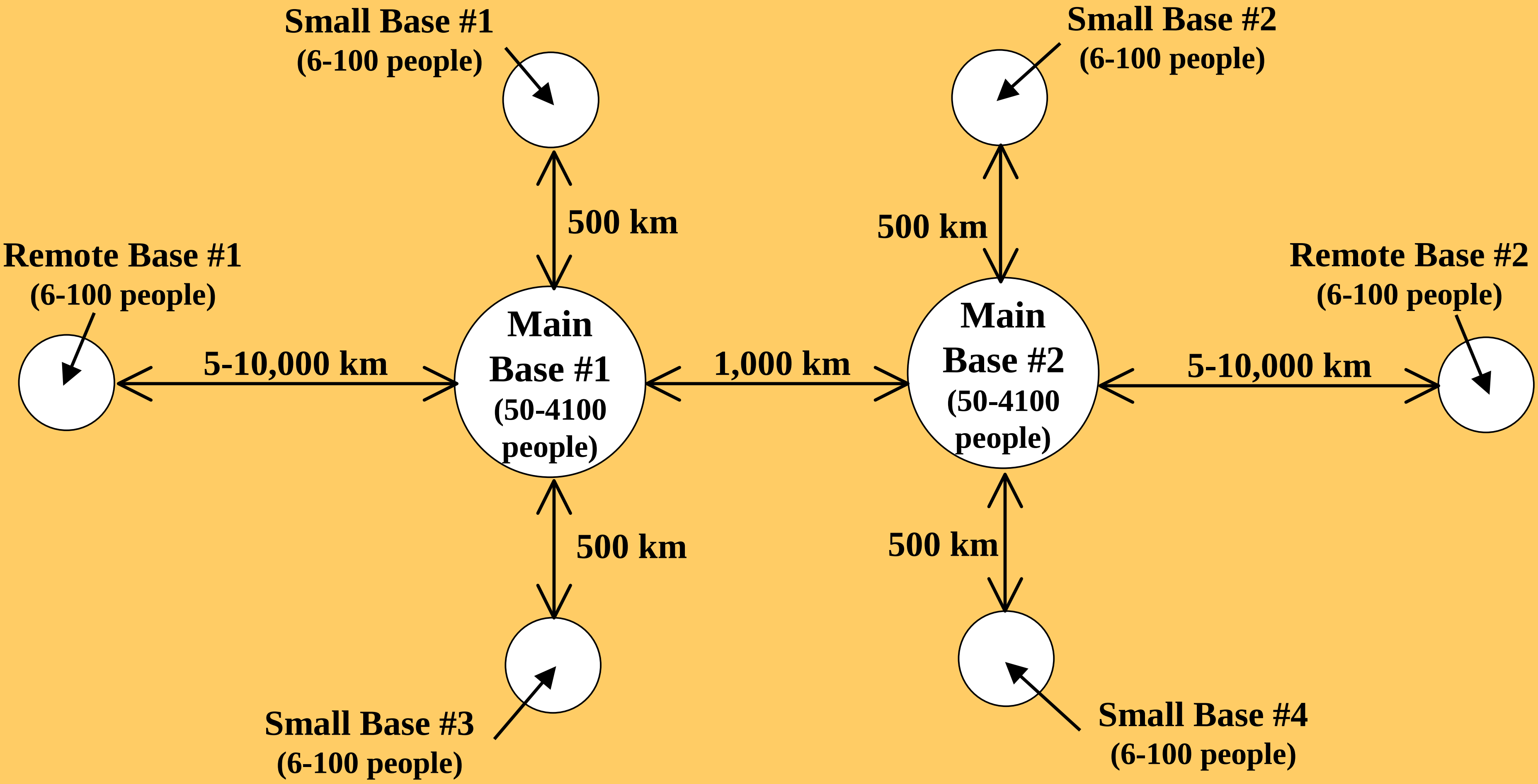

Small Base #1
(6-100 people)

Small Base #2
(6-100 people)

500 km

500 km

Remote Base #1
(6-100 people)

Remote Base #2
(6-100 people)

5-10,000 km

Main Base #1 (50-4100 people)

1,000 km

Main Base #2 (50-4100 people)

5-10,000 km

500 km

500 km

Small Base #3
(6-100 people)

Small Base #4
(6-100 people)

POPULATION GROWTH MODEL ASSUMPTIONS

- A colony cycle is defined to correspond to each launch window (~26 months) and all transports of people to/from Earth occur once during each colony cycle
- Starting population of 20 in 2040 with linear growth to 100 in 2050
- Linear population growth to 10,000 in 2090 (high scenario) or stable population at 100 (low scenario)
- No permanent inhabitants between 2040 and 2050
- After 2050, 50% of the colonists from Earth are transient and the other 50% are permanent (high scenario)
- Transient population lives on Mars in 70-72 month intervals
- 2% per year net increase in the permanent population due to the results of births and deaths of the permanent colonists

POPULATION GROWTH MODEL (HIGH SCENARIO)

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Colony Cycle	Years	Mars Surface Population			Births - Deaths	Transportation		Surface to Orbit Trips
		Transient	Perm.	Total		To Mars	To Earth	
0	<2040	20	0	20	0	20	0	1
1	2040-42	36	0	36	0	16	0	1
2	2042-44	52	0	52	0	16	0	1
3	2044-46	68	0	68	0	36	20	1
4	2046-48	84	0	84	0	32	16	1
5	2048-50	50	50	100	0	32	16	1
6	2050-53	325	325	650	2	564	16	8
7	2053-55	600	600	1200	13	573	36	8
8	2055-57	875	875	1750	24	558	32	7
9	2057-59	1150	1150	2300	35	806	291	11
10	2059-61	1425	1425	2850	46	795	291	10
11	2061-63	1700	1700	3400	57	804	311	11
12	2063-66	1975	1975	3950	68	789	307	10
13	2066-68	2250	2250	4500	79	1037	566	13
14	2068-70	2525	2525	5050	90	1026	566	13
15	2070-72	2800	2800	5600	101	1035	586	13
16	2072-74	3075	3075	6150	112	1020	582	13
17	2074-76	3350	3350	6700	123	1268	841	16
18	2076-79	3625	3625	7250	134	1257	841	16
19	2079-81	3900	3900	7800	145	1266	861	16
20	2081-83	4175	4175	8350	156	1251	857	16
21	2083-85	4450	4450	8900	167	1499	1116	19
22	2085-87	4725	4725	9450	178	1488	1116	19
23	2087-90	5000	5000	10000	189	1497	1136	19

POPULATION GROWTH MODEL (LOW SCENARIO)

Colony Cycle	Year	Mars Population	Transportation		Surface to Orbit Trips
			To Mars	To Earth	
0	<2040	20	20	0	1
1	2040-42	36	16	0	1
2	2042-44	52	16	0	1
3	2044-46	68	36	20	1
4	2046-48	84	32	16	1
5	2048-50	100	32	16	1
6	2050-53	100	36	36	1
7	2053-55	100	32	32	1
8	2055-57	100	32	32	1
9	2057-59	100	36	36	1
10	2059-61	100	32	32	1
11	2061-63	100	32	32	1
12	2063-66	100	36	36	1
13	2066-68	100	32	32	1
14	2068-70	100	32	32	1
15	2070-72	100	36	36	1
16	2072-74	100	32	32	1
17	2074-76	100	32	32	1
18	2076-79	100	36	36	1
19	2079-81	100	32	32	1
20	2081-83	100	32	32	1
21	2083-85	100	36	36	1
22	2085-87	100	32	32	1
23	2087-90	100	32	32	1

MARS MISSION CATEGORY IDENTIFICATION

- 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
- Life Support
- Waste/Trash Management
- Health Care/Maintenance
- Virtual Travel Market

[Underlined missions major ISRU consumers]

TERRAFORMED MARS
by KANDIS ELLIOT

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EXAMPLE OF MISSION DEFINITION

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Mission Category: Commercial

Mission/Submission Scope?	Line Item Specifics	Mission Frequency				# of Crew/Robotic	Mission Duration	Distance from Base (km)	Travel Time	Payload (kg)	Mission Reference Number	System Type Required
		Low		High								
		Year 1-5	Year 45-50	Year 1-5	Year 45-50							
Resource development	Far-ranging ballistic hopper missions to remote sites for sample collection, or on-site testing	12	12	12	28	2	5 days	5000	minutes	200	26	flight
		3	3	3	7	2	10 days	10000	minutes	200	27	flight
		13	15	13	30	rob	10 days	5000	minutes	100	28	flight
		7	8	7	15	rob	20 days	10000	minutes	100	29	flight
	Short-range rover missions	150	25	150	120	2	3 days	<500	hours	200	30	ground
		37	6	37	30	rob	6 days	<500	hours	200	31	ground
	Long-range robotic missions for extended observation	10	10	10	10	rob	2 mo	10000	minutes	100	32	flight
		10	5	10	5	rob	1 mo	1000	days	100	33	ground
	nuclear powered rover*	***3***	***3***	***3***	***4***	rob	infinite	arbitrary	n/a	50	34	ground
	Deep drilling rig	7	8	7	20	rob	2 mo	1000	weeks	3000	35	ground

*Bold italicized entries in the frequency column indicate a quantity, not a frequency (for missions of indefinite duratio

DEVELOPMENT OF MARS MISSION MODEL

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Mission Reference Number	Colony Cycle (one cycle is ~26 Earth months)																							Total Number of Missions
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	
1	5	5	6	6	6	7	7	7	8	8	8	9	9	9	10	10	10	11	11	11	12	12	13	201
2	1	1	1	1	1	1	1	2	2	2	2	2	2	2	3	3	3	3	3	3	3	4	4	50
3	6	6	6	7	7	7	8	8	8	9	9	9	10	10	10	11	11	11	12	12	12	13	13	215
4	3	3	3	3	3	3	4	4	4	4	4	5	5	5	5	5	6	6	6	6	6	6	7	110
7	5	5	5	5	5	5	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	6	6	125
10	5	6	6	6	6	7	7	7	8	8	8	9	9	9	10	10	10	11	11	11	12	12	12	200
11	1	1	1	1	1	1	1	2	2	2	2	2	2	2	3	3	3	3	3	3	3	4	4	50
12	6	6	6	7	7	7	8	8	8	9	9	9	10	10	10	11	11	11	12	12	12	13	13	215
13	3	3	3	3	3	3	4	4	4	4	4	5	5	5	5	5	6	6	6	6	6	6	7	106
16	5	5	5	5	5	5	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	6	6	125
19	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	5	5	5	85
20	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	95
21	6	6	6	7	7	7	8	8	8	9	9	10	10	10	11	11	11	12	12	12	13	13	14	220
22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	782
23	87	91	95	99	103	107	111	115	119	123	127	131	135	139	143	147	151	155	159	163	167	170	174	3011
24	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	55
25	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	30
26	5	5	6	6	6	7	7	7	8	8	8	9	9	9	10	10	10	11	11	11	12	12	13	200
27	1	1	1	1	1	1	1	2	2	2	2	2	2	2	3	3	3	3	3	3	3	4	4	50
28	6	6	6	7	7	7	8	8	8	9	9	9	10	10	10	11	11	11	12	12	12	13	13	215
29	3	3	3	3	3	3	4	4	4	4	4	5	5	5	5	5	6	6	6	6	6	6	7	106
32	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	92
36	1	1	1	1	1	8	8	7	11	10	11	10	13	13	13	13	16	16	16	16	19	19	19	243
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39!	2	6	4	4	4	4	28	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	30	517
46	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	253
47	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	253
48	0	0	0	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3	4	4	4	4	4	50
49	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	253
50*	1	1	1	2	2	3	3	3	4	4	4	5	5	5	6	6	6	7	7	8	8	9	9	109
52*	1	1	1	2	2	2	3	3	3	4	4	5	5	5	6	6	6	7	7	7	8	8	8	104

Mission Reference Number in italics indicates round trip. **! Indicates that the traffic model for this mission is dependent on the propellant used in the vehicle (numbers for methane listed).**

FLIGHT VEHICLE ASSIGNMENT TO MISSIONS

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- **All of the flight vehicle missions requirements were compared to determine several general vehicle types**
- **After analyzing the current flight vehicle missions, six generic vehicle types were identified**
- **The requirements for these vehicle types are highlighted in green**
- **Missions in red were not included in this analysis**

Mission Reference Number	Vehicle Type	# of Crew/ Robotic	Mission Duration (days)	Distance from Base (km)	Travel Time	Payload (kg)	Equivalent Payload (kg)	Delta V (m/sec)
3	V3	rob	60	5,000	minutes	100	100	7,548*
28	V3	rob	60	5,000	minutes	100	100	7,548*
12	V3	rob	60	5,000	minutes	300	300	7,548*
1	V4	2	20	5,000	minutes	100	5,905	7,548*
26	V4	2	20	5,000	minutes	200	6,005	7,548*
10	V4	2	20	5,000	minutes	300	6,105	7,548*
46	V1	2	1	5,000	minutes	20 people	9,203	3,774
47	V1	2	1	5,000	minutes	4,000	5,421	3,774
52	V1	3	7	5,000	minutes	1 person + 50	6,530	3,774
48	V1	3	1	5,000	minutes	2 people	2,865	3,774
49	V1	3	1	5,000	minutes	2 people	2,865	3,774
50	V4	3	1	5,000	minutes	2 people + 100	2,965	7,548*
19	V2	rob	1	10,000	minutes	10	10	4,189
4	V3	rob	60	10,000	minutes	100	100	8,378*
29	V3	rob	60	10,000	minutes	100	100	8,378*
7	V3	rob	60	10,000	minutes	100	100	8,378*
32	V3	rob	60	10,000	minutes	100	100	8,378*
13	V3	rob	60	10,000	minutes	300	300	8,378*
16	V3	rob	60	10,000	minutes	300	300	8,378*
2	V4	2	20	10,000	minutes	100	5,905	8,378*
27	V4	2	20	10,000	minutes	200	6,005	8,378*
11	V4	2	20	10,000	minutes	300	6,105	8,378*
39	V6	rob	minutes	transfer to/from orbit	hours	383,000	383,000	4,360
36	V5	2	minutes	transfer to/from orbit	hours	80 people + 1650	18,560	4,360
24		rob	7	orbit	hours	500	500	
25		3	7	orbit	hours	1,000	6,233	
23		rob	minutes	n/a	minutes	2		
20		rob	indefinite	n/a	indefinite	2		
22		rob	hours	n/a	hours	4		
21		rob	hours	<500	hours	2		

* = Total value is for a round trip

GROUND VEHICLE ASSIGNMENT TO MISSIONS

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- **The general ground vehicle types have not yet been assigned to the missions identified**
- **An approach similar to the flight vehicle analysis will be used for the ground vehicle assignments**

Mission Reference Number	Vehicle Type	# of Missions per Year	# of Crew/ Robotic	Mission Duration (days)	Distance from Base (km)	Travel Time	Payload (kg)	Equivalent Payload (kg)
6		30	rob	6	500	hours	100	100
43			rob	days	500	days	100	100
31		37	rob	6	500	hours	200	200
15		7	rob	6	500	hours	300	300
44			rob	days	500	days	1000	1000
45			rob	days	500	days	5000	5000
5		120	2	3	500	hours	100	1736
30		150	2	3	500	hours	200	1836
14		24	2	3	500	hours	300	1936
40		500	2	days	500	days	2 people	
41		1000	2	days	500	days	5 people	
8		6	rob	30	1000	days	100	100
33		10	rob	30	1000	days	100	100
17		12	rob	30	1000	days	300	300
35		20	rob	60	1000	weeks	3000	3000
42		700	2	1	1000	days	20 people	5881
9		4	rob	infinite	arbitrary	n/a	50	50
18		4	rob	infinite	arbitrary	n/a	50	50
34		4	rob	infinite	arbitrary	n/a	50	50
51		25	3	1	500	hours	2 people + 100	2210

DEVELOPMENT OF MARS TRAFFIC MODEL

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Vehicle #1 (V1)

Mission Reference Number	Colony Cycle (one cycle is ~26 Earth months)																							Total Number of Missions
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	
46	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	253
47	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	253
48	0	0	0	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3	4	4	4	4	4	50
49	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	253
52*	1	1	1	2	2	2	3	3	3	4	4	5	5	5	6	6	6	7	7	7	8	8	8	104
TOTAL	**1**	**4**	**7**	**12**	**15**	**18**	**22**	**25**	**29**	**33**	**36**	**40**	**43**	**47**	**51**	**54**	**57**	**61**	**65**	**68**	**72**	**75**	**78**	**913**

Vehicle #2 (V2)

Mission Reference Number	Colony Cycle (one cycle is ~26 Earth months)																							Total Number of Missions
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	
19	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	5	5	5	85
TOTAL	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**5**	**5**	**5**	**85**

Vehicle #3 (V3)

Mission Reference Number	Colony Cycle (one cycle is ~26 Earth months)																							Total Number of Missions
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	
3	6	6	6	7	7	7	8	8	8	9	9	9	10	10	10	11	11	11	12	12	12	13	13	215
4	3	3	3	3	3	3	4	4	4	4	4	5	5	5	5	5	6	6	6	6	6	6	7	110
7	5	5	5	5	5	5	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	6	6	125
12	6	6	6	7	7	7	8	8	8	9	9	9	10	10	10	11	11	11	12	12	12	13	13	215
13	3	3	3	3	3	3	4	4	4	4	4	5	5	5	5	5	6	6	6	6	6	6	7	106
16	5	5	5	5	5	5	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	6	6	125
28	6	6	6	7	7	7	8	8	8	9	9	9	10	10	10	11	11	11	12	12	12	13	13	215
29	3	3	3	3	3	3	4	4	4	4	4	5	5	5	5	5	6	6	6	6	6	6	7	106
32	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	92
TOTAL	**41**	**41**	**41**	**44**	**44**	**44**	**50**	**50**	**50**	**53**	**53**	**56**	**59**	**61**	**61**	**64**	**67**	**67**	**70**	**70**	**70**	**73**	**76**	**1309**

DEVELOPMENT OF MARS TRAFFIC MODEL

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Vehicle #4 (V4)

Mission Reference Number	Colony Cycle (one cycle is ~26 Earth months)																							Total Number of Missions
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	
1	5	5	6	6	6	7	7	7	8	8	8	9	9	9	10	10	10	11	11	11	12	12	13	201
2	1	1	1	1	1	1	1	2	2	2	2	2	2	2	3	3	3	3	3	3	3	4	4	50
10	5	6	6	6	6	7	7	7	8	8	8	9	9	9	10	10	10	11	11	11	12	12	12	200
11	1	1	1	1	1	1	1	2	2	2	2	2	2	2	3	3	3	3	3	3	3	4	4	50
26	5	5	6	6	6	7	7	7	8	8	8	9	9	9	10	10	10	11	11	11	12	12	13	200
27	1	1	1	1	1	1	1	2	2	2	2	2	2	2	3	3	3	3	3	3	3	4	4	50
50*	1	1	1	2	2	3	3	3	4	4	4	5	5	5	6	6	6	7	7	8	8	9	9	109
TOTAL	**19**	**20**	**22**	**23**	**23**	**27**	**27**	**30**	**34**	**34**	**34**	**38**	**38**	**38**	**45**	**45**	**45**	**49**	**49**	**50**	**53**	**57**	**59**	**860**

Vehicle #5 (V5)

Mission Reference Number	Colony Cycle (one cycle is ~26 Earth months)																							Total Number of Missions
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	
36	1	1	1	1	1	8	8	7	11	10	11	10	13	13	13	13	16	16	16	16	19	19	19	243
TOTAL	**1**	**1**	**1**	**1**	**1**	**8**	**8**	**7**	**11**	**10**	**11**	**10**	**13**	**13**	**13**	**13**	**16**	**16**	**16**	**16**	**19**	**19**	**19**	**243**

Vehicle #6 (V6)

Mission Reference Number	Colony Cycle (one cycle is ~26 Earth months)																							Total Number of Missions
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	
39!	2	6	4	4	4	4	28	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	30	517
TOTAL	**2**	**6**	**4**	**4**	**4**	**4**	**28**	**29**	**29**	**29**	**29**	**29**	**29**	**29**	**29**	**29**	**29**	**29**	**29**	**29**	**29**	**29**	**30**	**517**

MARS INFRASTRUCTURE MODEL

- Inputs to model
  - Population growth model
  - Requirements for habitat volume per person
  - Power requirements per person
- Functions of model
  - Calculate total habitat volume and power requirements
  - Convert habitat volume and power requirements to mass estimates
- Outputs from model
  - Habitat module mass required for delivery during each colony cycle
  - Nuclear power system mass required for delivery during each colony cycle

MARS INFRASTRUCTURE MODEL EXAMPLE

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Colony Cycle	Years	Mars Surface Population			Total Habitat Mass (kg)	Habitat Power System* (kg)	Processing Plant Power (kW)	Processing Plant Power* (kg)	Shipment Mass (kg)	Trips Required
		Transient	Perm.	Total						
0	<2040	20	0	20	158,279	18,500	0	0	176,779	1
1	2040-42	36	0	36	284,902	37,000	17,893	444,000	589,123	2
2	2042-44	52	0	52	411,525	37,000	18,251	462,500	145,123	1
3	2044-46	68	0	68	538,149	55,500	18,941	481,000	163,623	1
4	2046-48	84	0	84	664,772	55,500	20,072	499,500	145,123	1
5	2048-50	50	50	100	791,395	74,000	20,125	499,500	145,123	1
6	2050-53	325	325	650	5,144,068	407,000	21,948	555,000	4,741,173	13
7	2053-55	600	600	1,200	9,496,740	740,000	23,699	592,000	4,722,673	13
8	2055-57	875	875	1,750	13,849,413	1,091,500	24,851	629,000	4,741,173	13
9	2057-59	1,150	1,150	2,300	18,202,085	1,424,500	26,458	666,000	4,722,673	13
10	2059-61	1,425	1,425	2,850	22,554,758	1,757,500	27,210	684,500	4,704,173	13
11	2061-63	1,700	1,700	3,400	26,907,430	2,109,000	27,336	684,500	4,704,173	13
12	2063-66	1,975	1,975	3,950	31,260,103	2,442,000	29,505	740,000	4,741,173	13
13	2066-68	2,250	2,250	4,500	35,612,775	2,775,000	30,533	758,500	4,704,173	13
14	2068-70	2,525	2,525	5,050	39,965,448	3,126,500	31,223	777,000	4,722,673	13
15	2070-72	2,800	2,800	5,600	44,318,120	3,459,500	33,711	832,500	4,741,173	13
16	2072-74	3,075	3,075	6,150	48,670,793	3,792,500	34,507	869,500	4,722,673	13
17	2074-76	3,350	3,350	6,700	53,023,465	4,144,000	35,718	888,000	4,722,673	13
18	2076-79	3,625	3,625	7,250	57,376,138	4,477,000	37,034	925,000	4,722,673	13
19	2079-81	3,900	3,900	7,800	61,728,810	4,810,000	37,858	943,500	4,704,173	13
20	2081-83	4,175	4,175	8,350	66,081,483	5,161,500	38,216	943,500	4,704,173	13
21	2083-85	4,450	4,450	8,900	70,434,155	5,494,500	39,445	980,500	4,722,672	13
22	2085-87	4,725	4,725	9,450	74,786,828	5,827,500	41,733	1,036,000	4,741,173	13
23	2087-90	5,000	5,000	10,000	79,139,500	6,179,000	43,336	1,073,000	4,741,173	13

*** Assume each power system produces 750 kWe has a mass of 18,500 kg.**

VEHICLE SYSTEMS DEFINITIONS

- Objectives
- Ground rules
- Flight vehicle types/analysis/etc.
- Results

VEHICLE SYSTEM DEFINITION OBJECTIVES

- **Conceptually design a family of vehicles for each propellant combination to accommodate all flight and ground missions**
- **Establish the propellant requirements for each mission**
- **Treat all propellant combinations and vehicle types fairly**
- **Calculate vehicle drymass**
- **Provide component masses to the cost model**
- **Investigate the effects of various mission options**

GENERAL GROUND RULES

- All initial mass estimations based on existing technology
- The effects of mass savings due to future technology will be explored
- Weather balloons and atmospheric vehicles are not modeled in detail due to their low mass and propellant requirements
- Specific ground rules for each vehicle type and subsystem drive estimations and are outlined in the Vehicle Design Ground Rules Document

FLIGHT VEHICLE TYPES

Vehicle Types (aerobraking used for all)

- One-way surface hopper
- Roundtrip surface hopper
- Personnel shuttle
- Cargo shuttle

Hybrid Vehicles

- Chamber pressure: 300, 400, or 500 psia
- Nozzle expansion ratio: 200
- I_{SP} efficiency: 95% of theoretical maximum
- Tank configuration: grain case nested in liquid tank

Bi-Propellant Vehicles

- Chamber pressure: 1000 psia
- Nozzle expansion ratio: 200
- I_{SP} efficiency: 95% of theoretical maximum
- Tank configuration: two tanks for each propellant

PERFORMANCE CALCULATIONS FOR CONSIDERED PROPELLANTS

- **CEA Code Used to Calculate the Propellant Performances**

- **Combinations Include:**

Combinations Include	I_{SP} (sec)	O/F
– LH_2/LOX (Bi-propellant)	476.8	5.5
– LH_2/SOX (Cryo hybrid)	469.3	5.5
– C/LOX (Vortex hybrid)	338.4	2.2
– LCO/LOX (Bi-propellant)	300.5	0.57
– SCO/LOX (Cryo hybrid)	294.4	0.56
– SC_2H_2/LOX (Cryo hybrid)	401.0	2.0
– LC_2H_4/LOX (Bi-propellant)	395.4	2.8
– SC_2H_4/LOX (Cryo hybrid)	387.6	2.75
– LCH_4/LOX (Bi-propellant)	393.0	3.7
– SCH_4/LOX (Cryo hybrid)	387.0	3.6

FLIGHT MODEL INPUT

Propellant Characteristics

- Specific impulse
- Characteristic velocity
- Physical properties
- Mixture ratio
- Percent hydrogen

Mission Requirements

- Duration
- Delta-V
- Cargo
- Personnel

Subsystem Input

- Environmental characteristics
- Tank insulation
- Tank material
- Nozzle area ratio
- Number of tanks
- Chamber pressure
- Technology factor
- Reserve propellant
- Percent hydrogen

FLIGHT MODEL OUTPUT

Detailed Sizing and Mass Breakdown

- **Overall vehicle drymass**
- **Structure**
- **Consumables**
- **Tanks and insulation**
- **Crew cabin**
- **Turbomachinery**
- **Lines and valves**
- **Chamber and nozzle**
- **Attitude control**
- **Cryocooler**
- **ISRU processor**
- **Power plant**
- **Propellant requirements**
- **Hydrogen requirements**

ARES

ROUND TRIP SURFACE HOPPER VEHICLE PROPELLANT: SCH_4/LOX - BY KANDIS ELLIOT

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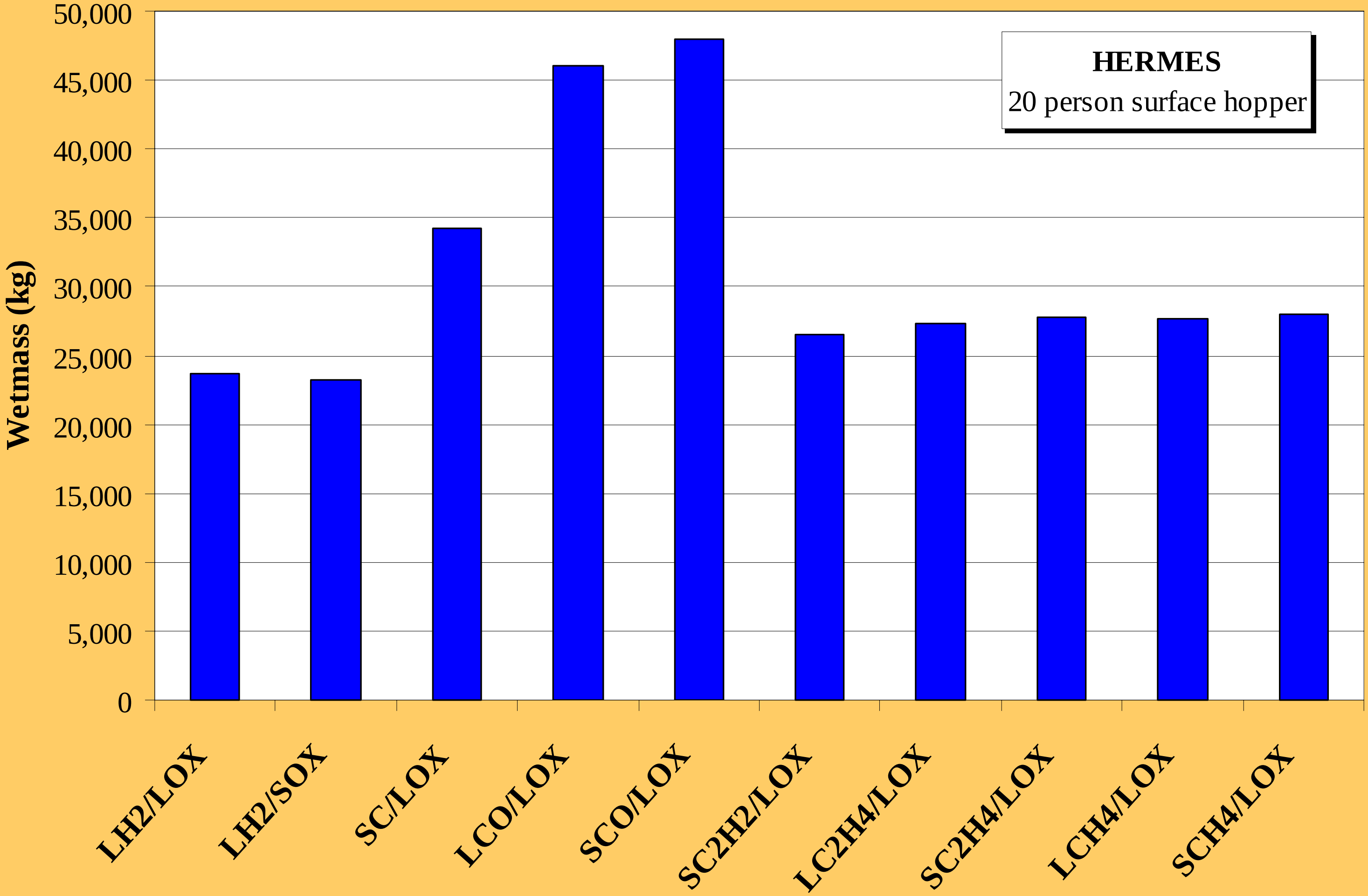
VEHICLE WET MASS
HERMES



VEHICLE WET MASS
EOS

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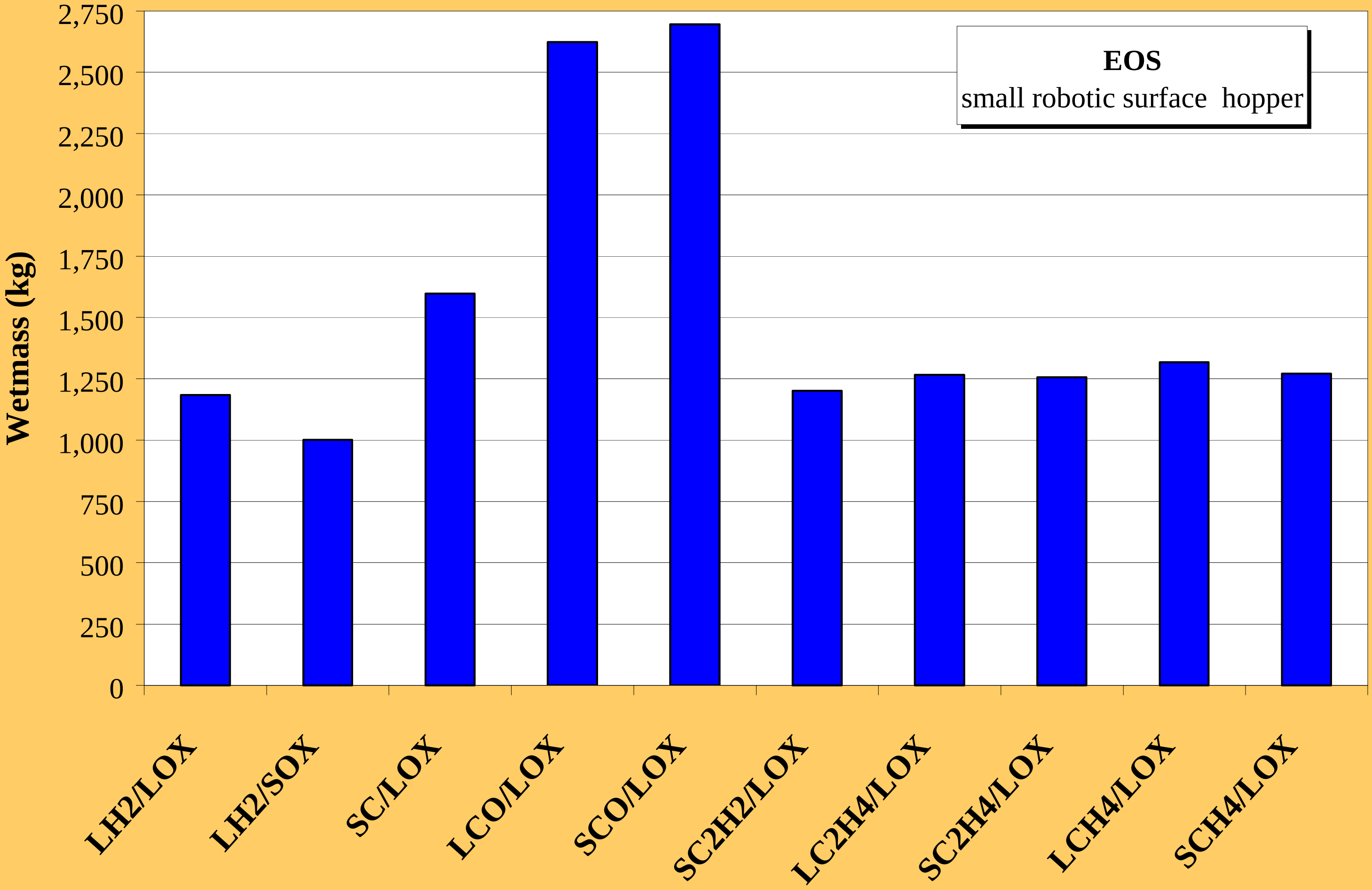

VEHICLE WET MASS
IRIS

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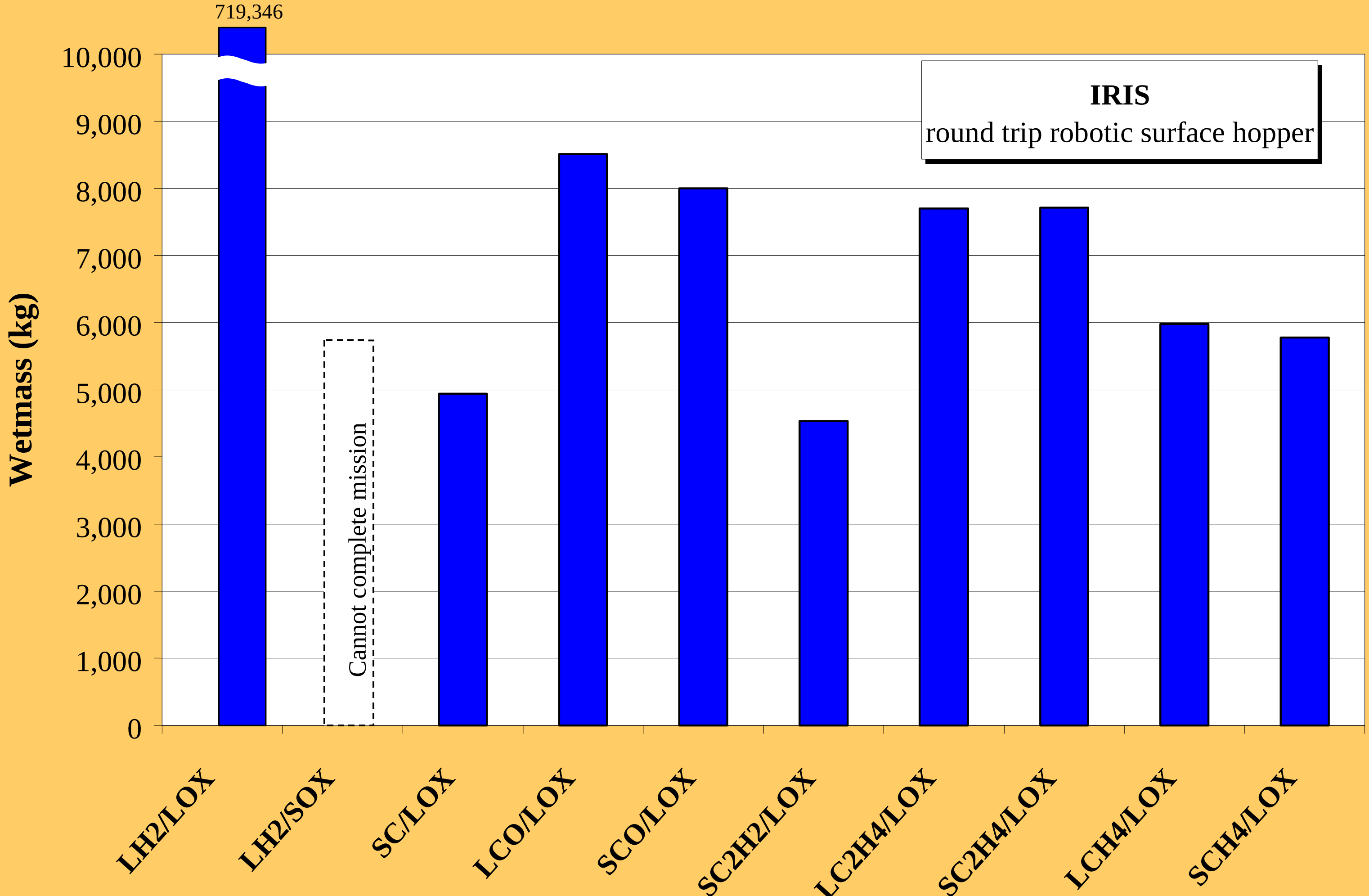

VEHICLE WET MASS ARES

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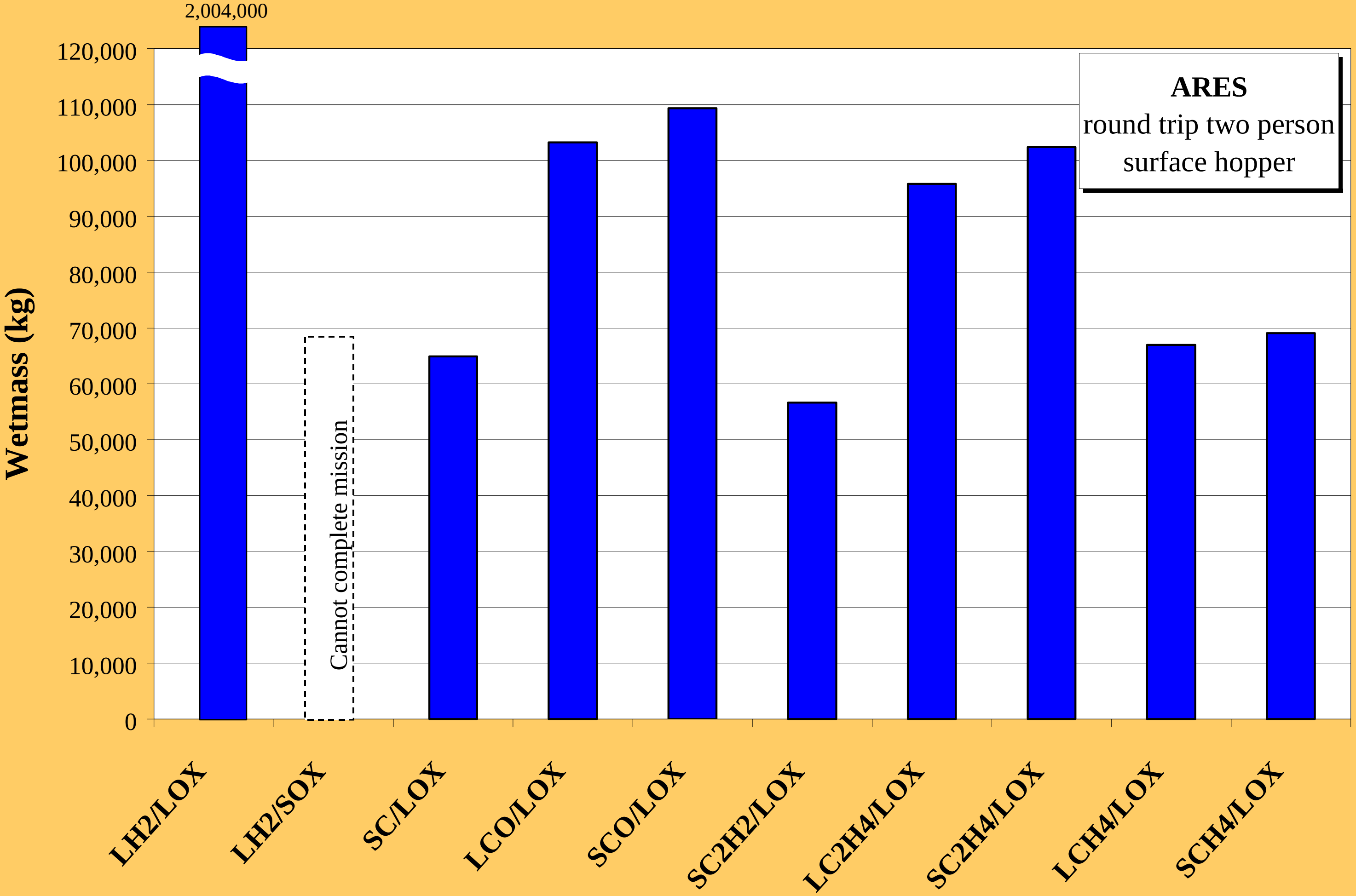

ARES
round trip two person
surface hopper

VEHICLE WET MASS HYPERION

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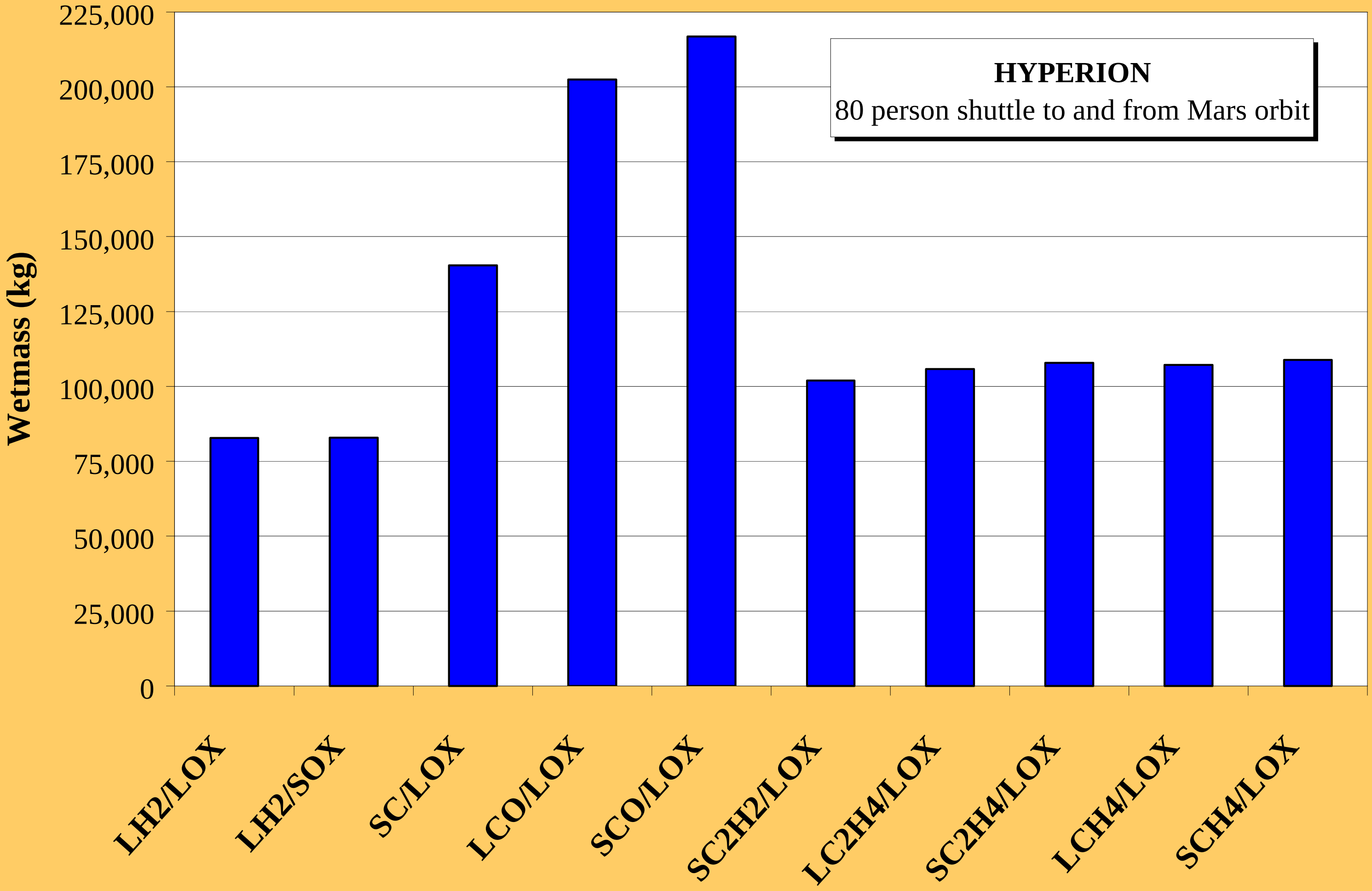

VEHICLE WET MASS
ZEUS

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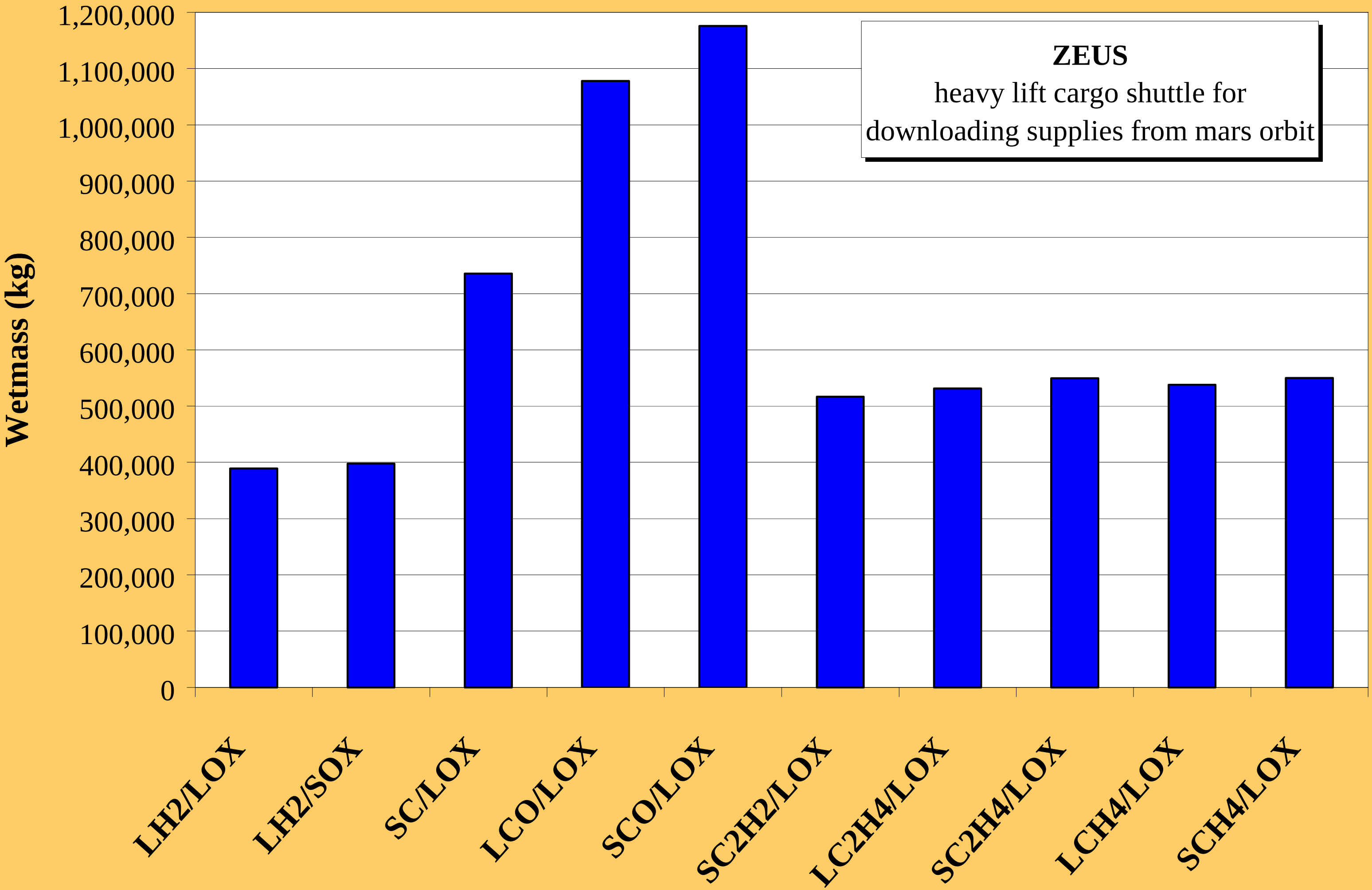

COST MODEL

- Determines incremental and total (50-year) scenario costs
- Presently assumes $5K/kg payload cost for mass launched from Earth’s surface and delivered to Mars orbit
- Receives as input, the mass transport requirements dictated by the 50-year scenario, choice of propellants, vehicle designs and family makeups, and direct support activities
- Determines elemental costs using mass based CER’s obtained from available models and historical data
- Implemented in Engineering Equation Solver (EES)

ETO COST MULTIPLIER FOR EO-MO-EO MISSIONS

- **For this study, the Earth-Mars transportation system has three elements: (1) Earth-to-orbit (ETO) launch and return system; (2) Earth orbit to Mars-orbit to Earth-orbit (EO-MO-EO) transfer stage; and (3) Mars Ascent/Decent (A/D) vehicle**
- **The Mars A/D vehicle is being treated as part of the Mars vicinity infrastructure, and is included as part of the Earth-to-Mars payload mass**
- **The EO-MO-EO transfer stage and its propellants are not considered part of the Earth-to-Mars payload**
- **For the purposes of this study, we have assumed this stage is a nuclear-thermal propulsion stage**
- **The stage is based on-orbit, but all of its propellants must be supplied from Earth via the ETO system**
- **Preliminary analyses of the stage and the EO-MO-EO mission show that for every kg of payload delivered to Mars orbit, 4kgs of propellant are expended by the stage**
- **Thus, for every kg of payload delivered to Mars orbit, 5 kg must be launched from Earth on the ETO system**
- **The present study requires an effective ETO cost multiplier of 5 to account for EO-MO-EO transportation**

COST OF DELIVERING MARS TO MARS ORBIT

- Raw ETO costs are expected to be in the range of $100-$1000 per kg delivered to Earth Orbit
- The EO-MO-EO multiplier increases this to $500-$5000 per kg delivered to Mars orbit
- The development and operation costs of the EO-MO-EO Transfer Stage (yet to be analyzed) are expected to double this cost to $1000 to $10,000 per kg delivered to Mars orbit
- For purposes of the present cost analysis iteration a delivery cost of $5000 per kg has been baselined

ETO COSTS

- **Current Shuttle/STS ETO payload delivery costs are of the order of $20,000/kg**
- **NASA has extensively studied replacement options for the current Shuttle and has concluded that ETO payload cost can be reduced by a factor of 10 by 2010, and by a factor 100 by 2025**
- **NASA’s “Space Launch Initiative” has goals to achieve these cost reductions by the targeted dates**
- **Many organizations have concluded that these goals are achievable**
- **We therefore expect, that for a future Mars exploration/-colonization efforts, ETO costs will be in the range of $100 to $1000 per kilogram**

TOTAL COST FOR 50-YEAR SCENARIO

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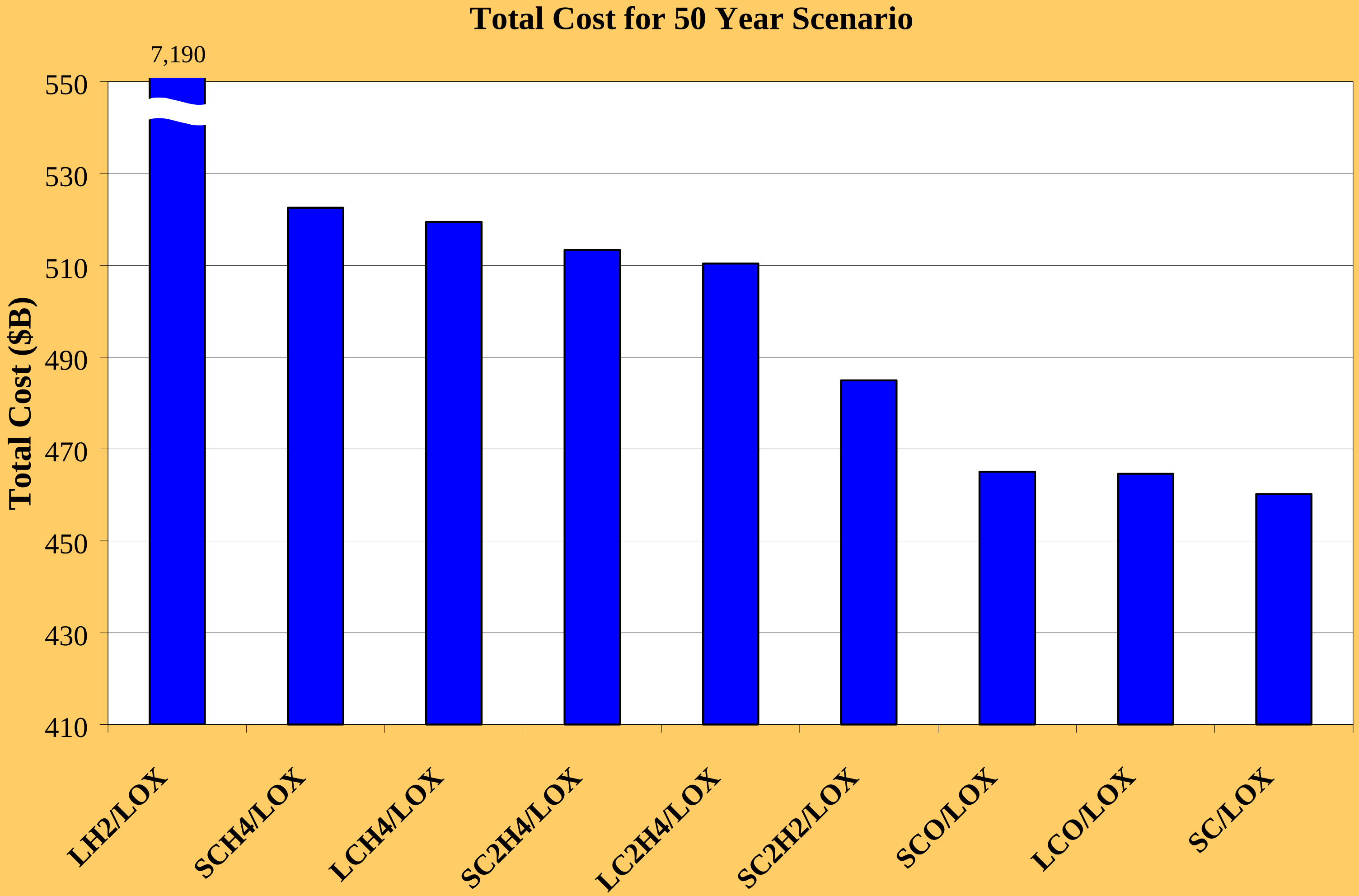
Total Cost for 50 Year Scenario

TOTAL RELATIVE COST FOR 50-YEAR SCENARIO TERRESTRIAL LH_2/LOX = 100

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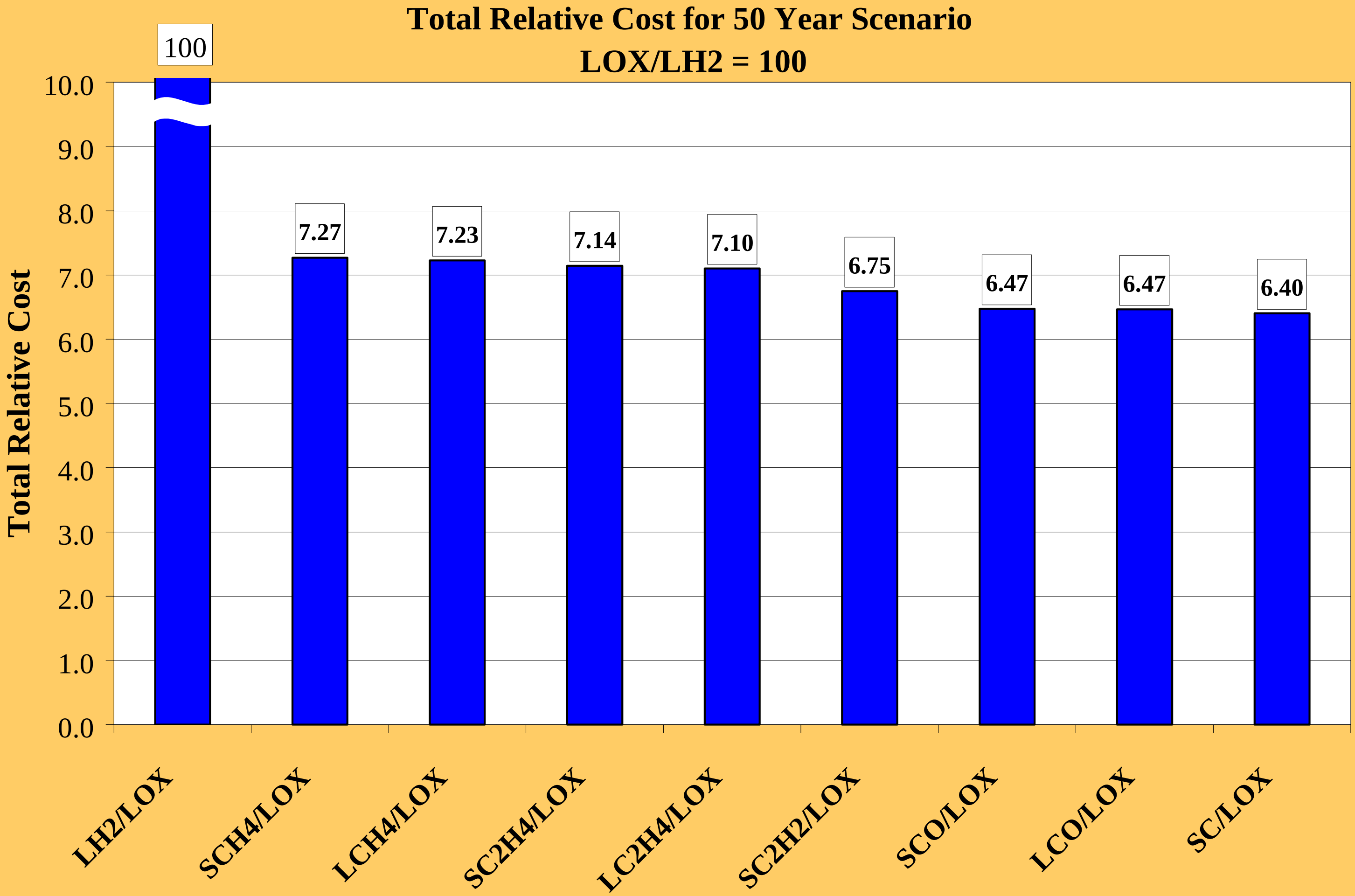

CUMULATIVE COST BREAKDOWN FOR SC/LOX

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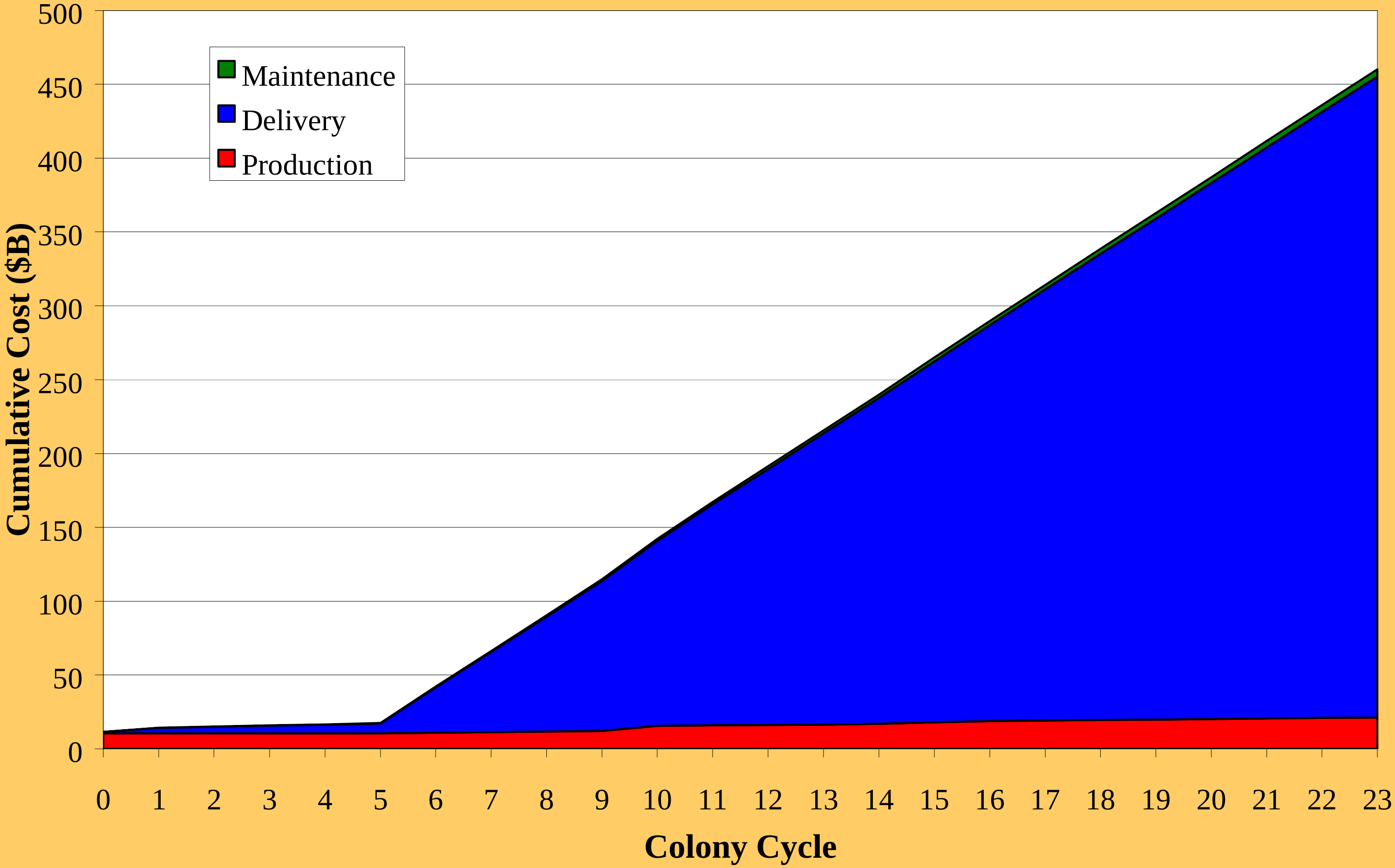
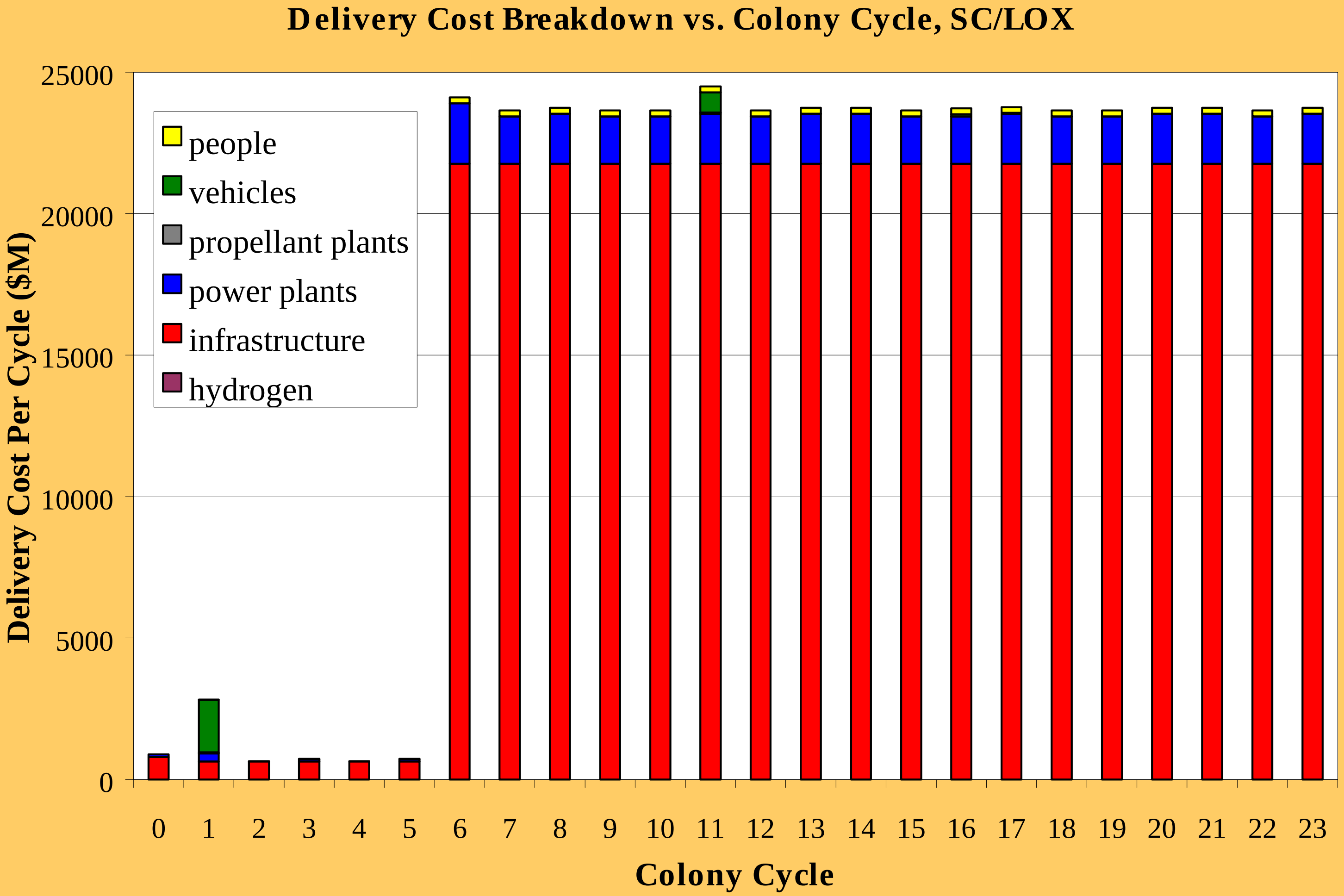
Cumulative Cost vs. Colony Cycle, SC/LOX



DELIVERY COST BREAKDOWN SC/LOX



DELIVERY COST BREAKDOWN
LC_2H_4/LOX

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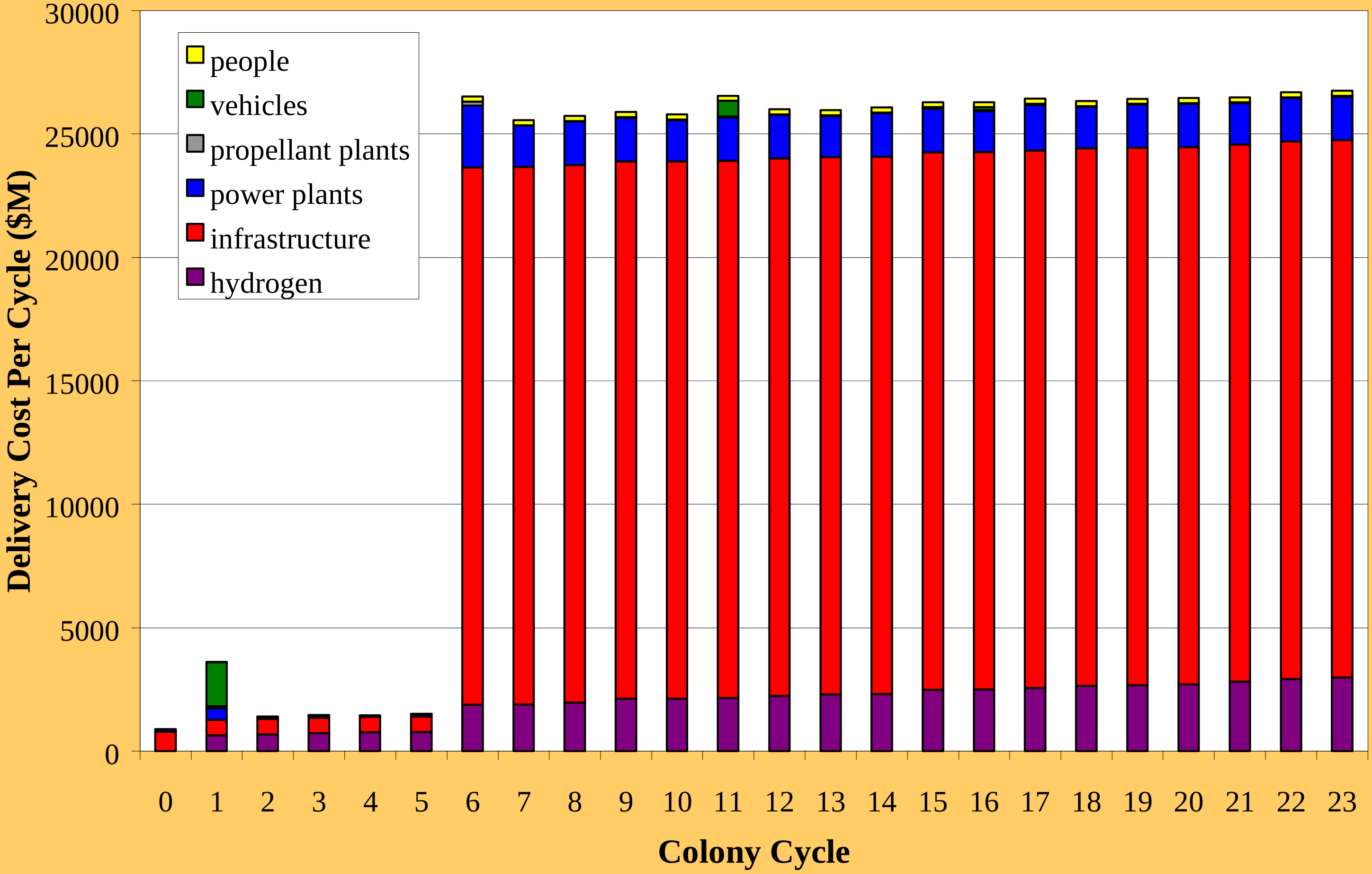
Delivery Cost Breakdown vs. Colony Cycle, LC2H4/LOX



CUMULATIVE PROPULSION RELATED COST

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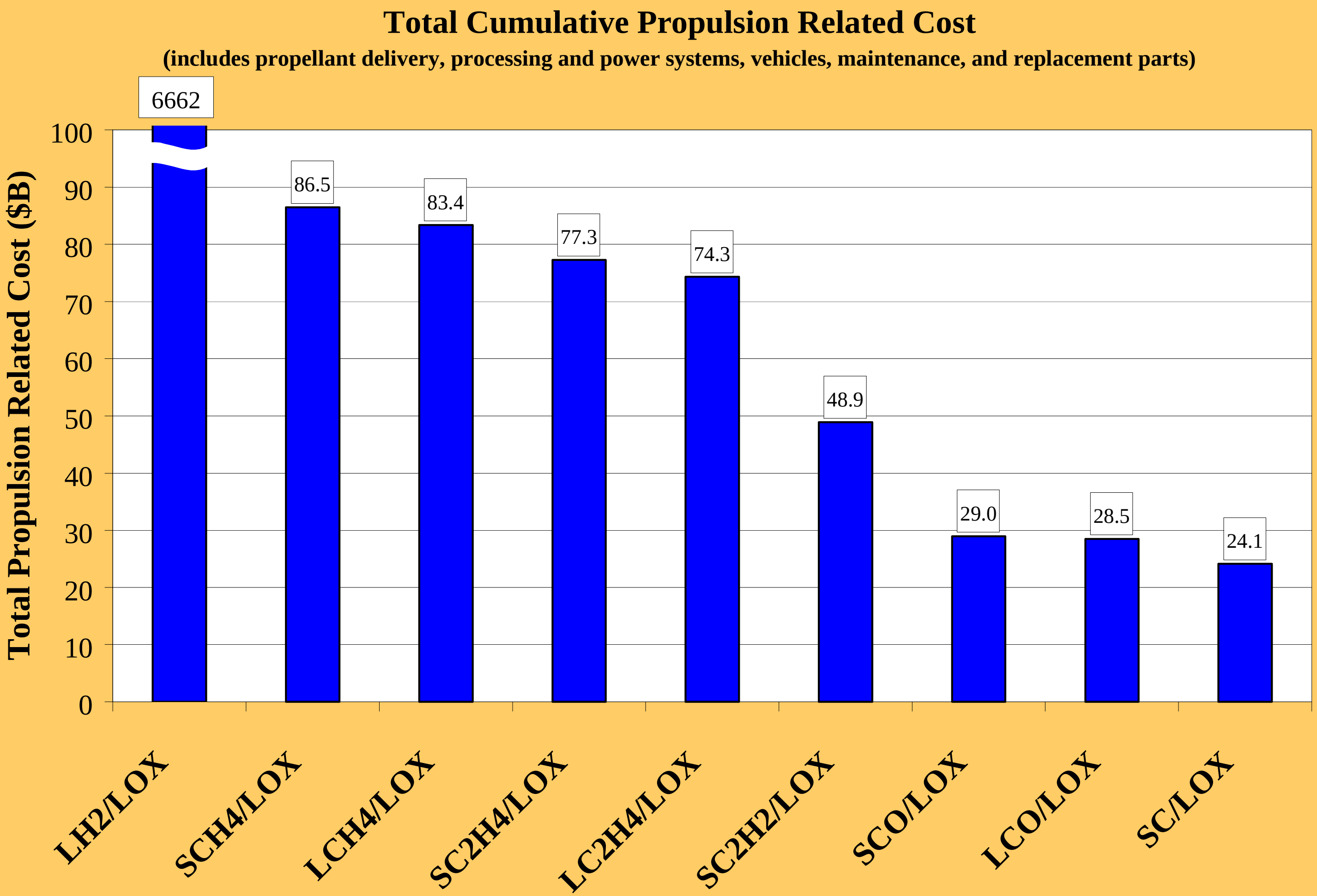
Total Cumulative Propulsion Related Cost

(includes propellant delivery, processing and power systems, vehicles, maintenance, and replacement parts)

WORK TO BE COMPLETED

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- Complete ground vehicle design
- Integrate ground vehicles into models
- Analyze low-model 100 person base (to 2090)
- Analyze propellant families not completed (2, 3, 4, 8, 10, 12, 13, 14, 15, 16)
- Analyze propellant family combinations
- Analyze sensitivites/options
- Develop total system analysis database
- Develop final conclusions & recommendations

PRELIMINARY CONCLUSIONS TO DATE

- **Preliminary results indicate that for Earth-supplied hydrogen and oxygen, ISRU provides overall cost reduction by factors ranging from ~14 to 16, depending on propellant choice**
- **Preliminary results indicate that for Earth-supplied hydrogen and oxygen. use of ISRU reduces the total propulsion cost by a factor of 77 to 276 depending on propellant choice**
- **For Earth-supplied hydrogen, C/O and CO/O propellant combination are the lowest-cost options, with CH_4/O the highest cost of ISRU propellants -- we expect this conclusion may change if Mars water is used -- as H/O or CH_4/O propellant combinations may win**
- **The non-propulsion related costs far out weigh propulsion system costs**
- **Development of Mars infrastructure from ISRU is strongly recommended to reduce cost**
- **Transportation to Mars orbit dominates overall cost scenarios, as such, the total cost ranking is driven by the percent of hydrogen in the propellant**