FINAL REPORT

on

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

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by

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FOREWORD

This document represents the Final Report on the Phase II feasibility analysis of an "Advanced System Concept for Total ISRU-based Propulsion and Power Systems for Unmanned and Manned Exploration." The NIAC-Phase II study contract (research grant #07600-041), was conducted and prepared by Orbital Technologies Corporation (ORBITEC™), Madison, Wisconsin, for NASA and the NASA Institute for Advanced Concepts (NIAC), managed by the Universities Space Research Association (USRA). The work reported and summarized here was performed from April 14, 2000 through April 30, 2002.

ORBITEC wishes to acknowledge the excellent communications and support from Dr. Robert Cassanova, NIAC Director and his project team. Dr. Eric E. Rice, PI and author, wishes also to acknowledge the excellent contributions to this effort of Mr. Robert Gustafson, Mr. Daniel Gramer, Mr. Brant White, Mr. Ronald Teeter, Dr. Marty Chiaverini, Mr. Chris St.Clair, Mr. William Knuth, Mr. Pete Priest, Dr. Douglas O'Handley, Mr. Matthew Malecki, Ms. MaryAnn Knoke and Ms. Lori Koffarnus. In addition, we wish to thank Mr. Robert Cataldo (NASA/GRC), Mr. Jerry Sanders (NASA/JSC) and Mr. Jeff Antol (NASA/LaRC) for their comments and suggestions. Special thanks go to our artist, Ms. Kandis Elliot, of the University of Wisconsin-Madison, for her great work in capturing our imaginations.

ORBITEC also wishes to acknowledge the input of the Approach Workshop Participants. A NIAC/ORBITEC project workshop was held in Madison, Wednesday, June 21-23, 2000, for the purpose of gaining valuable interaction between certain exploration/ISRU experts and the ORBITEC study team. The workshop focused on two study tasks: (1) to refine the study approach, ground rules, and possible advanced concepts, and (2) assess the possible activities that would be needed at a Mars base (the Mission Model). The participants who attended and contributed to the project workshop are listed below. We greatly appreciated their contributions to the goals of the project Workshop Participants: ORBITEC -- Dr. Eric Rice, Dr. Doug O'Handley, Mr. Robert Gustafson, Dr. Martin Chiaverini, Mr. Dan Gramer, Mr. Jerry Hanley, Dr. Jim Jordan, Mr. Bill Knuth, Dr. T. D. Lin, Mr. Matt Malecki, Dr. Bob Morrow, Mr. Pete Priest, Mr. Ron Teeter, Mr. Brant White, Dr. Leslie Gerstch, Dr. Richard Gerstch, and Mr. Marty Harms; NASA -- Dr. Mike O'Neal (KSC); Universities: Dr. George Miley (U of IL), Dr. Mike Duke (CSM), Dr. Jerry Kulcinski (UW); Others: Mr. Niklas Jarvstrat (Literati), Dr. Paul Spudis (LPI), Mr. John Hunt (DOA/FPL), and Dr. Ed McCullough (Boeing).

It should be noted that the baseline analysis was conducted based upon the "dry Mars" assumption. Recent findings of the Odyssey Mission that has apparently discovered vast amounts of sub-surface water ice may likely change the study results if re-analyzed.

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1.0 STUDY BACKGROUND

In this feasibility study, ORBITEC has conceptualized systems and an evolving architecture for producing and utilizing Mars-based in-situ resources utilization (ISRU) propellant combinations derived from the Mars atmosphere and surface resources of a "dry Mars" to support ground and flight propulsion and power systems that would be part of Mars exploration and colonization. The key aspect of the study was to show the benefits of ISRU, develop an analysis methodology, as well as provide some guidance to propellant system choices in the future based upon what we know today about Mars. Ground transport systems included are: automated robotic roving vehicles, and human crewed pressurized transport rovers, and unmanned cargo transports. Flight vehicles include: Mars sample return vehicles, human surface-to-surface "ballistic hoppers", surface-to-orbit vehicles, sounding rockets, interplanetary transport vehicles, balloons, winged aerocraft, Additionally, we have included the study of early robotic and human missions to also help assess the benefits of in-situ resources utilization.

During the Phase I study (NASA Research Grant 07600-0020), we accomplished a preliminary systems scoping study which provided the approach and direction to fully assess the benefits of an ISRU approach (e.g., carbon/oxygen, carbon monoxide/oxygen, methane/oxygen or hydrogen/oxygen) compared to one of using all Earth-supplied propellants. There is no question that for the cost-effective human exploration of Mars, we will need to use in-situ resources that are available on Mars. The real question is what propellant ingredients are available and where and what propellants do we use in specific applications to achieve the best economic benefit for humanity. This report can be downloaded from the NIAC website http://www.niac.usra.edu.

Probably the most cost-effective and easiest use of Martian resources is the atmosphere (95% CO_2). The CO_2 can be easily processed and converted to carbon monoxide or carbon and oxygen. Water vapor is also present in the Mars atmosphere in small proportion; soil-based water (especially in the polar regions) is in much greater abundance. With the availability of C, CO, O_2, and H_2O through processing the atmosphere, excellent propellants can be made (SC/LOX, SCO/LOX, LCO/LOX, LCH_4/LOX, SCH_4/LOX, SC_2H_2/LOX, LC_2H_4/LOX, SC_2H_4/LOX, LH_2/SOX, LH_2/LOX, H_2O_2/CH_3OH, and etc). For this study period, we have focused upon a 50-year period beyond the initial manned Mars exploration activity (from 2040 through 2090). For the 2040-2090 periods, we have assumed that two different levels of activity and missions that require the use of propellants and fuels are possible, as driven by various reasons: (a) continued presence/research/exploration, and (b) a terraforming program that includes significant colonization, etc.). Therefore, we are defining what we call "low" and "high" traffic models. To define the use of propellants/fuels, we define the vehicles that would use them. ORBITEC's overall approach in this effort was to develop a feasible study methodology/approach such that a credible detailed study could be conducted. Additionally, results would provide reasonable answers that would provide knowledgeable guidance to NASA technology development of systems that use the ISRU propellants, as well as the definition of the ISRU processing systems themselves.

Part way through the study, ORBITEC conducted rocket engine firings of various carbon-based propellants and decided to discard solid carbon (in the hybrid mode) and acetylene (solid in hybrid mode). The inability to get carbon to burn and the very rapid (explosive) decomposition of solid acetylene in the hybrid led to the discardings. However, ORBITEC tests with solid toluene burning with oxygen in a hybrid mode, did prove promising, but was not included in the study.

2.0 OVERALL APPROACH AND ASSUMPTIONS

The overall study approach was initially defined in the Phase I study effort and refined during the early part of the Phase II study. Figure 1 provides an overview of the final study approach.

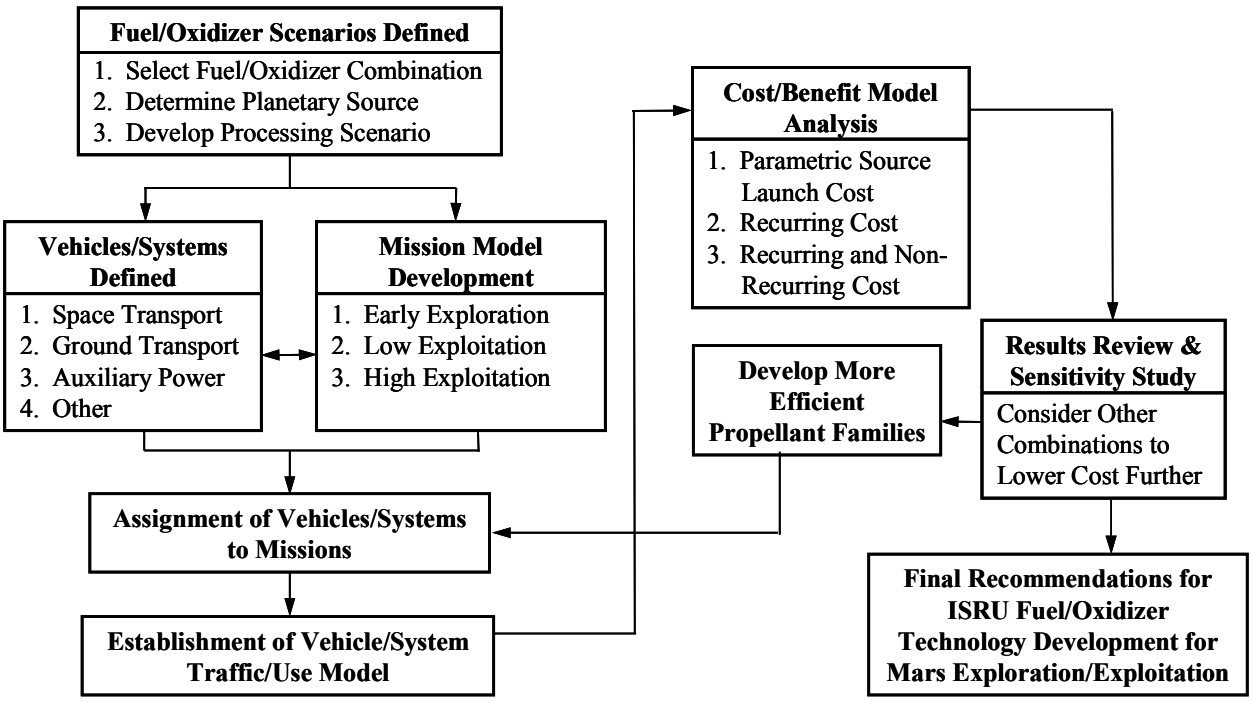

Figure 1. Overall Study Approach

The first step in the study was to define the fuels and oxidizers to be considered in the analysis. The steps were to select the fuel/oxidizer combinations, determine their planetary sources, and develop their processing system definition. The next step was to determine the missions and frequencies that were possible that would require propellant/fuel resource and then define the vehicles for the mission and the propellant selected.

For the mission definition as we defined an "Early Exploration" period (from now to 2040, including robotic and human activity) considered an ISRU-based Mars sample return analysis and a look at an ISRU-based human "Mars Direct" scenario. The purpose in evaluating these missions was to see how an ISRU choice might be affected by a particular mission choice.

For the major part of the study; however, we defined "Low Exploration" and "High Exploration" scenarios that would be used to bracket a "high" and "low" human base and colony activity. During the study we developed the ground rules that would characterize these two scenarios. The top-level study ground rules were:

- 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 unmanned and manned exploration period (now to-2040) and extends 50 years from 2040 to 2090 for the colonization period

- Missions to be used are those defined by the project team
- Mission vehicle assignment and mission frequency will be determined by the project team
- Earth launch mass (ELM) costs are to be parametrically assessed around a baseline
- 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
- Cost estimates will be in current year dollars
- Ground vehicles included: automated unmanned roving vehicles, manned pressurized transport rovers, and unmanned cargo transports
- Flight vehicles included: Mars sample return vehicles, unmanned and manned surface-to-surface "ballistic hoppers", surface-to-orbit vehicles, interplanetary transport vehicles, balloons, sounding rockets, winged aerocraft
- 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 study task.

We will utilize these ground rules along with more detailed assumptions that are defined in the various sections of the report.

Cost analysis were carried out for the various scenarios that show the value of ISRU and the predicted value of each propellant option for the assumed propellant ingredient available on Mars. Sensitivity analyses were then performed to look at how the results could be modified by different conditions or assumptions.

The overall study approach that was initially proposed as a result of the Phase I study was presented to a group of experts for review and comment at the start of the Phase II effort. Appendix B provides a summary of the workshop results.

3.0 PROPELLANT FAMILY DEFINITION

The subsections below describe the identification of propellants and their propulsion system application, rocket propellant performance, as well as the processing definitions.

3.1 Propellant Family Identification and Use

The propellant/propulsion systems that were initially considered for flight vehicles to be analyzed in the system tradeoffs are shown below. The goal was to assess the potential ISRU economic benefit for each propellant and propulsion use method as given below:

1. LH_2/LOX Bi-Propellant Liquid Propulsion
2. LH_2/SOX Cryogenic Solid Hybrid Propulsion
3. SC/LOX Vortex Hybrid Propulsion (later dropped from final analysis)
4. LCO/LOX Bi-Propellant Liquid Propulsion
5. SCO/LOX Cryogenic Solid Hybrid Propulsion
6. SC_2H_2/LOX Cryogenic Solid Hybrid Propulsion (later dropped from final analysis)
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.

Propellants for ground vehicles that were initially selected were:

1. LH_2/LOX
2. LH_2O_2
3. LCH_3OH/LH_2O_2
4. LCO/LOX
5. LCH_4/LOX.

The sixteen propellant families (PF) and their sources to be considered for analysis are defined as:

H_2/O_2 or H_2O_2

All Earth-Supplied H_2 and O_2 (PF1)

Earth-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 (later dropped from final analysis)

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 (later dropped from final analysis)

C_2H_2 Made from Earth-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-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)

CH_4/O_2

CH_4 Made from Earth-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-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-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)

3.2 Propellant Processing Scenarios

The theoretical performance data for the various propellant combinations were calculated using CEA performance code. In all cases, the calculations assumed an expansion area ratio of 200:1, expanding to an atmospheric pressure of 0.044 psia (2.3 torr). For liquid bi-propellant engines, a chamber pressure of 1000 psia was used; for hybrid engines, a chamber pressure of 300 psia was used. The following propellant combinations as given at the top of Section 3.1 were considered. Graphs of specific impulse (in seconds) are presented in (Figures 2 through 11) below for each of the ten propellant combinations.

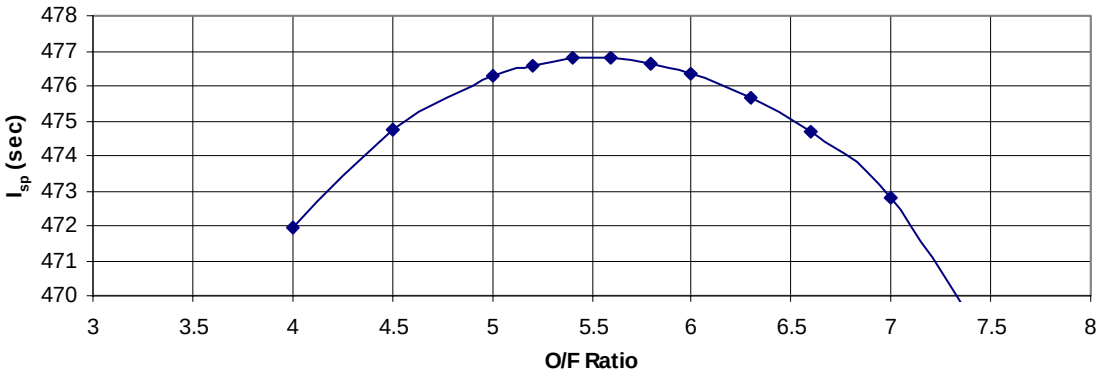

Figure 2. LH_2/LOX Theoretical Performance

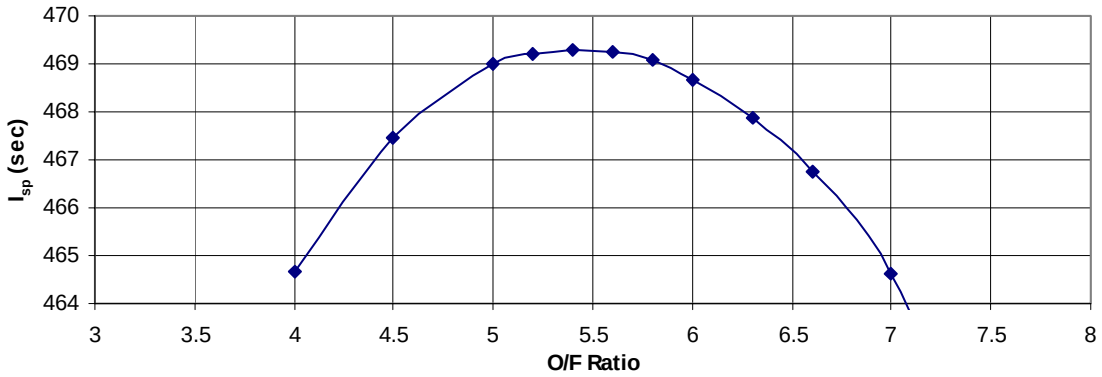

Figure 3. LH_2/SOX Theoretical Performance

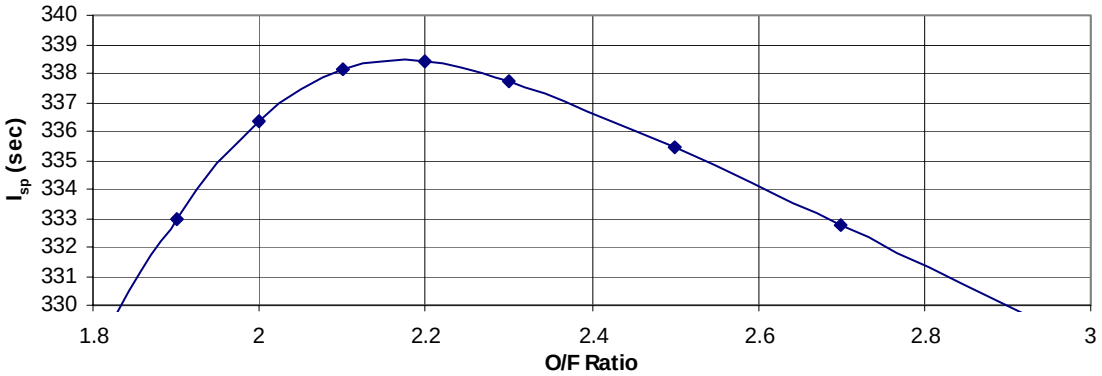

Figure 4. C/LOX Theoretical Performance

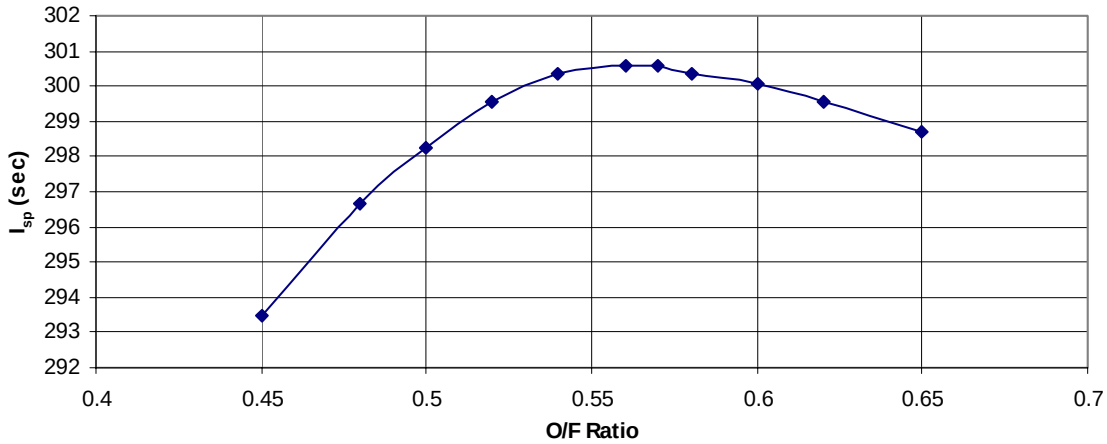

Figure 5. LCO/LOX Theoretical Performance

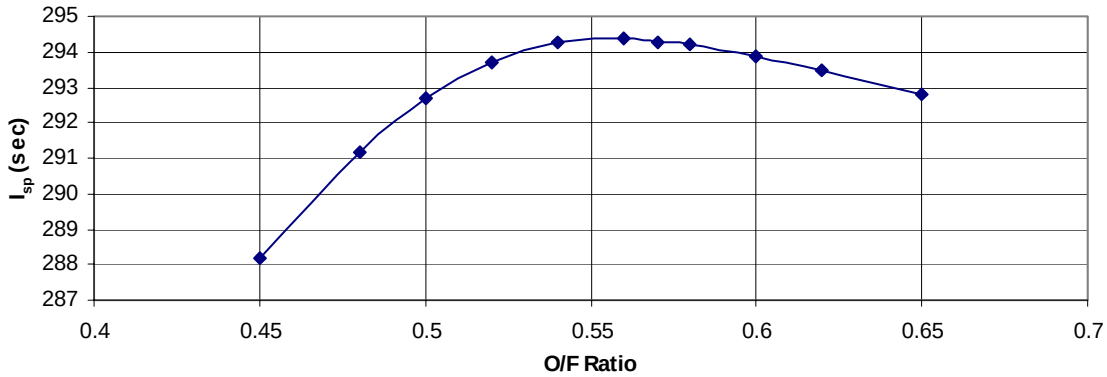

Figure 6. SCO/LOX Theoretical Performance

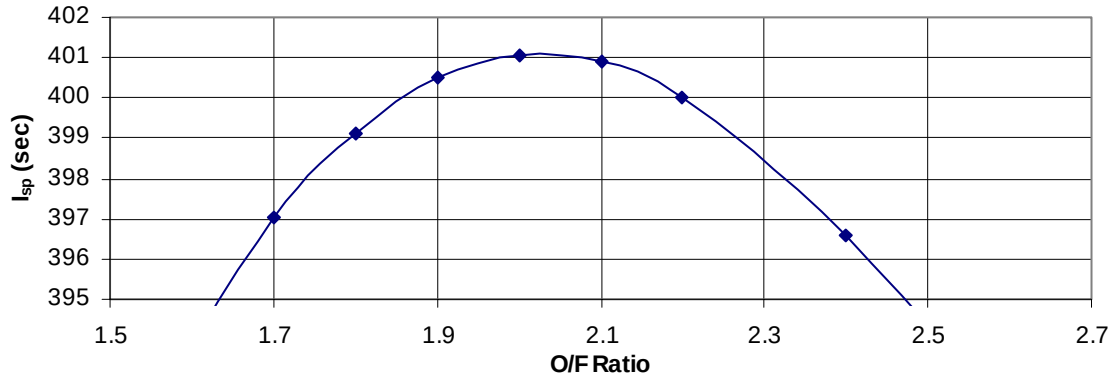

Figure 7. SC_2H_2/LOX Theoretical Performance

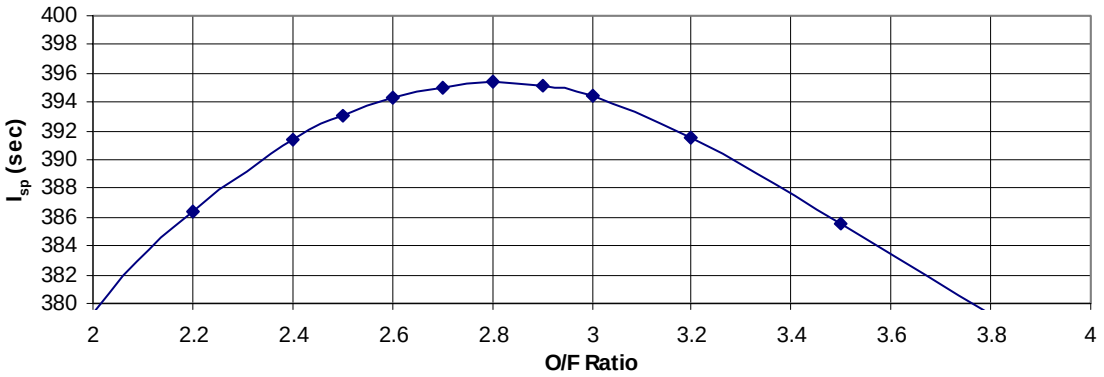

Figure 8. LC_2H_4/LOX Theoretical Performance

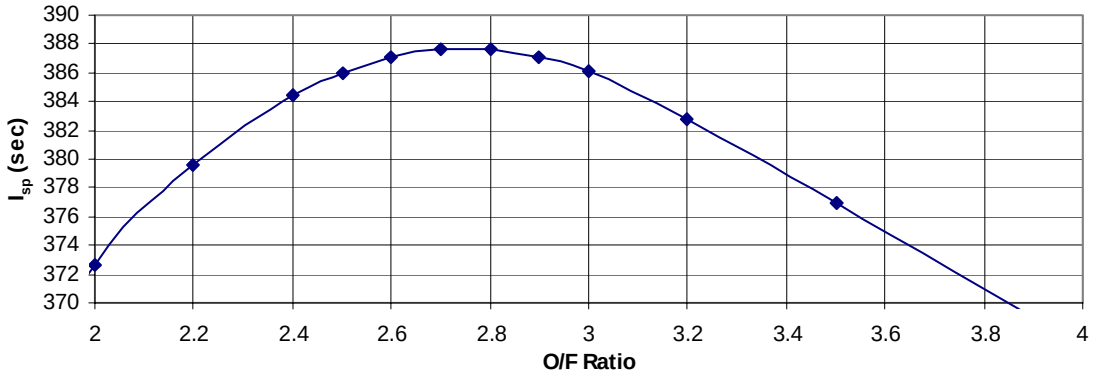

Figure 9. SC_2H_4/LOX Theoretical Performance

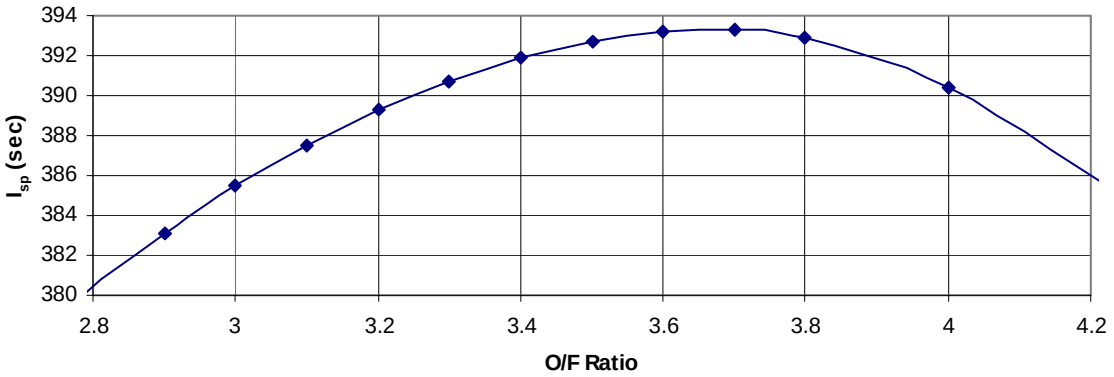

Figure 10. LCH_4/LOX Theoretical Performance

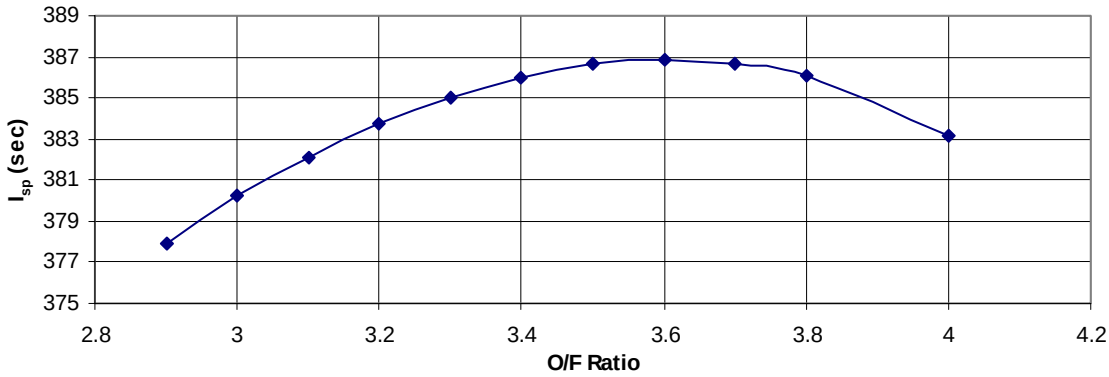

Figure 11. SCH_4/LOX Theoretical Performance

3.3 Propellant Processing

Once the propellant families were identified, literature searches were conducted to identify means of producing the propellants from Martian resources. Most of the production scenarios use the Mars atmosphere with its plentiful supply of carbon dioxide, while bringing hydrogen from the Earth or obtaining it from the water in Martian atmosphere.

The various propellant processing methods and hydrogen sources, used in the analysis, are summarized in Table 1. The ethylene process produces a fuel-rich mixture, requiring an additional oxygen supply from a zirconia cell or from the Earth. The carbon/oxygen system uses carbon from either the Mars atmosphere or transported from Earth. All other systems obtain their fuel or hydrogen from sources listed in Table 1.

Table 1. Processing Options for the Mars Propellant Families

Fuel	System	Fuel Source	
		Earth	Mars
Hydrogen	Electrolysis	X	X
	Zirconia Electrolysis	X	
Carbon	Sabatier with Coking Reactor	X	X
Carbon Monoxide	Zirconia Electrolysis		X
Ethylene	Fischer-Tropsch Direct Reduction	X	X
Methanol	Zirconia Cell with Methanol Reactor	X	X
	Reverse Water Gas Shift with Methanol Reactor	X	X
Methane	Sabatier Process	X	X
	Sabatier with Methane Pyrolysis	X	X
	Reverse Water Gas Shift with Sabatier	X	X

Several assumptions were made for the mass and power scale-up calculations on the processing plants. These assumptions were taken from Rosenberg, et. al, (1999), and Green, et. al, (1999), as well as from chemical engineering practices concerning normal plant operating parameters. The mass scaling factor is 80% the increase in production capacity, based on the scaling of piping and complex process systems. Power scaling is equal to the increase in production capacity since efficiencies will not change significantly for the equipment involved and heat generation/removal is the largest demand on energy loads. All production systems were normalized to a system operating mass of 6000-kg or 6 MT.

All production systems operate using nuclear power, allowing for production on a steady-state, round-the-clock basis. Production time units are all on Earth-based time. The calculations do not include energy or mass losses during start-up or shutdown; actual systems will incur these losses. For optimal production, steady-state operation will be performed as often as possible. A two-week downtime period per year is assumed as well as a 0.5%/yr loss rate due to fugitive emissions. A boil-off rate of 0.3%/day is also assumed, but the propellants are recondensed using the cryo-coolers. Parts replacement is assumed as 10% of total system mass per year; however, this estimation is very liberal and will likely be reduced upon further system analysis beyond this study effort. All production systems are assembled to be without components typically needing excessive maintenance in plant operations, leading to a lower parts requirement and fewer operating personnel.

System inputs are at 1 atmosphere (Earth) and 25 C; outputs are gaseous (except methanol is a liquid) and are approximately at 1 atm and 25 C. Energy for compression of the Mars atmosphere has been added to the process energy and are typically two orders of magnitude lower than the energy costs of the baseline production process; mass estimates for the process hardware have also been included in the analysis. Mass and energy estimates of the cryo-coolers are also included.

Hydrogen transport penalties for boil-off or re-liquefaction equipment are not included in the baseline analysis that included hydrogen from Earth. It has been examined in the sensitivity analysis, however. Systems using Mars hydrogen obtain it from electrolysis of atmospheric water obtained with the WAVAR system (Grover, et. al, 1998). In these cases the WAVAR and electrolysis system mass and power requirements are added to the propellant production requirements. These systems produce excess oxygen which may then be used for other base requirements including life support, resulting in lower mass requirements for those systems.

For the other propellant processing systems, mass and energy data were estimated using process equipment and methods used in Green, et. al, (1999) to insure a uniform determination of masses given a process. Using this method, normalized errors and resulted in equal mass or energy savings from technology advancements in specific process equipment. Chemical advancements in the field of catalysts and other reaction pathways would be process specific and would likely have the largest influence on the future development of these processes.

Specific data are presented and discussed in Section 7. The required inputs and outputs of the propellant production model are summarized below.

Required Input:

- Mass requirements for each propellant from the vehicle design model
- Vehicle traffic schedules for total propellant calculation per cycle
- Propellant production plant capacity per 6000-kg unit
- Propellant production plant energy and liquefaction/solidification requirements per 6000-kg unit.

Outputs:

- Number of production units required as a function of time
- Shipping schedule of units from Earth
- Storage tank shipment requirements
- Hydrogen shipment requirements (if applicable)

- Parts shipment schedule for equipment maintenance and replacement during process downtime
- Maximum production energy requirements per cycle
- Energy requirements of cooling stored propellant and hydrogen boil-off.

3.4 Nuclear Power Plant Requirements

A correlation between nuclear power plant mass and the electrical power output needs was developed. (see Figure 12). The data points represent various designs for space nuclear power systems, such as a SP-100 power system (based on the SP-100 reactor developed by a joint DOE/DOD/NASA program). It is important to note that this correlation is based on current technology. Projections of future nuclear power systems indicate that these masses may be reduced by up to 50%. This correlation was combined with the various processing plant designs to determine the combined mass of a propellant processing plant and power plant as a function of propellant processing rate. After this correlation was developed, the decision was made to use a modular approach to the power system (i.e. additional power units would be added as they are needed). Each unit is based upon the SP-100 power system and produces 750 kW of electrical energy.

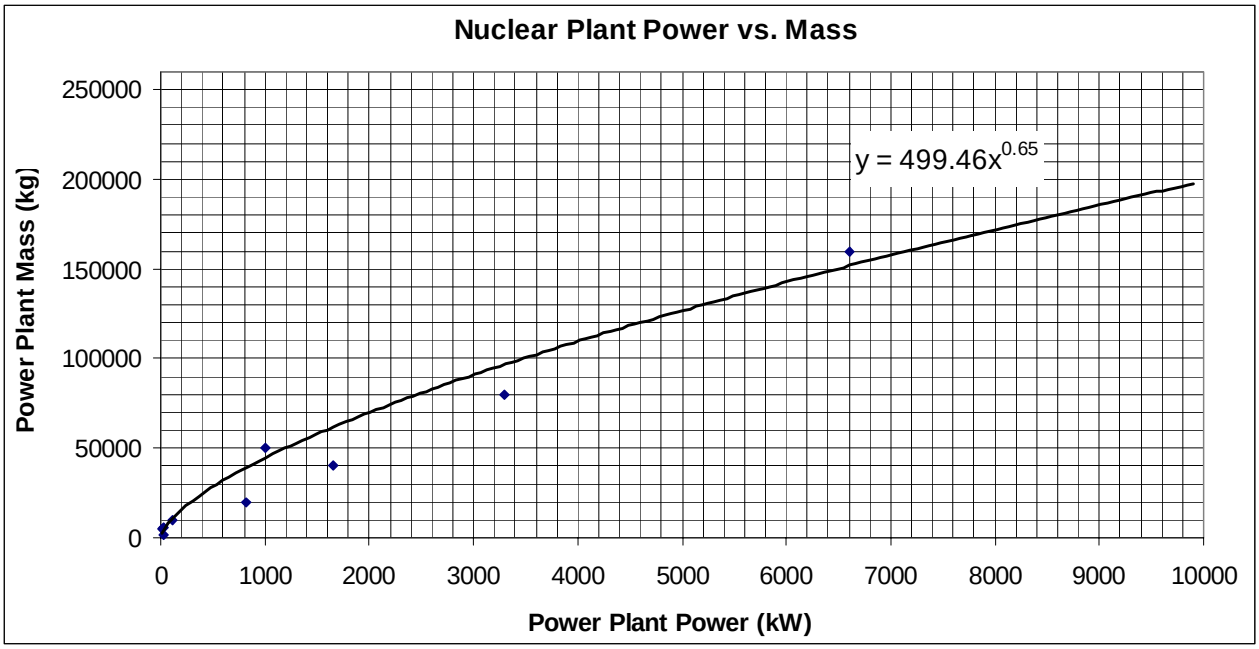

Figure 12. Plot of Nuclear Power Plant Mass vs. Electrical Power

4.0 COLONY CHARACTERIZATION

For Mars colonization, two different scenarios were considered in this study, namely: (1) a 100-person colony scenario, and (2) a 10,000-person colony scenario. Each scenario begins with the same size, but they have different growth rates. Each scenario has different mission requirements for ground and flight vehicles. The population growth models, location of the bases, mission and traffic models, and infrastructure models are discussed in the following sections.

4.1 Colony Size and Population Growth Model

Population models were developed for both the 100-person colony and 10,000-person colony scenarios. The population on the surface of Mars grows from 20 in 2040 to 100 in 2050 under both scenarios. In the 100-person colony scenario, the population remains stable at 100 people from 2050 to 2090, representing an Antarctic-type scenario. In the 10,000-person colony scenario, the population continues to increase up to a population of 10,000 people in the year 2090. A linear growth rate was assumed for both scenarios. A fast-transit transfer trajectory was assumed for transportation of personnel to and from Mars, with launch opportunities occurring ~26 months apart. The period of time between shipments of people and cargo from Earth are called colony cycles. The populations listed in the following tables, Tables 2 and 3, represent the nominal population levels that occur. For example, the Mars population at the end of Colony Cycle 1 would be 36 after the arrival of new colonists from Earth. Colony Cycle 2 would begin and the population would remain at 36 until the arrival of new colonists at the end of the cycle (for a new total of 52 inhabitants). Due to the constraints of this trajectory, personnel will be arriving on Mars and departing for Earth at different times. The launch opportunity from Mars occurs approximately 5 months before the new personnel will arrive from Earth. This will either create periods with fewer personnel (~5 months) or more personnel (~21 months) than the nominal population level. Both cases will present challenges for the base/colony and must be accounted for in future analyses.

The population model for the 100-person colony is summarized in Table 2. This model assumes a starting population of 20 people in the year 2040. The population grows linearly to a total of 100 by 2050. The population remains at 100 people through 2090. All of the inhabitants will stay on the surface of Mars for approximately 6 years. The typical service rotation would include a 4-6 month transit from Earth to Mars, a 70-72 month surface stay, and a 4-6 month transit from Mars to Earth. The last two columns list the number of people that will need to be transported to and from Mars during each launch opportunity.

The population model for the 10,000-person colony scenario is summarized in Table 3. This model assumes a starting population of 20 people in the year 2040. The population grows linearly to a total of 100 by 2050. All of the inhabitants during this period will stay on the surface of Mars for approximately 6 years (3 colony cycles). The typical service rotation would include a 4-6 month transit from Earth to Mars, a 70-72 month surface stay, and a 4-6 month transit from Mars back to Earth. After 2050, one half of the colony population is assumed to become permanent inhabitants. It is assumed that the remaining half will continue to operate under the service rotation. The colony population will increase linearly to 10,000 people by 2090. A 2% per year net increase in the permanent population is assumed (due to births and deaths). The last two columns list the number of people that will need to be transported to and from Mars during each launch opportunity.

Table 2. ORBITEC Population Model for the 100-Person Colony 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

Table 3. ORBITEC Population Model for the 10,000-Person Colony Scenario

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

4.2 Location of Mars Bases

Each colony consists of one or more bases located on the surface of Mars. The number and size of Mars bases are dependent on the colony scenario selected. The 100-person colony scenario utilizes a single main base with a population of 20-100 people. This single base would contain sufficient redundancy to protect its inhabitants in the case of an emergency. The 10,000-person colony scenario utilizes two main bases and numerous smaller bases (see Figure 13). The two large bases would be located ~1,000 km apart from each other. Each large base would be capable of supporting the entire Mars colony population in case of a catastrophic failure of the other bases. The population of each large base would grow from 50 to 4,700 people during the study period. Three small bases would surround each large base (for a total of six small bases). Two small bases would be located ~500 km from each large base. An additional remote base would be located 5,000 to 10,000 km from each main base. The population of the small bases would grow from 6 to 100 people in the year 2090.

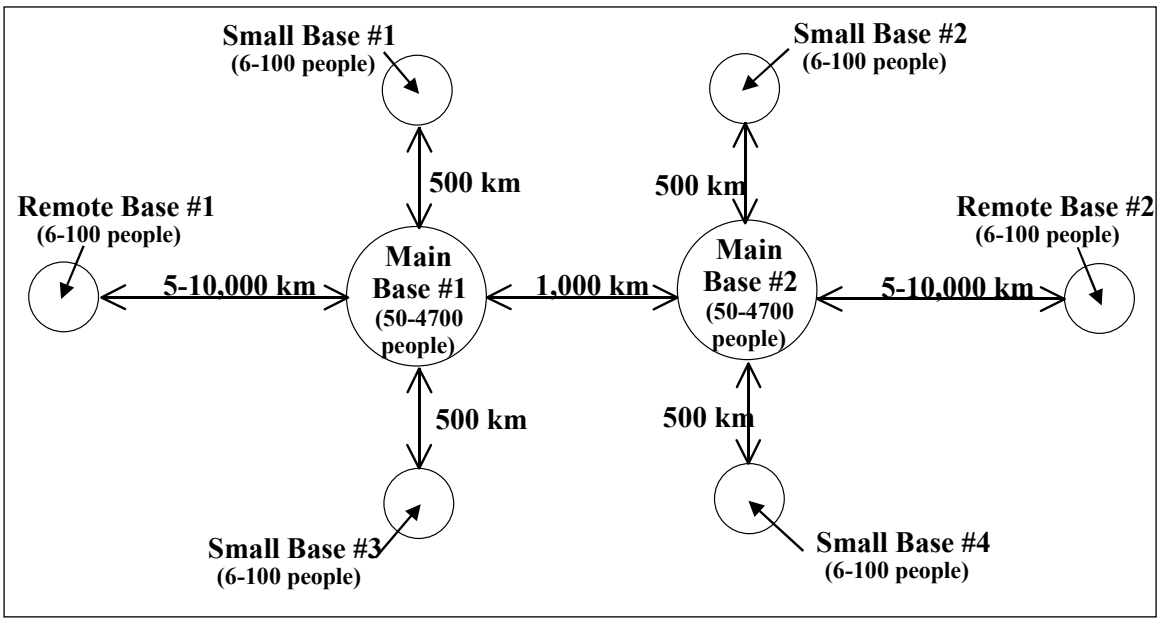

Figure 13. Size and Location of Mars Bases Under the 10,000-Person Scenario

4.3 Infrastructure Requirements and Concept Models

The infrastructure model is designed to calculate the mass of various components, other than vehicles and propellant processing plants, required to be transported from Mars orbit to the surface. The main inputs to the infrastructure model are the population growth model, habitat power required per colonist, and habitat volume required per colonist. The infrastructure model calculates the total volume of habitat volume and power requirements and determines an estimate of the power systems and habitat module masses.

4.3.1 Colony Requirements and Concepts

The elements and layout of the Mars colony under the 100-person colony scenario were developed to determine the needs of the colony on a per person basis. The colony design is based on a self-sustaining lunar colony concept previously developed by ORBITEC (O'Handley, et al., 2000). The specifications for the pressurized modules of the base are summarized in the Table 4. These specifications represent the

minimal requirements that must be satisfied to accommodate 100 persons for extended periods of time. It should be noted that some of the spaces identified could be combined into common areas. For example, some of the plant growth and animal areas could be integrated into public open spaces (parks). This would provide the inhabitants important interaction with plants and animals. The numbers are not based on a specific design, but they are simply being used to determine the overall scale of the base. Figure 14 shows one potential layout of the 100-person Mars colony.

Table 4. Summary of Pressurized Module Requirements of the 100-Person Mars Colony

Use of Space	Surface Area Required (m^2)	Estimated Height (m)	Volume (m^3)
COMMAND & CONTROL CENTER	**500**	**3**	**1,500**
HABITATATION	**16,190**	**--**	**73,010**
Personal Habitats	***4,900***	***3***	***14,700***
Public Habitats	***3,090***	***--***	***21,410***
Business, Shops, Offices	340	4	1,360
Hospital/Clinic	150	3	450
Assembly (churches, halls)	150	5	750
Recreation and Entertainment	500	3	1,500
Public Open Space (park)	1,000	14	14,000
Service Industry	400	3	1,200
Transportation	200	3	1,200
Mechanical Subsystems	50	1	50
Miscellaneous	300	3	900
Storage Areas	***1,500***	***3***	***4,500***
Repair and Maintenance	***1,000***	***10***	***10,000***
CELSS Facilities	***5,700***	***-***	***22,400***
Environmental Control	400	3	1,200
Waste Recycling	800	4	3,200
Plant Growing Area	2,500	4	10,000
Animal Areas	1,000	4	4,000
Food Processing, Storage	500	4	2,000
Agriculture Drying Areas	500	4	2,000
ISRU PROCESSING	**2,500**	**10**	**25,000**
PRODUCT MANUFACTURING	**1,500**	**10**	**15,000**
POWER GENERATION, STORAGE, & DISTRIBUTION	**250**	**4**	**1,000**
SCIENCE AND TECHNOLOGY LABORATORY	**1,500**	**4**	**6,000**
LAUNCH & LANDING AREA	**--**	**--**	**--**
TOTAL	**--**	**--**	**121,510**

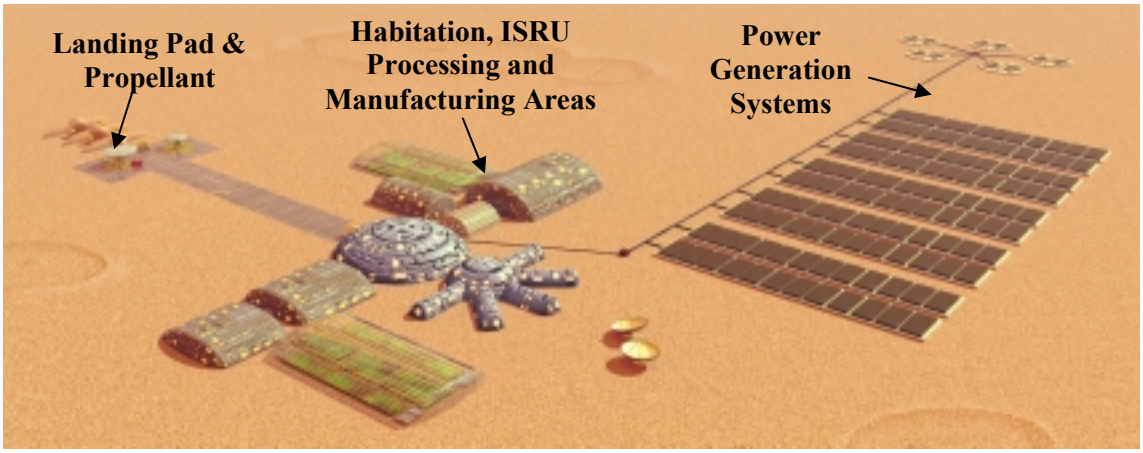

Figure 14. Overall Layout of the 100-Person Mars Colony

Figure 15 shows the detailed layout of the pressurized modules in the 100-person colony. The public habitat areas would occupy the central location of the base along with the central command and control center. The ISRU processing and manufacturing facility is the primary structure to be established after the initial habitat areas are in place. The Closed Ecological Life Support System (CELSS) would provide all the atmospheric requirements for living on Mars. The food acreage sized to support 100 people and will include growing, harvesting, and producing foodstuffs. A second greenhouse is included for complete redundancy in the case of a large-scale crop failure or accident. By proper design, it would be possible to integrate the agriculture and animal areas into attractive park areas that could be used for leisure and recreation. Power generation (nuclear reactors and solar photovoltaic arrays) are located at an optimum distance from the habitat areas and a safe distance from the launch and landing complex. The nuclear reactors must be located far enough away from the rest of the base to ensure safety while the solar arrays must be far enough from any dust generating activities (see Figure 16).

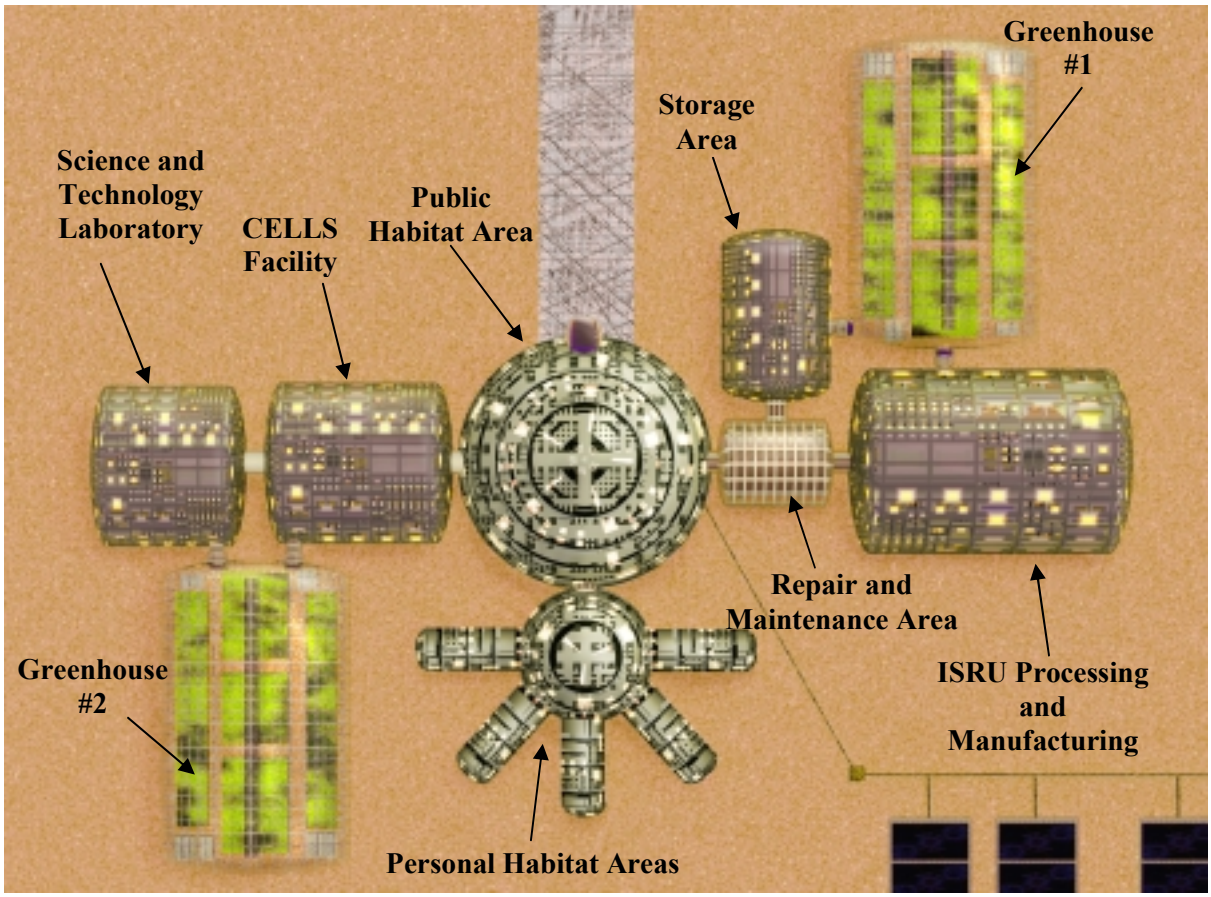

Figure 15. Layout of Pressurized Modules of the 100-Person Colony

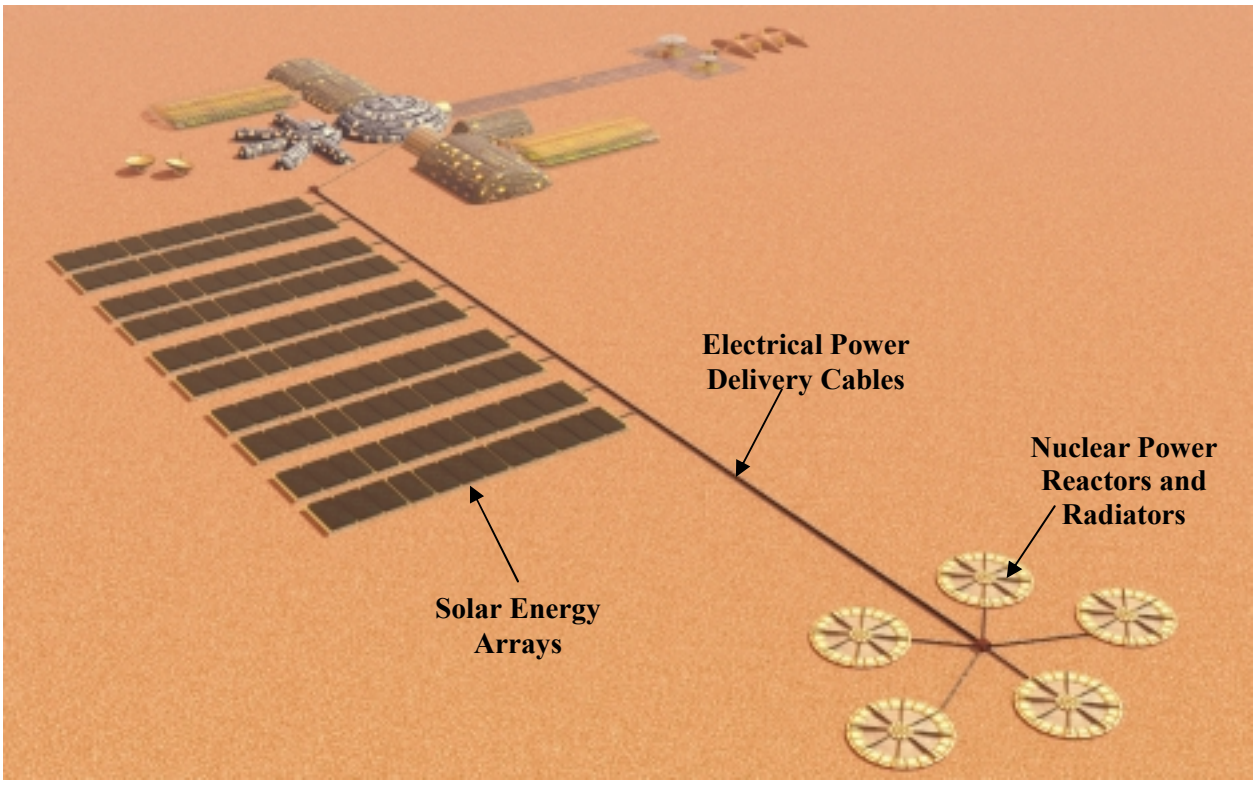

Figure 16. Power Generation Systems in the 100-Person Colony

The launch and landing facility for the base should be located away from the base because of possible blast debris. Figure 17 shows the launch and landing complex for the 100-person colony. Two different flight vehicles can be accommodated at the launch and landing complex. The propellants are generated by ISRU production plants and stored in four spherical tanks. The tanks are separated by mounds of Mars soil for safety. A paved road extends from the launch and landing complex back to the main colony.

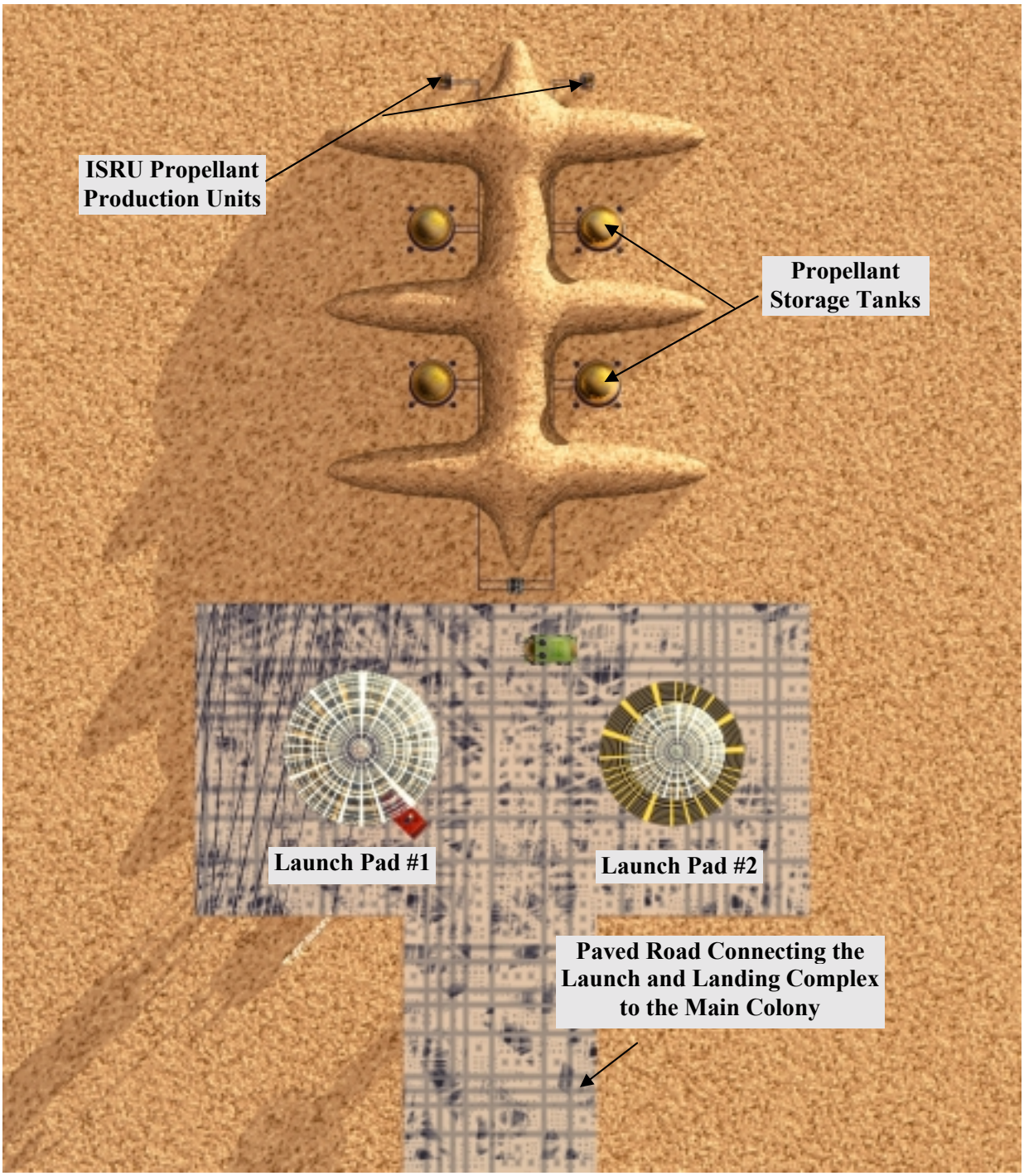

Figure 17. Launch and Landing Complex for the 100-Person Colony

4.3.2 Infrastructure Model for 100-Person Colony

The two major components in the infrastructure model are the habitat mass and the power system mass. According to the colony design and analysis discussed in the previous section, each colonist requires 1,215 m^3 of pressurized volume. The colony is expected to utilize inflatable structures to minimize the mass that must be sent from Earth. Based on previous inflatable module concepts (Nowak, et al, 1992;

Sadeh, et al, 1996; Rice, et al, 1998), a mass of 2.8 kg/m^3 is assumed for the structural mass. The crew systems mass is estimated at 1,833 kg/person and the other subsystems mass is estimated at 3,250 kg/person (Kennedy, 1992). The habitat power system requirements are based on a power estimate of 25 kW per person (Larson, Pranke, 2000). The power system mass is based on a modular SP-100 power system design with a 750 kWe output and a mass of 18,500 kg (Mason and Bloomfield, 1989). Multiple power systems are used to meet the power needs of the habitat. Table 5 shows the results of the infrastructure model. Note that the total infrastructure mass stays the same after Colony Cycle 5 where the population reaches its maximum (100 people).

Table 5. Infrastructure Model for 100-Person Colony

Colony Cycle	Years	Mars Surface Population			Total Habitat Mass (kg)	Habitat Power System* (kg)	Total Infrastructure Mass (kg)
		Transient	Perm.	Total			
0	<2040	20	0	20	158,279	18,500	176,779
1	2040-42	36	0	36	284,902	37,000	321,902
2	2042-44	52	0	52	411,525	37,000	448,525
3	2044-46	68	0	68	538,149	55,500	593,649
4	2046-48	84	0	84	664,772	55,500	720,272
5	2048-50	100	0	100	791,395	74,000	865,395
6	2050-53	100	0	100	791,395	74,000	865,395
7	2053-55	100	0	100	791,395	74,000	865,395
8	2055-57	100	0	100	791,395	74,000	865,395
9	2057-59	100	0	100	791,395	74,000	865,395
10	2059-61	100	0	100	791,395	74,000	865,395
11	2061-63	100	0	100	791,395	74,000	865,395
12	2063-66	100	0	100	791,395	74,000	865,395
13	2066-68	100	0	100	791,395	74,000	865,395
14	2068-70	100	0	100	791,395	74,000	865,395
15	2070-72	100	0	100	791,395	74,000	865,395
16	2072-74	100	0	100	791,395	74,000	865,395
17	2074-76	100	0	100	791,395	74,000	865,395
18	2076-79	100	0	100	791,395	74,000	865,395
19	2079-81	100	0	100	791,395	74,000	865,395
20	2081-83	100	0	100	791,395	74,000	865,395
21	2083-85	100	0	100	791,395	74,000	865,395
22	2085-87	100	0	100	791,395	74,000	865,395
23	2087-90	100	0	100	791,395	74,000	865,395

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

4.3.3 Infrastructure Model for 10,000-Person Colony

Table 6 shows the infrastructure model that was developed for the 10,000 person colony. The same analysis used for the 100-person colony was applied to this scenario. The total amounts of infrastructure for Colony Cycles 1-5 are the same for both scenarios. After Colony Cycle 5, the amount of infrastructure continues to increase along with the colony population.

Table 6. Infrastructure Model for 10,000-Person Colony

Colony Cycle	Years	Mars Surface Population			Total Habitat Mass (kg)	Habitat Power System* (kg)	Total Infrastructure Mass (kg)
		Transient	Perm.	Total			
0	<2040	20	0	20	158,279	18,500	176,779
1	2040-42	36	0	36	284,902	37,000	321,902
2	2042-44	52	0	52	411,525	37,000	448,525
3	2044-46	68	0	68	538,149	55,500	593,649
4	2046-48	84	0	84	664,772	55,500	720,272
5	2048-50	50	50	100	791,395	74,000	865,395
6	2050-53	325	325	650	5,144,068	407,000	5,551,068
7	2053-55	600	600	1,200	9,496,740	740,000	10,236,740
8	2055-57	875	875	1,750	13,849,413	1,091,500	14,940,913
9	2057-59	1,150	1,150	2,300	18,202,085	1,424,500	19,626,585
10	2059-61	1,425	1,425	2,850	22,554,758	1,757,500	24,312,258
11	2061-63	1,700	1,700	3,400	26,907,430	2,109,000	29,016,430
12	2063-66	1,975	1,975	3,950	31,260,103	2,442,000	33,702,103
13	2066-68	2,250	2,250	4,500	35,612,775	2,775,000	38,387,775
14	2068-70	2,525	2,525	5,050	39,965,448	3,126,500	43,091,948
15	2070-72	2,800	2,800	5,600	44,318,120	3,459,500	47,777,620
16	2072-74	3,075	3,075	6,150	48,670,793	3,792,500	52,463,293
17	2074-76	3,350	3,350	6,700	53,023,465	4,144,000	57,167,465
18	2076-79	3,625	3,625	7,250	57,376,138	4,477,000	61,853,138
19	2079-81	3,900	3,900	7,800	61,728,810	4,810,000	66,538,810
20	2081-83	4,175	4,175	8,350	66,081,483	5,161,500	71,242,983
21	2083-85	4,450	4,450	8,900	70,434,155	5,494,500	75,928,655
22	2085-87	4,725	4,725	9,450	74,786,828	5,827,500	80,614,328
23	2087-90	5,000	5,000	10,000	79,139,500	6,179,000	85,318,500

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

4.4 Traffic Models

4.4.1 Identification and Definition of Missions

Several potential classes of activities or missions were identified in Phase I and early in the Phase II project. The mission categories included the following:

- Scientific Exploration & Research (past life, current life, meteorology, atmospheric soundings – rockets, astronomy, geology, etc.)
- Commercial Exploration (water, minerals, metals, biochemistry, etc.)
- Terraforming (beginning experiments, and building with time accordance with a terraforming

program plan)
- Infrastructure Construction (habitats, buildings, stores, offices, ports, production facilities, roads, launch and landing ports, etc.)
- Agriculture/Farming (harvesting, animals, breeding, slaughter, food production)
- Manufacturing/Industrial Activities (product manufacturing, chemical processing, other industrial activities)
- Resource Mining (water from soil, oxygen, metals concrete, basalt, etc.)
- Weather/Environmental (station deployment, repair, satellite launch)
- Communications Navigation Services (station deployment, repair, satellite launch)
- Surveying/Mapping (airplane/balloon/satellite)
- Personal Transportation (job, school, shopping, living, vacation/sight-seeing, recreation/sports, etc.)
- 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 (oxygen, water, nitrogen, etc.)
- Waste/Trash Management (human wastes, farming wastes, manufacturing wastes, construction wastes, etc.)
- Health Care/Maintenance
- Virtual Travel Market.

The mission categories were examined to determine if those activities required ISRU-derived propellants for propulsion or power. The following four mission categories were identified as significant consumers of ISRU propellants:

- Scientific Missions
  - Search for Past/Present Life
  - Planetary Science
  - Mars Moon Studies
- Commercial
  - Resource Development
- Transportation
  - Human Transport Between Mars Surface and Orbit
  - Cargo Transport Between Mars Surface and Orbit
  - Ground/Surface Transportation
  - Flight Transportation
- Government
  - Law Enforcement
  - Search and Rescue
  - Medical Transport.

Specific missions were developed for each mission category. Mission definition sheets were used to describe each mission under each of the mission categories (see Appendix C). Figure 18 shows an example of a mission definition sheet. These sheets describe the mission, the mission frequency, number of crew required, mission duration, mission distance from a base, approximate travel time, payload, and vehicle type required. A mission reference number was assigned to each mission for easy identification.

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 Refernce Number	System Type Required
		Low		High								
		Year 1	Year 50	Year 1	Year 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
Note: Bold italicized entries in the frequency column indicate a quantity, not a frequency (for missions of indefinite duration)												

Figure 18. Example of a Mission Definition Sheet

A mission model for flight and ground vehicles was developed from the mission definition sheets. The mission model lists the number of trips required for each mission during each colony cycle period. It also lists the total number of trips required for each mission. The flight vehicle mission model for the 10,000-person colony scenario is shown in Figure 19. The flight vehicle mission model for the 10,000-person colony scenario is shown in Figure 20. Please refer to Appendix C to view all the mission models developed.

Mission Reference Number	Colony Cycle (one cycle is ~26 Earth months)																						
	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	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	8
4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4
7	5	5	5	5	5	5	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	6	6
10	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	8
13	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4
16	5	5	5	5	5	5	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	6	6
19	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
20	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
21	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
22	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23
23	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87
24	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
25	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
26	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
27	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
28	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	8
29	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4
32	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
36	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
37	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
39*																							
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
52	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
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.**																							

Figure 19. Flight Vehicle Mission Model for the 100-Person Colony Scenario

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

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).

Figure 20. Flight Vehicle Mission Model for the 10,000-Person Colony Scenario

4.4.2 Traffic Model for 100-Person Colony

After the flight vehicles were assigned to the individual missions, a traffic model was developed from the mission model. The number of trips in the mission model was multiplied by the mission duration to determine the number of mission-days required during each colony cycle. The missions were grouped by the general vehicle assigned. The net result of this activity was a complete traffic model for each general vehicle type. The minimum number of each vehicle type required for each colony cycle was calculated by dividing the total number of mission-days required for each vehicle type by the total number of hours available. This information was used as an input to the life and maintenance model. The life and maintenance model determines the total number of each vehicle type required during each colony cycle after factoring in vehicle lifetimes, maintenance requirements and fleet efficiency issues. Please refer to Appendix C for the 100-person colony traffic model.

4.4.3 Traffic Model for 10,000-Person Colony

After the flight vehicles were assigned to the individual missions, a traffic model was developed from the mission model. The number of trips in the mission model was multiplied by the mission duration to determine the number of mission-days required during each colony cycle. The missions were grouped by the general vehicle assigned. The net result of this activity was a complete traffic model for each general vehicle type. The minimum number of each vehicle type required for each colony cycle was calculated by dividing the total number of mission-days required for each vehicle type by the total number of hours available. This information was used as an input to the life and maintenance model. The life and maintenance model determines the total number of each vehicle type required during each colony cycle after factoring in vehicle lifetimes, maintenance requirements and fleet efficiency issues. Please refer to Appendix C for the 10,000-person colony traffic model.

5.0 TRANSPORTATION SYSTEM ANALYSIS

The overall objective of the transportation system analysis was to conceptually design a family of vehicles for each Propellant Family (PF) that can accommodate all missions identified by the Traffic Models (see Sections 4.4.2 and 4.4.3). They include hopper vehicles, ground vehicles, sounding rockets, unmanned airplanes, and balloons.

Specific objectives included:

- Design a fleet of vehicles that can accomplish all missions in the traffic model
- Investigate the effects of various mission options
- Determine the propellant requirements for each mission
- Calculate the overall vehicle dry mass
- Provide vehicle and component masses to the cost model
- Treat all propellant combinations fairly.

The sections that follow cover hopper vehicles, ground vehicles, sounding rockets, aeroplanes and balloons.

5.1 Hopper Vehicles

"Hopper Vehicles" collectively refers to all rocket-powered vehicles included in this study, with the exception of sounding rockets. They are used to transport people and supplies, for science and exploration missions, and for emergency rescue, from either one place to another on the surface or from orbit-to-surface or surface-to-orbit.

5.1.1 Requirements and Definition

The missions dictated by the traffic models (see Section 4 and Appendix C) for the two colony sizes were grouped according to the following parameters:

- Manned/unmanned
- Mission type
  - Surface-to-orbit, and orbit-to-surface
  - Base-to-base, or
  - Base-to-remote area and remote area-to-base
- Payload mass
- ΔV requirement.

The next step was to identify a fleet of vehicles that could collectively meet all these mission requirements. The goal of the fleet design process was to balance the total number of vehicle types required against efficient usage. For example, it would be uneconomical to use a vehicle with a 10,000 kg payload capability for several missions that transport only 10 kg. Alternatively, development and maintenance costs are driven up along with the total number of vehicle types. A total of six vehicle types were identified for the 10,000-person colony with the characteristics shown in Table 7.

Table 7. Characteristics of the Six Hopper Vehicle Types

Vehicle	Personnel Capability	Maximum Payload (kg)	Maximum ΔV (m/s)	Mission Type
HERMES	22	3300	3774	Base-to-base
EOS	robotic	10	4189	Base-to-base
IRIS	robotic	300	8378	Base-to-remote area
ARES	2	600	8378	Base-to-remote area
HYPERION	82	12,300	4360	Surface-to-orbit
ZEUS	robotic	383,000	4360	Surface-to-orbit

The hopper vehicle fleet was then evaluated against the 100-person colony traffic model, comprised of a subset, and reduced frequency of the missions required for the 10,000-person colony. The number of flight vehicle types was reduced from 6 to 3, where the vehicles IRIS, ARES, and HYPERION are used for all missions. The very low number of missions associated with EOS and HERMES in the 100-person colony scenario does not justify the development of two additional vehicles. Therefore, IRIS flies the missions previously accomplished by EOS in the 10,000-person scenario, and ARES flies the missions accomplished by HERMES (which do not require large numbers of personnel transport for the 100-person colony). The 82-person crew cabin on HYPERION was designed to be removable to allow inert cargo transport, replacing the heavy lifter used for the 10,000-person colony scenario (ZEUS). Without the crew cabin, the total payload accommodated by HYPERION increases to over 20,000 kg. During the first 5 colony cycles where the colony is growing, HERMES operates for up to a year downloading cargo from Mars orbit in preparation for next wave of people (for the 100-person colony).

A description of each vehicle and its function follows. As noted above, the missions described for EOS, HERMES, and ZEUS are flown by IRIS, ARES, and HYPERION, respectively, for the 100-person colony traffic model.

HERMES
Maximum people: 22
Maximum range: 5000 km one way

Nominally, HERMES is designed to transport personnel and cargo to and from a main base. The vehicle carries enough propellant to make a single ballistic hop from one base to the next, and refuels at the destination base for the return trip. The majority of the HERMES' missions are dedicated to disseminating the growing population and supplies from a main base to an outpost base. However, HERMES also serves a variety of government related missions such as rescue for emergency medical situations which require patient transport from a remote base to an established medical facility at a main base, criminal transport, and government personnel transport.

EOS
Maximum people: zero - robotic
Maximum range: 10,000 km one way

EOS is a highly instrumented one-way robotic surface hopper vehicle solely dedicated to collecting data during its flight. The information is used for scientific research, weather prediction/observation, and surface visualization/imaging. The vehicle obtains all its propellant from an established Martian base.

IRIS
Maximum people: zero - robotic
Maximum range: 10,000 km round trip (20,000 km total)

IRIS is a small robotic hopper that flies from an established base to a remote location up to 10,000 km away. Mission operations are completed during a 60-day period, during which time, in-situ resource utilization (ISRU) is applied to process the atmosphere into enough propellant for the return trip home (with the exception of PF1, which brings along all the propellant for the return journey). The vehicle is equipped with liquid hydrogen tanks if the propellant combination of interest is partially comprised of hydrogen (for return trip propellant manufacture; hydrogen is assumed to only be available at a base). All carbon and oxygen are directly obtained from the atmosphere. Applications for IRIS include: remote site sample collection, on-site testing, and extended observation at a remote location. Generally, IRIS is designed to address issues such as the search for past/present life, initial resource detection, and planetary science. IRIS is used for a substantial amount of science during the early colonization years and shifts more towards industrial applications as the colony grows.

ARES
Maximum people: 2
Maximum range: 10,000 km round trip (20,000 km total)

ARES is essentially the manned version of Iris. It flies from an established base to a remote location up to 10,000 km away. Mission operations are nominally completed during a 20-day period, during which time, in-situ resource utilization (ISRU) is applied to process the atmosphere into enough propellant for the return trip home (with the exception of PF1, which brings along all the propellant for the return journey). The vehicle is equipped with liquid hydrogen tanks if the propellant combination of interest is partially comprised of hydrogen (for return trip propellant manufacture; hydrogen is assumed to only be available at a base). All carbon and oxygen are directly obtained from the atmosphere. Applications for ARES include: remote site sample collection, on-site testing, and extended observation at a remote location. Generally, ARES is designed to address issues such as the search for past/present life, initial resource detection, and planetary science. This vehicle is used for a substantial amount of science during the early colonization years and shifts more towards industrial applications as the colony grows.

HYPERION
Maximum people: 82
Maximum range: shuttle between Mars orbit and Mars surface

HYPERION is dedicated to shuttling personnel to and from Mars orbit. The number of missions reflects a growing Mars population in addition to the dynamics of starting people on their journey home after their tour of duty on the Martian surface. HYPERION docks in Mars orbit where it receives and delivers personnel to a nuclear powered shuttle vehicle operating between Earth orbit and Mars orbit. HYPERION fuels at a main base and brings enough propellant up for the return landing, which relies on aerobraking.

ZEUS
Maximum people: zero – robotic cargo vehicle
Maximum range: shuttle between Mars orbit and surface

ZEUS is dedicated to shuttling cargo from Mars orbit down to the Mars surface. It flies up to orbit empty, and returns with a cargo of up to 386,000 kg. The number of missions reflects a growing Mars population requiring infrastructure, including: habitats, nuclear power systems, ISRU plants, construction equipment, liquid hydrogen (and oxygen for PF1), flight vehicles, and rovers. ZEUS docks in Mars orbit where it receives cargo from a nuclear powered shuttle vehicle operating between Earth orbit and Mars orbit. ZEUS fuels at a main base and brings enough propellant along for the return landing, which relies on aerobraking.

5.1.2 Analysis Codes

The hopper vehicle models consist of parametric correlations and engineering analysis which are linked together through the ΔV equation (also known as the ideal rocket equation). The software environment used for the analysis is Engineering Equation Solver (EES), which simultaneously solves all of the interrelated equations to arrive at the individual subsystems and overall vehicle size and mass.

Sources for the analysis include: internal estimates/analysis, papers and journal articles, books, and discussions with individuals. A Vehicle Design Ground Rules document, included as Appendix D, details the approach, assumptions, and sources for each area of the model, including:

- Miscellaneous systems (structures, aerobraking, attitude control, etc.)
- Propellant performance
- Propellant tanks
- Insulation, cooling, and thermal analysis
- Crew cabin and life support
- Thrust
- Combustion chamber and nozzle
- Propellant delivery
- ISRU, cryocooler, and power
- Hybrid engine and bi-propellant liquid engine characteristics.

There are four basic types of vehicles, summarized in Table 8. All vehicles employ a reusable aerobrake shell for landing. Two propulsion systems were analyzed for each vehicle type and propellant combination: hybrid and bi-propellant. An ORBITEC thermal analysis code is integrated into all hopper vehicle models to calculate the propellant tank radiant and convective heat leaks as a function of several parameters, including: tank size, propellant temperature, and insulation thickness.

Table 8. Hopper Vehicles Types

Vehicle Type	Function	Vehicle Names
One-way surface hopper	Fly between established bases on the surface	HERMES, EOS
Roundtrip surface hopper	Fly out to remote areas and return back to base	IRIS, ARES
Personnel shuttle	Shuttle people to and from a 500-km Mars docking orbit	HYPERION
Cargo shuttle	Deliver cargo from a 500-km orbit down to the Martian surface	ZEUS, HYPERION (for 100-person colony)

The one-way hopper vehicles carry along enough propellant to get from one base to the next, where they refuel for the next hop. The shuttle vehicles also carry along all of the propellant for their mission; they do not refuel in orbit. The only exception to this approach is for PF1, which uses all terrestrial propellants. In this case, the vehicle launches from the surface with only enough propellant to dock in orbit, where it is then filled up for the landing portion of the mission. The capacity of the cargo shuttle vehicles (ZEUS for the 10,000-person colony and HYPERION for the 100-person colony) are based on

launching with an empty payload bay, which is then filled in orbit before landing back on the surface.

An artistic rendering of the HYPERION shuttle vehicle using LCO/LOX as the propellant is shown in Figure 21. All of the major components (personnel module, combustion chambers/nozzles, and propellant tanks) are drawn to scale; Table 9 lists the key dimensions.

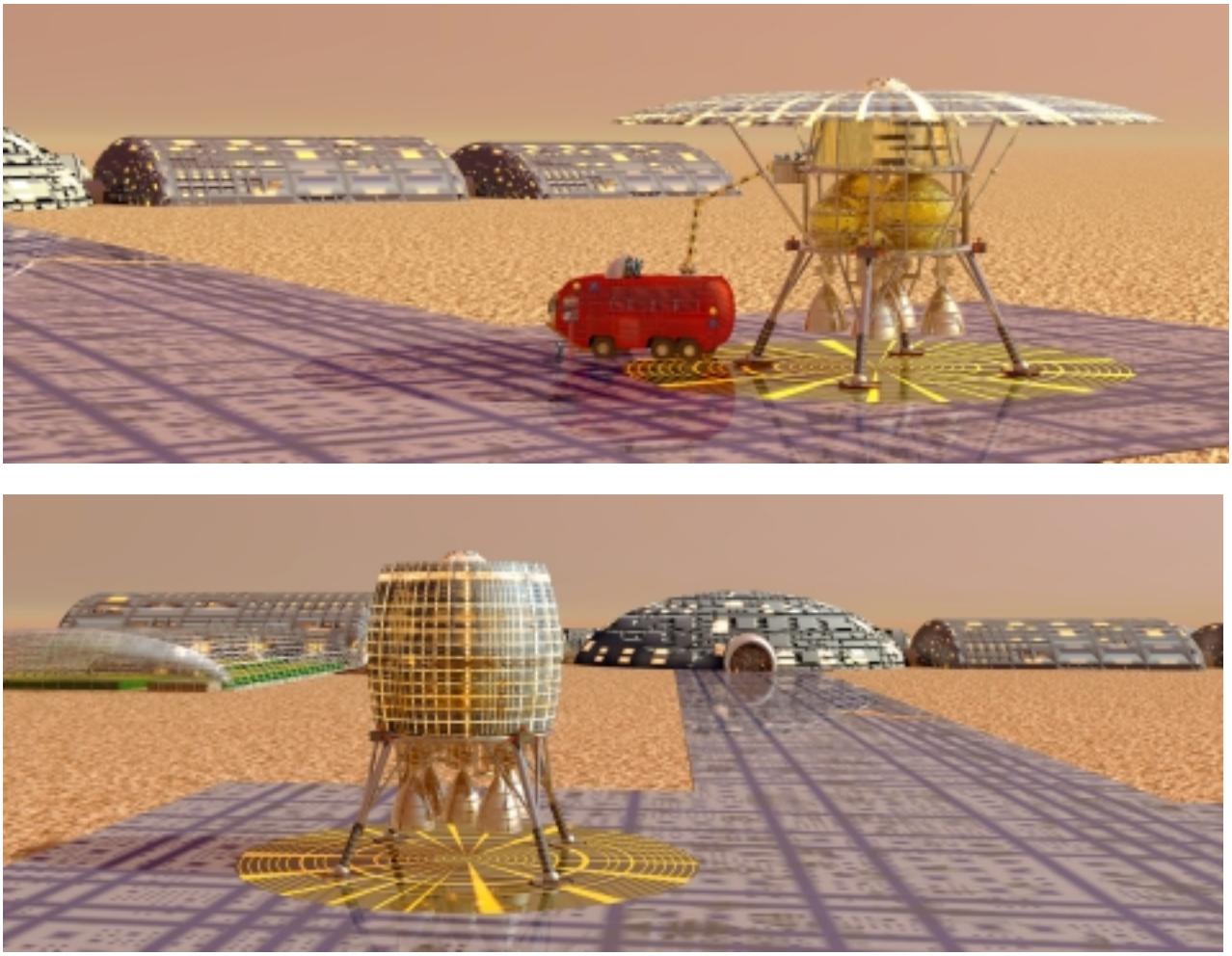

Figure 21. Artistic Rendering of HYPERION for PF6-LCO/LOX on the 100-Person Colony Landing Pad Top View: Personnel Unloading from Vehicle Bottom View: Aeroshell in Closed Position

A few additional elements are required for the roundtrip vehicle models. These vehicles fly out to a remote location and either bring along all of their propellant for the return trip, or an ISRU propellant processing system. Hydrogen is assumed to be available only at the bases, and so it must be brought along for return trip propellant processing, if required by the propellant family.

Table 9. Characteristic of HYPERION for PF6-LCO/LOX

Number of Engines	5
Nozzle Exit Diameter (AR = 200)	2.3 m
LCO Tank Diameter (2 required)	5.1 m
LOX Tank Diameter (2 required)	3.7 m
Personnel Cabin Volume	246 m^3

The roundtrip vehicles utilize power beaming, where large microwave antennas built into the aerobrake and electronics systems accept and condition energy beamed to them from a constellation of orbiting nuclear power satellites. None of the propellant combinations (except for PF1) can accomplish all of the IRIS or ARES missions if they have to carry along all of their propellant for the return trip, or a nuclear power reactor for propellant processing. Thus, power beaming enables these two vehicles to use all of the propellant combinations in the study by greatly reducing the mass of the onboard power system (reduced to a receiver, conditioner, and distribution network). The ramifications of this assumption are discussed under "Sensitivity Analysis" in this report.

The roundtrip vehicles also carry along cryocoolers for propellant liquefaction, required for both ISRU production and handling boiloff. There is a tradeoff between the mass of the insulation (thickness) and the refrigeration system. The cryogenic tank insulation thickness was parametrically varied while solving for the overall vehicle mass. The insulation thickness which resulted in the minimum total vehicle mass was selected for each propellant family and roundtrip vehicle type. Figure 22 is an artistic rendering of ARES using PF12-LCH_4/LOX (also equivalent to PF11-LCH_4/LOX). Figure 23 shows another view of the 100-person landing area with both HYPERION and ARES, and a mobile robotic fueling station on the pad. The propellant storage tanks and ISRU processors are shown in the background.

The top-level hopper vehicle model input is shown in Table 10 and an example of the model output for both hybrid and bi-propellant systems using PF6 is show in Table 11. A mass summary of each hopper vehicle for all propellant families is included in Appendix E.

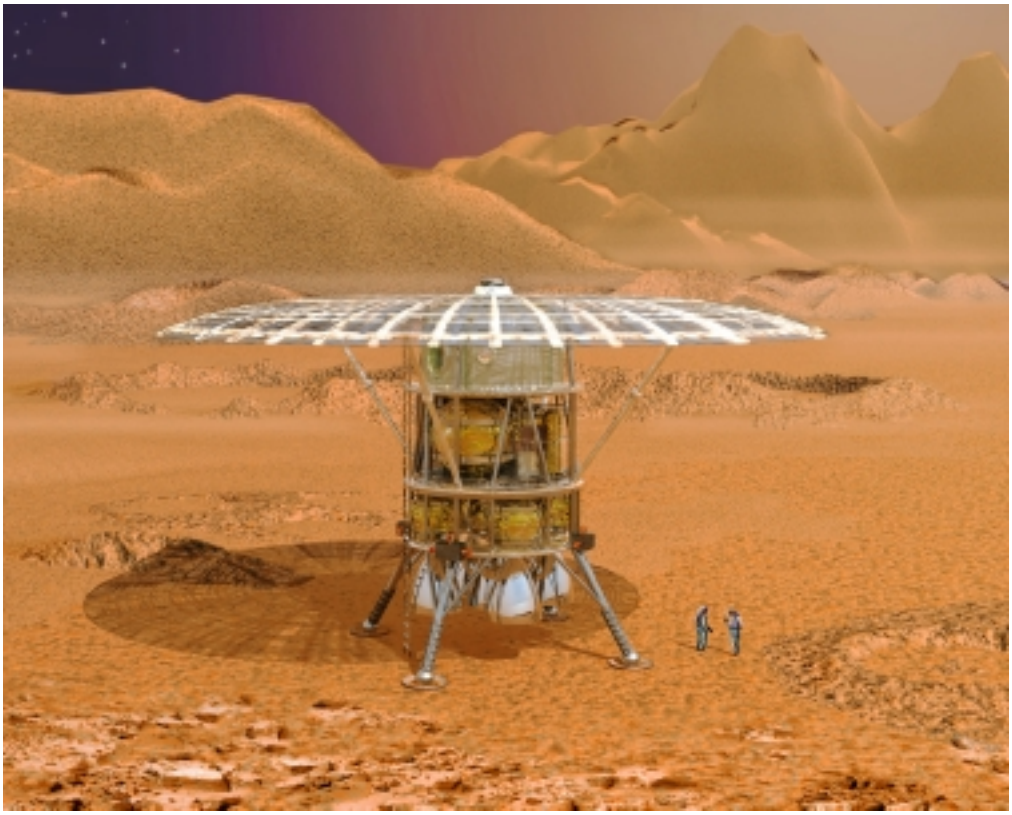

Figure 22. Artistic Rendering of ARES for PF12-LCH$_4$/LOX

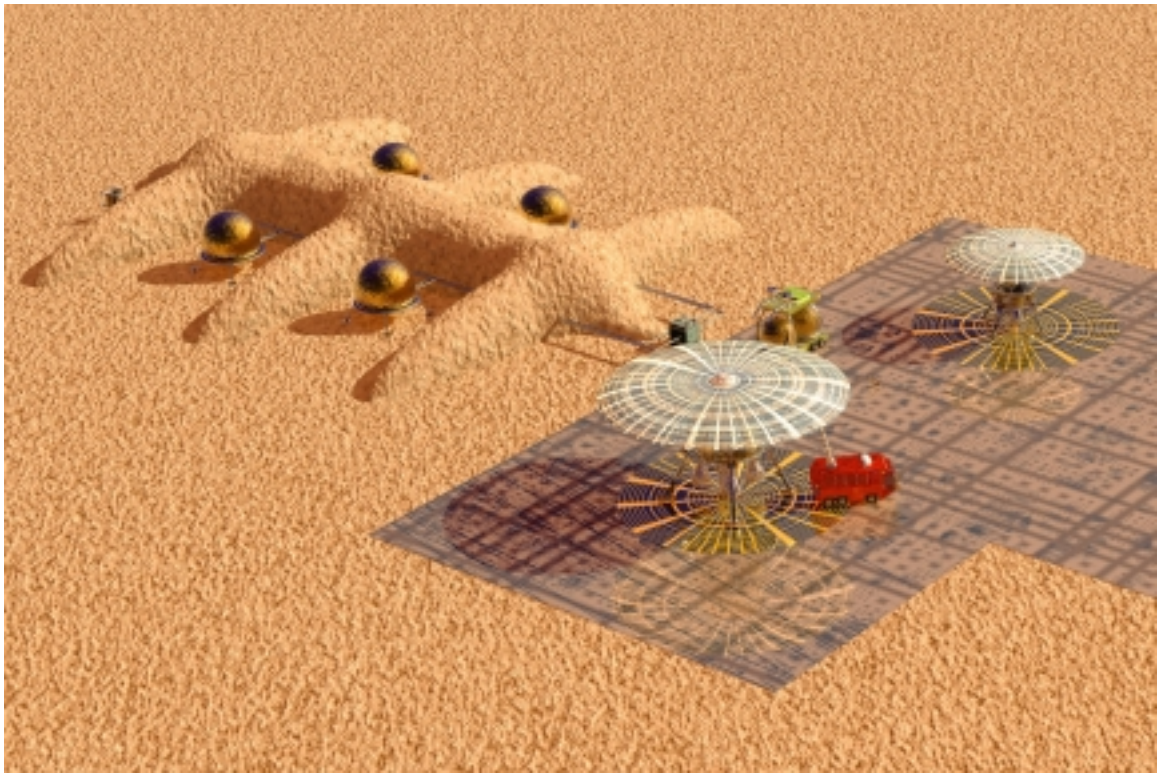

Figure 23. Vehicle Landing Area for 100-Person Colony

Table 10. Hopper Vehicle Model Input

Propellant Characteristics	Mission Requirements
Specific Impulse	Duration
Characteristic Velocity	ΔV
Mixture Ratio	Cargo
Physical Properties	Personnel
Mass Percent Hydrogen[1]	
ISRU Processor Parametrics[1]	

[1]For roundtrip vehicles only

Table 11. ARES Hopper Vehicle Characteristics for Two Propellant Families

Vehicle: ARES two person ISRU roundtrip hopper vehicle		
Propellants	PF6-SCO/LOX	PF6-LCO/LOX
P_c (psia)	300	1000
I_{SP} (sec)	279.7	285.6
Engine Type	hybrid	bi-propellant
Reserve Propellant (%)	3.5	3.5
Thrust to Weight	2	2
Engine Mass[1]	438	766
Engine Thrust to Weight2	189	101
Oxidizer Tank Mass	144	184
Fuel Tank/Grain Case Mass	692	346
Structure Mass	4062	3964
Crew cabin Mass	5981	5981
Space suit mass	100	100
Consumables mass	709	709
Cryocooler Mass	1330	1232
Power Systems Mass	1326	1255
ISRU Plant Mass	1652	1579
Avionics Mass	60	60
Electon. Thermal Control Mass	60	60
Aerobrake and Landing Mass	3456	3365
Attitude control Mass	237	231
Payload Mass	500	500
Payload/Wet Mass (%)	0.46	0.48
Dry Mass/Wet Mass (%)	19.0	19.7
Total Propellant Mass	88,569	82,878
Wet Mass	**109,316**	**103,210**

[1]Does not include grain case mass for hybrids
[2]Engine mass includes: turbomachinery, propellant feed lines, chamber, and nozzle (does not include grain case for hybrids)
All masses in kg.

5.1.3 Results

The wetmass for each vehicle and propellant family is shown in Figures 24 through 29. The results for the shuttle and one-way vehicles (HERMES, EOS, HYPERION, and ZEUS) are similar. The SCO/LOX vehicles are relatively massive by comparison, all H_2/O_2 vehicles are among the lightest, and the remaining propellant families are slightly heavier than the H_2/O_2 ones, with very little variation among them. In general, there is little difference between the hybrid and liquid vehicle masses for a given propellant family.

Note that the wetmass shown for ZEUS in Figure 29 reflects the empty cargo bay at launch; the vehicle actually lands heavier than when it took off (this is possible through the use of aerobraking during the decent).

The results for the roundtrip vehicles (IRIS and ARES) are much different. There are two additional variables that come into play for these systems which vary considerably from one propellant family to the next: (1) the need to haul along a given percent of the return propellant in the form of hydrogen, if hydrogen is required for that propellant family and (2) the mass efficiency of the propellant processor. The CH_4/O_2 propellant families yield the lightest vehicles where the hybrid and liquid systems are lightest for IRIS and ARES, respectively. The liquid vehicles for PF1 are orders of magnitude heavier than the others due to the requirement of bringing along all propellant for the return trip, and the hybrid version is not capable of completing the missions. Although SCO/LOX has a relatively low I_{SP}, it is comparable to the other systems because it does not have to bring along any hydrogen for the return trip. The C_2H_4/O_2 propellant families suffer from heavy propellant processors.

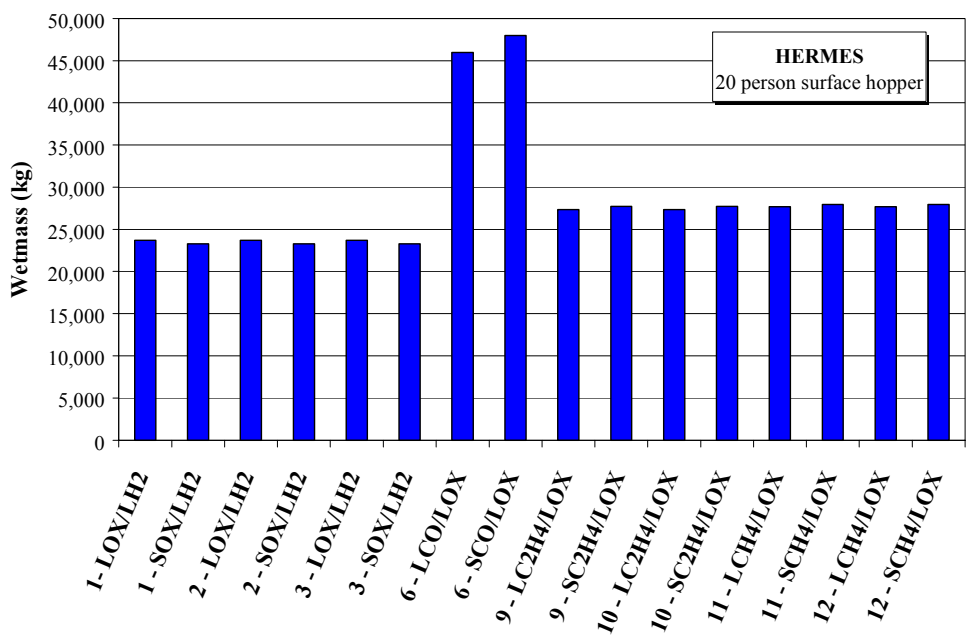

Figure 24. Fully-Loaded Wetmass for Vehicle HERMES for Propellant Families

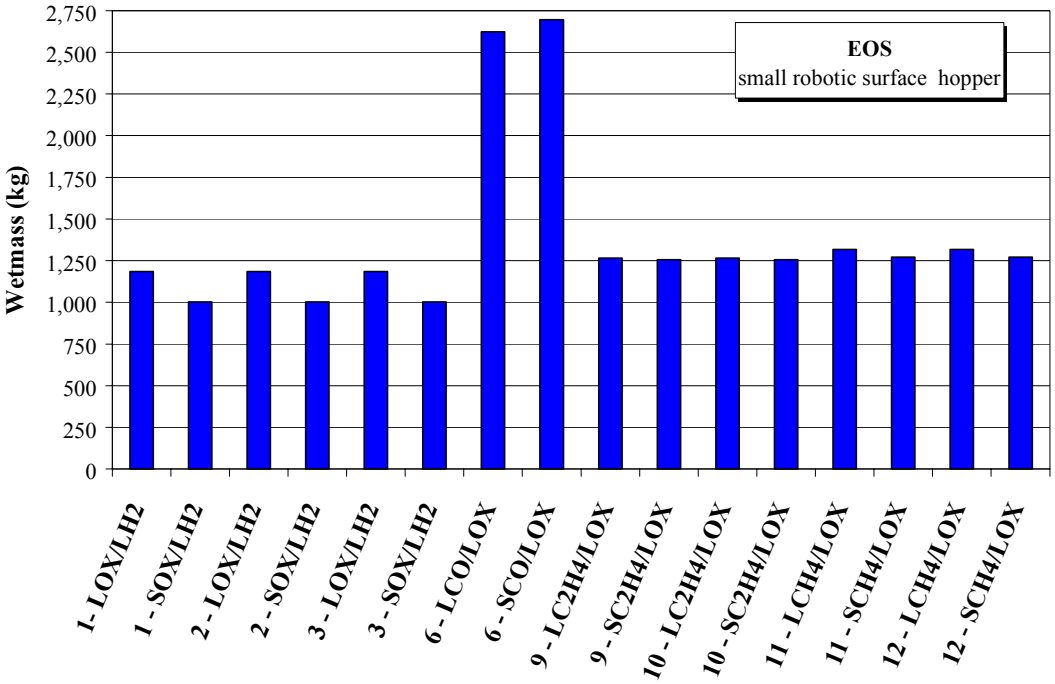

Figure 25. Fully-Loaded Wetmass for Vehicle EOS for Propellant Families

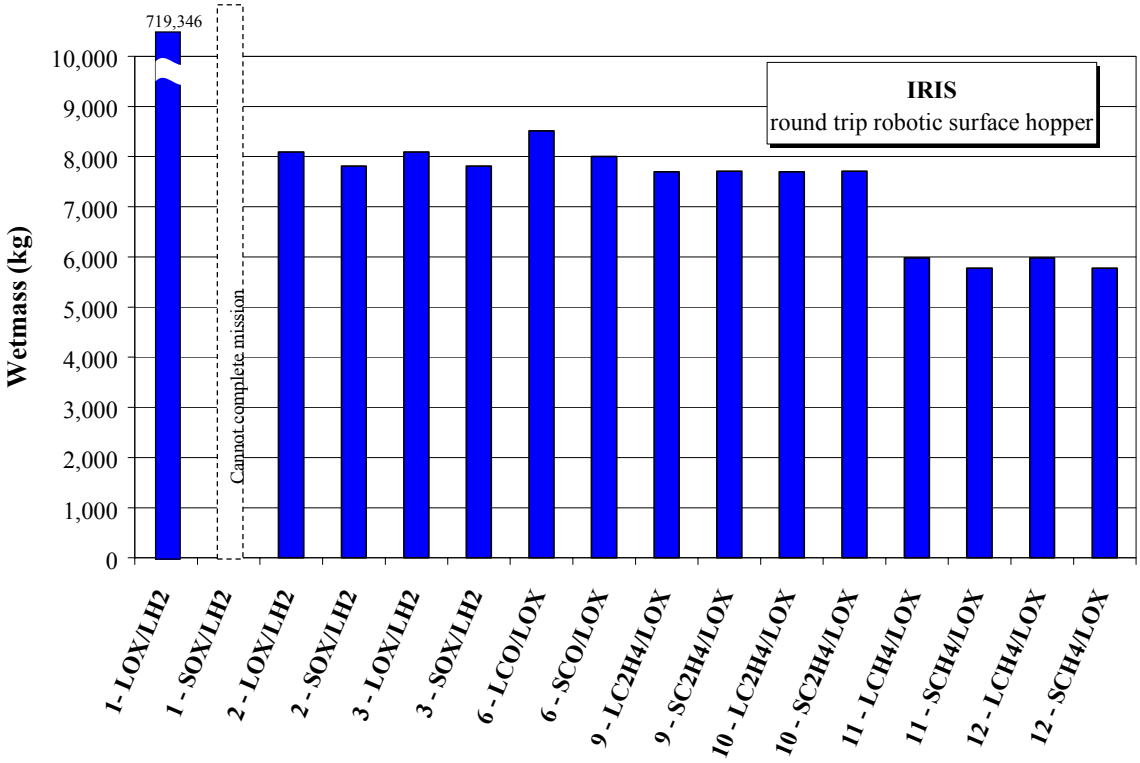

Figure 26. Fully-Loaded Wetmass for Vehicle IRIS for Propellant Families

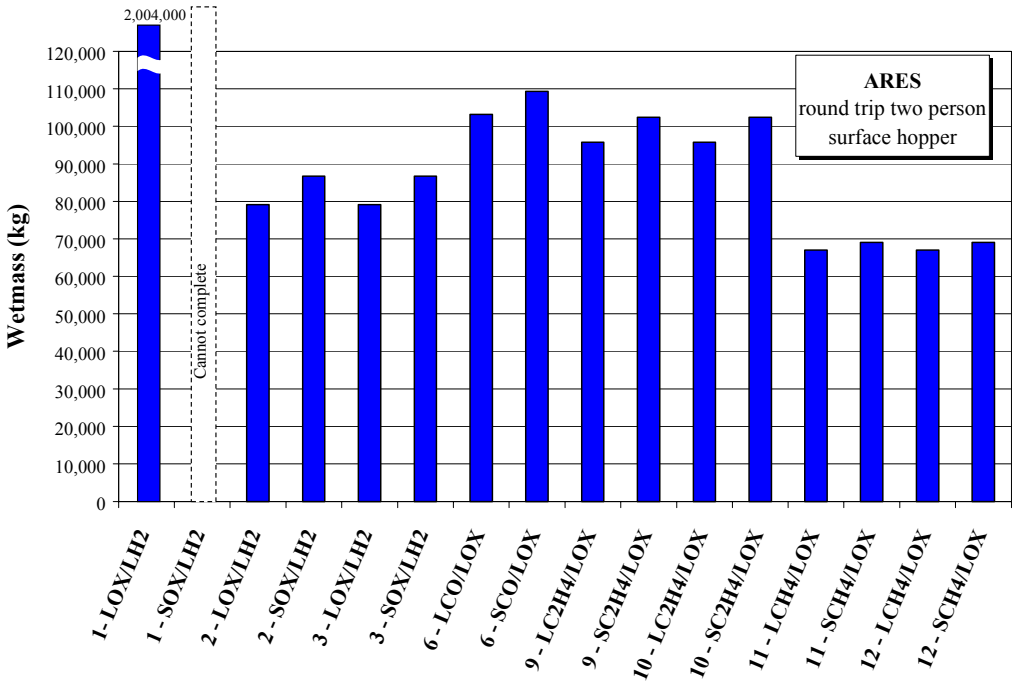

Figure 27. Fully-Loaded Wetmass for Vehicle ARES for Propellant Families

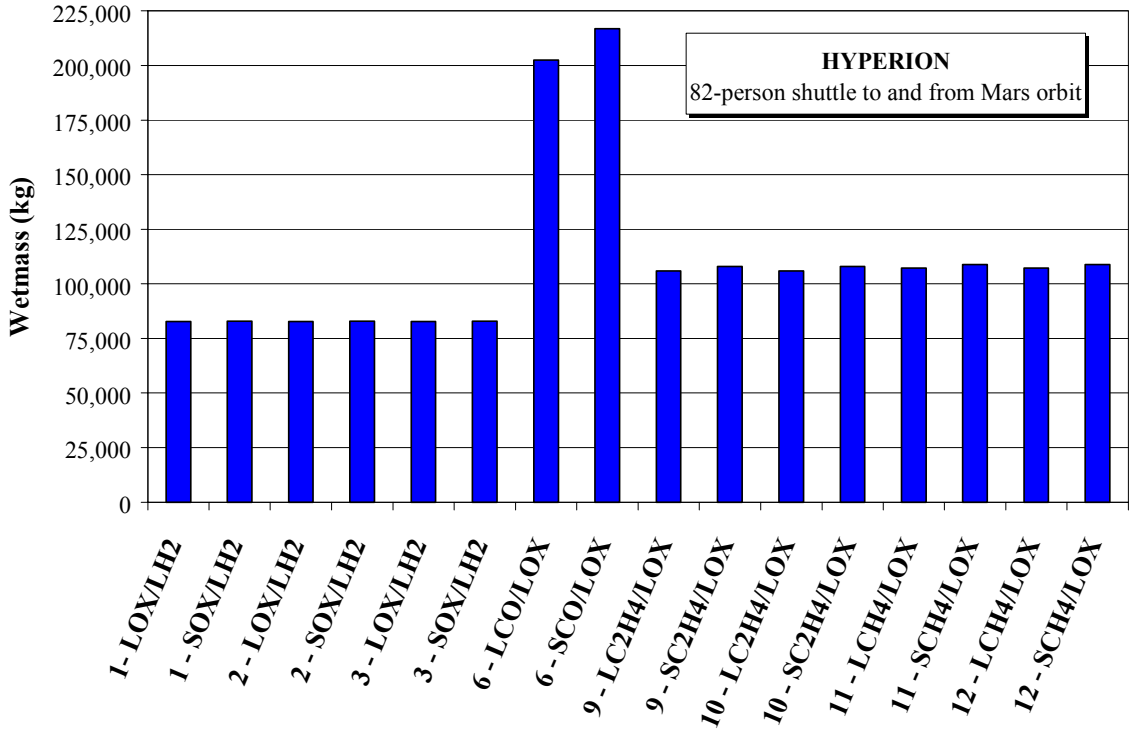

Figure 28. Fully-Loaded Wetmass for Vehicle HYPERION for Propellant Families

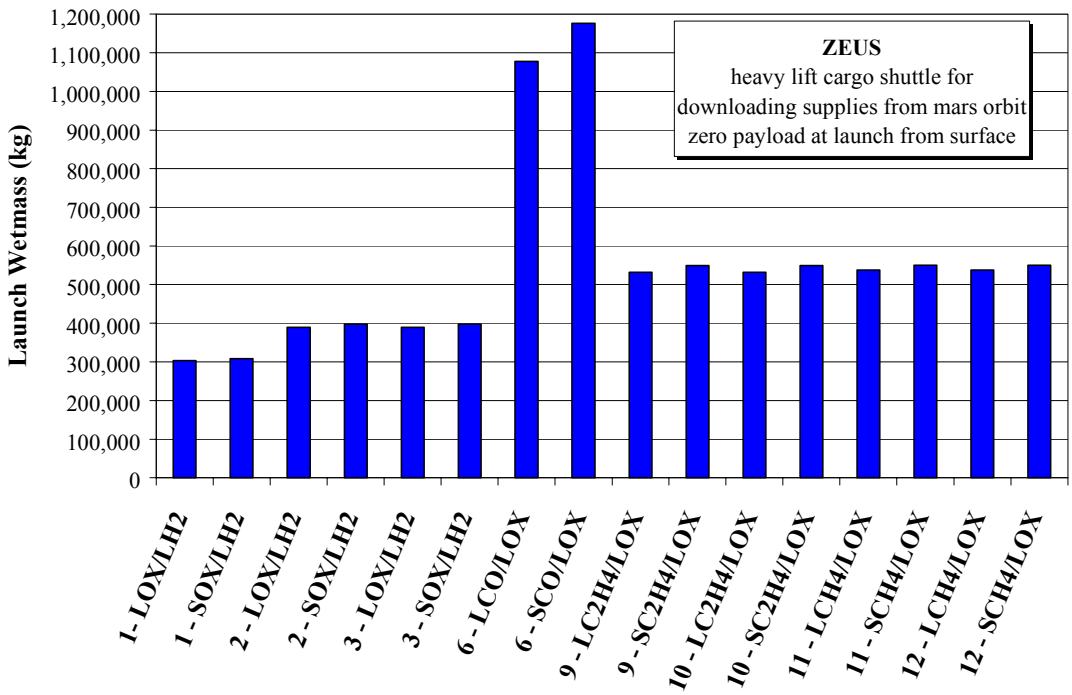

Figure 29. Wetmass for Vehicle ZEUS for Propellant Families

A missions analysis model was developed to calculate the total propellant and hydrogen required to complete each mission in the traffic model, for each propellant family. It accepted the following as input:

- Mission characteristics (payload, ΔV, number of people, duration, etc.)
- Vehicle drymass for the given propellant family
- Propellant characteristics for the given propellant family (I_{SP}, mixture ratio, percent hydrogen).

Sample results are shown in Figure 30 for PF6-LCO/LOX for the 100-person colony, and results for all propellant families and missions are included in Appendix F. The propellant requirements for each mission along with the traffic model were used to establish the total propellant consumption as a function of the colony cycle, propellant family, and engine type (hybrid or liquid). This information was used to calculate the total propellant processing, hydrogen, and power plant masses required as a function of the colony cycle.

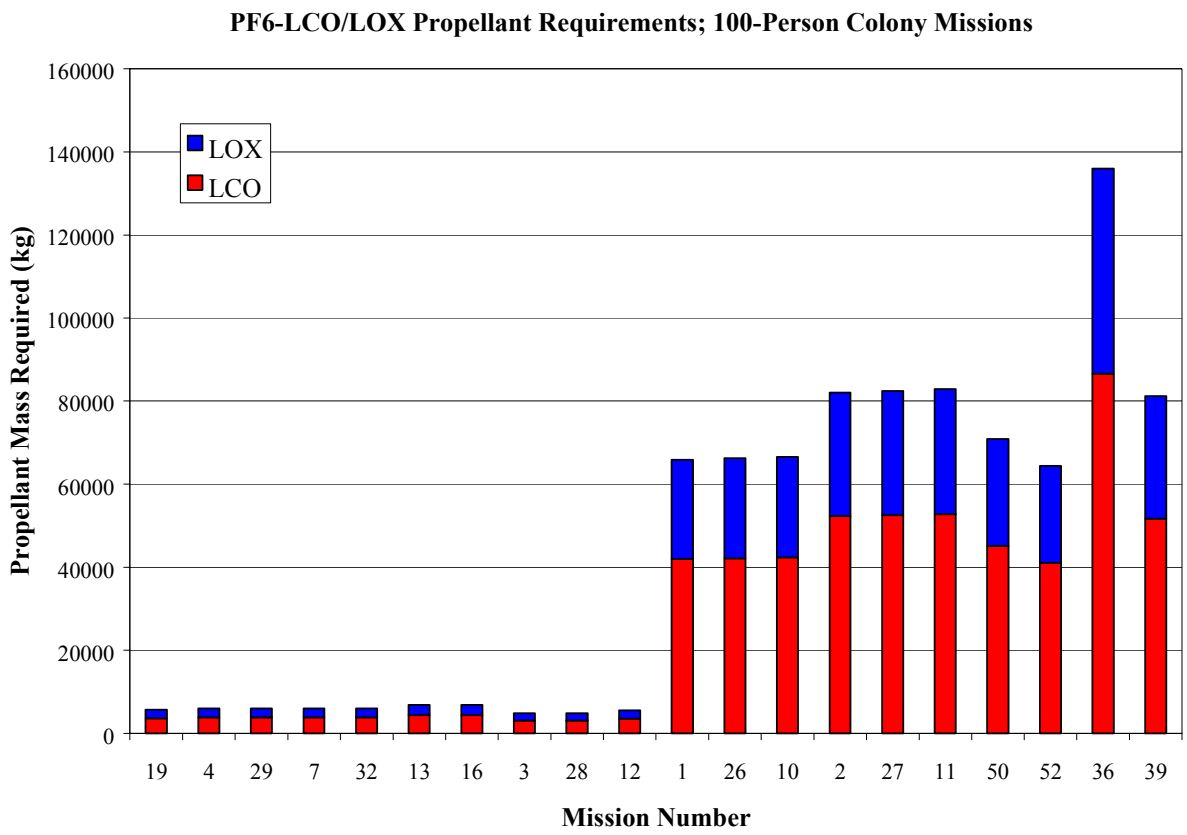

Figure 30. Single Mission Propellant Requirements for PF6-LCO/LOX; 100-Person Colony

5.1.4 Maintenance and Fleet Efficiency

The hopper vehicles are assumed to have a useful life of 500 flights, and are unavailable 25% of the time due to maintenance and logistics issues. Additionally, a minimum of two vehicles are required to be on hand at all times. Interfacing these ground rules with the traffic model mission frequencies and durations yields the hopper vehicle fabrication and delivery requirements as a function of the colony cycle. The results are show in Tables 12 and 13 for the 100 and 10,000-person colonies. The higher number of the IRIS vehicles required for both scenarios reflects its long mission duration of 60 days. The total number of vehicles required for the 100-person colony is about half that required for the 10,000-peson colony. There are two reasons the number of vehicles aren't proportional to the population. First of all, the number of flight missions dictated by the traffic model are not proportional to the population, and second, the vehicles in the 100-person colony are used less frequently then in the 10,000-person colony (due, in part, to the requirement of a minimum of 2 vehicles on hand at all time). A similar analysis was conducted for the vehicle engines, which were replaced after every 50 flights.

Table 12. Hopper Vehicle Requirements for 100-Person Colony

Colony Cycle	Flight Vehicle Type		
	IRIS	ARES	HERMES
1	4	2	2
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	1	0	0
13	0	0	0
14	1	0	0
15	0	0	0
16	0	0	0
17	0	0	0
18	0	0	0
19	0	0	0
20	0	0	0
21	0	0	0
22	1	0	0
23	1	0	0
Totals	**8**	**2**	**2**

Table 13. Hopper Vehicle Requirements for 10,000-Person Colony

Colony Cycle	Flight Vehicle Type					
	HYPERION	EOS	IRIS	ARES	HERMES	ZEUS
1	2	2	4	2	2	2
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	1	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	2	0	0	0
11	0	0	0	0	0	1
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0	0	0	0	0
15	0	0	0	0	0	0
16	0	0	1	1	0	0
17	1	0	0	0	0	0
18	0	0	1	0	0	0
19	0	0	0	0	0	0
20	0	0	0	0	0	0
21	0	0	0	0	0	0
22	0	0	1	0	0	0
23	0	0	0	0	0	0
Totals	3	2	10	3	2	3

5.2 Ground Vehicles

Ground vehicles are similar to terrestrial trucks. They are the most fuel efficient mode of getting around on the red planet, and are therefore the backbone of the Martian transportation system. They are used to transport people and supplies, and for science and exploration missions.

5.2.1 Requirements and Definition

The missions dictated by the traffic models for the two colony sizes were grouped according to the following parameters:

- Manned/unmanned
- Mission characteristics:
  - Speed
  - Distance
  - Duration
  - On/off road
- Cargo mass.

The next step was to identify a fleet of vehicles that could collectively meet all these mission requirements. Similar to the hopper vehicles, the goal of the fleet design process was to balance the total number of vehicle types required against efficient usage. A total of four vehicle types were identified for the 10,000-person colony with the characteristics shown in Table 14. HYGEIA is designed to transport people between bases on established roads, and all other vehicles are capable of off-road travel.

Table 14. Ground Vehicle Characteristics

Name	Range (km)	Max Cargo Mass (kg)	Personnel Capability	Function
TYCHE	2000	300	0	Light duty robotic rover
ZEPHYRUS	2000	5000	0	Heavy duty robotic rover
SELENE	1000	525	7	Multi-use manned vehicle
HYGEIA	1000	1650	22	Personnel transport vehicle

For the 10,000 person colony, HYGEIA was used to transport people between bases and is not required for the single base 100-person colony. The remaining three ground vehicles are unique and cannot be consolidated into a smaller number. In addition, a small nuclear powered robotic rover with a cargo capacity of 50 kg was designed to autonomously explore the Martian surface (GAMMA).

5.2.2 Ground Vehicle Analysis Codes

The ground vehicle models consist of parametric correlations and engineering analysis which are linked together through power and mass relations. The software environment used for the analysis is Engineering Equation Solver (EES), which simultaneously solves all of the interrelated equations to arrive at the individual subsystems and overall vehicle size and mass.

Sources for the analysis include: internal estimates/analysis, conference papers, books, and discussions with individuals. A Vehicle Design Ground Rules document, included as Appendix D, details the approach, assumptions, and sources for each area of the model, including:

- Power
- Propellant Performance
- Base Vehicle
- Propellant Tanks
- Insulation, Cooling, and Thermal Analysis
- Crew Cabin and Life Support.

The option of making propellants on the fly for some propellant combinations was investigated. It was found that less than 1% of the ground vehicle missions are of long enough duration to process adequate propellant for the mission. Accordingly, this option was not pursed further. It was decided to store spent propellant onboard the rovers and reprocess it at a main base for further use, rather than exhausting it as it was produced. Analysis was conducted to investigate the effects of exhausting CO_2 to the atmosphere as it is produced (as a product of the rover fuel cell reaction). These effects were found to be small, ever for LCO/LOX (which produces all CO_2 as exhaust).

Characteristics of the four propellant combinations analyzed for the ground vehicles are listed in Table 15. All ground vehicles are driven by a fuel cell powered electric motor, and carry along enough propellant to complete their entire mission. All fuel cell products are stored onboard the vehicle and later recycled at the destination base. Each vehicle has an onboard cryocooler (powered by the fuel cells) to re-liquefy propellant boiloff. Fuel economy for off-road missions is four times lower than those that travel on packed roads between bases.

Table 15. Ground Vehicle Propellant Properties

Propellant	Delivered Energy Density (J/kg)	Fuel Cell Mass (kg/kW)	Mixture Ratio	Products (% by mass)
H_2/O_2	9,450,000	2.5	8	H_2O: 100
CH_4/O_2	7,056,000	2.5	4	H_2O: 45, CO_2:55
CH_3OH/O_2	5,365,500	2.5	1.5	H_2O: 45, CO_2:55
CO/O_2	4,591,000	2.5	0.57	CO_2: 100

As an example, a few of the correlations used in the ground vehicle model are shown here. The rover base vehicle mass (BVM) is defined as the mass of the vehicle excluding: the power system, tanks, propellants, cryocooler, crew cabin, life support, consumables, personnel, space suits, and the cargo. The gross vehicle mass (GVM) is the total fully loaded mass of the vehicle. The relation used to calculate the BVM is displayed in Figure 31. Note that this correlation is independent of the propellant combination. The relation used to correlate the electric motor mass and power output is shown in Figure 32.

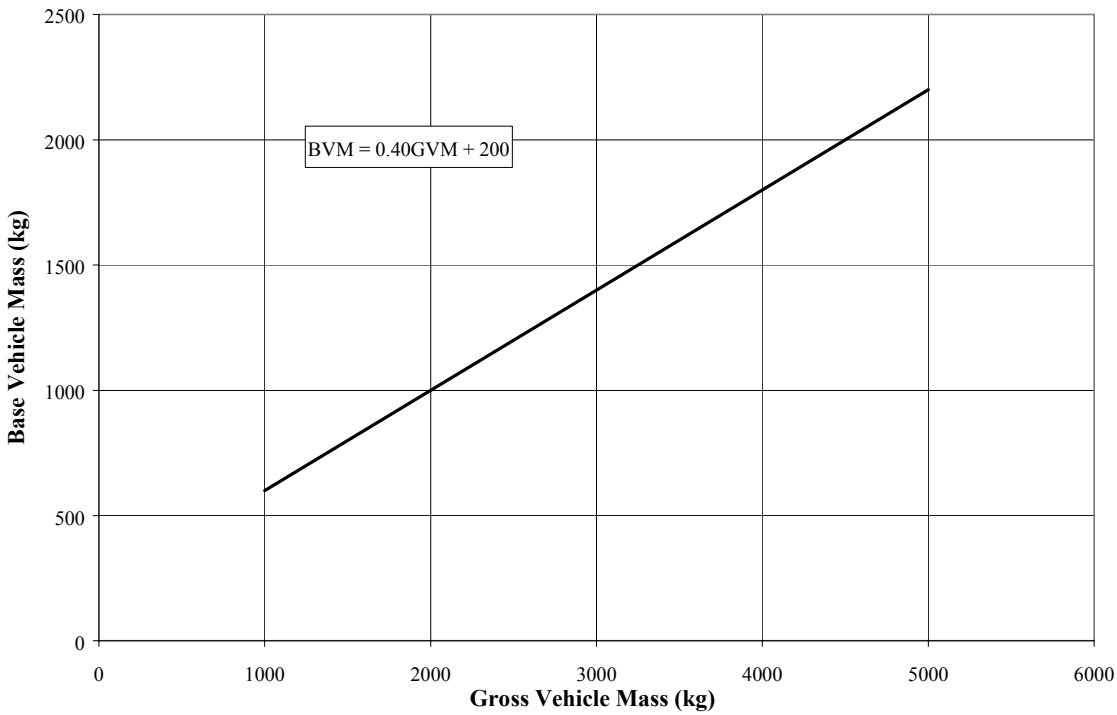

Figure 31. Base Vehicle Mass vs. Gross Vehicle Mass

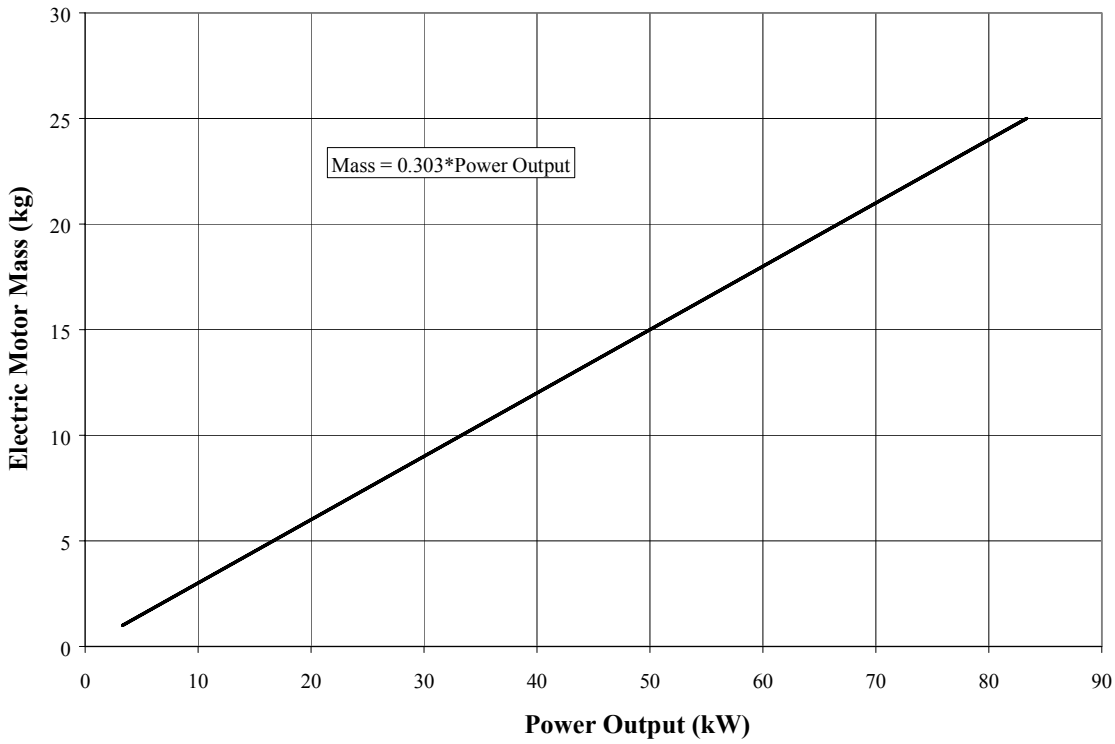

Figure 32. Electric Motor Mass vs. Power Output

The top-level ground vehicle model input is shown in Table 16 and an example of the model output for SELENE is given in Table 17.

Table 16. Ground Vehicle Model Input

Propellant Characteristics	Mission Requirements
Energy Density	Speed
Physical Properties	Trip Distance
Mixture Ratio	Trip Duration
Fuel Cell Characteristics	Personnel
Mass Percent Hydrogen	Cargo
	Road Quality

Table 17. Ground Vehicle Model Output for SELENE

Vehicle: SELENE multi-use manned ground vehicle		
Propellants	LCO/LOX	LCH_4/LOX
Propellant Energy Density (J/kg)	4,591,000	7,056,000
Power Supply	fuel cell	fuel cell
Reserve Propellant (%)	10	10
Maximum Number of People	7	7
Base Vehicle Mass	4053	3802
Fuel Cell Mass	96	90
Oxidizer Tank Mass	13	16
Fuel Tank Mass	23	13
Exhaust Propellant Tanks Mass	22	17
Crew Cabin Mass	3328	3328
Space Suit Mass	350	350
Cryocooler Mass	8	5
Electric Motor Mass	12	11
Mass People	525	525
Other Consumables	124	124
Cargo Mass	175	175
Total Propellant Mass	904	549
Fully Loaded Vehicle Mass	**9633**	**9005**

5.2.3 Results

Because none of the propellant is manufactured en route, the ground vehicle designs are only dependant on the propellant combination, and are not affected by the propellant source (ISRU/terrestrial) or specific propellant family. Figures 33 through 36 show the wetmass for each of the four vehicle types and propellant combinations. In sharp contrast to the hopper vehicles, the ground vehicle wetmass is not sensitive to the mass-based propellant performance. For example, even though LCO/LOX has a delivered energy density less than half that of LH_2/LOX, the vehicle wetmass for both are similar. The difference in vehicle size among the propellant combinations is further closed as they get larger, where the propellant mass becomes an increasingly smaller fraction of the overall vehicle mass.

GAMMA, the autonomous nuclear-powered ground vehicle, has a total mass of 450 kg.

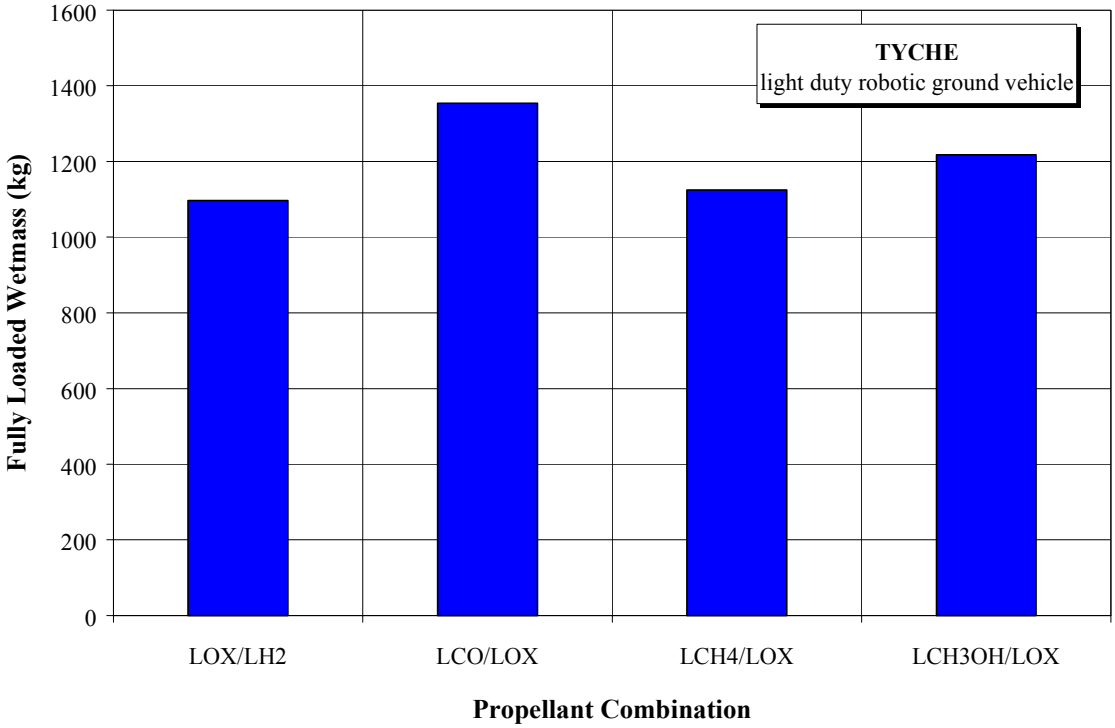

Figure 33. Fully-Loaded Vehicle Wetmass for TYCHE

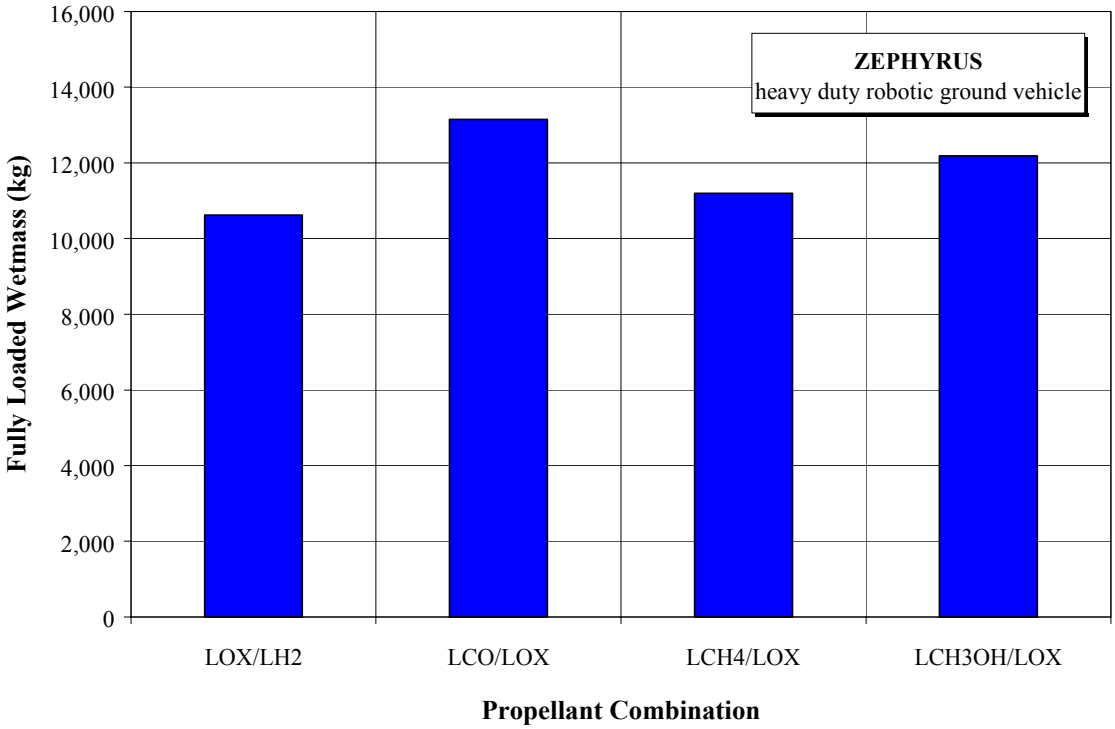

Figure 34. Fully-Loaded Vehicle Wetmass for ZEPHYRUS

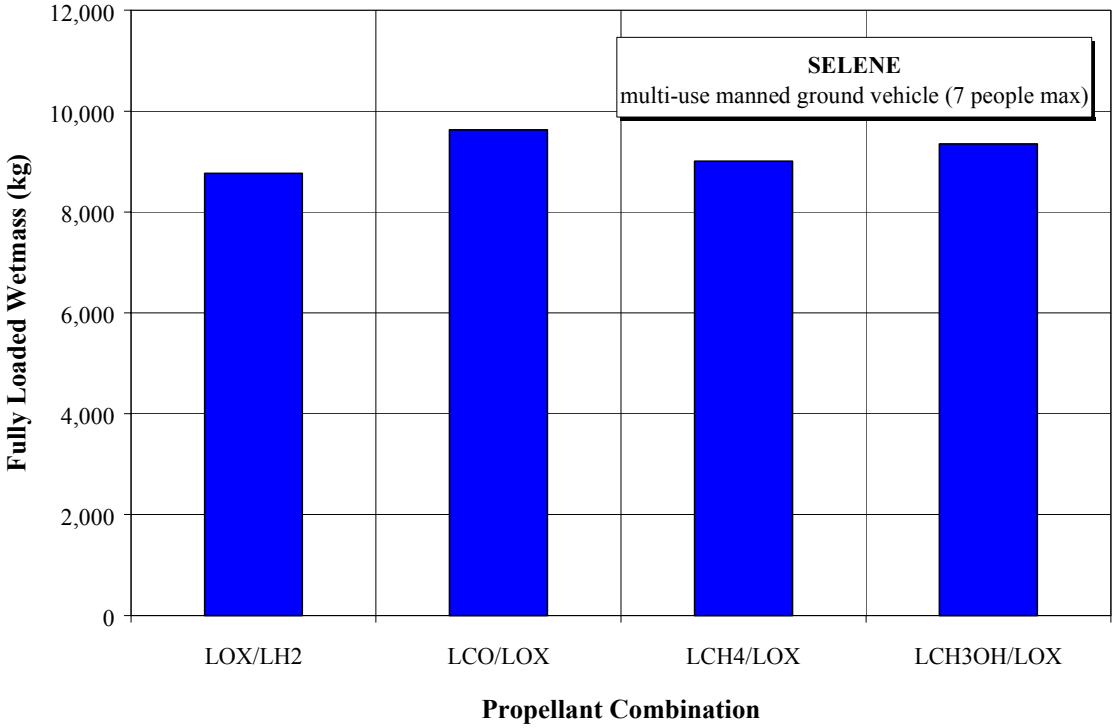

Figure 35. Fully-Loaded Vehicle Wetmass for SELENE

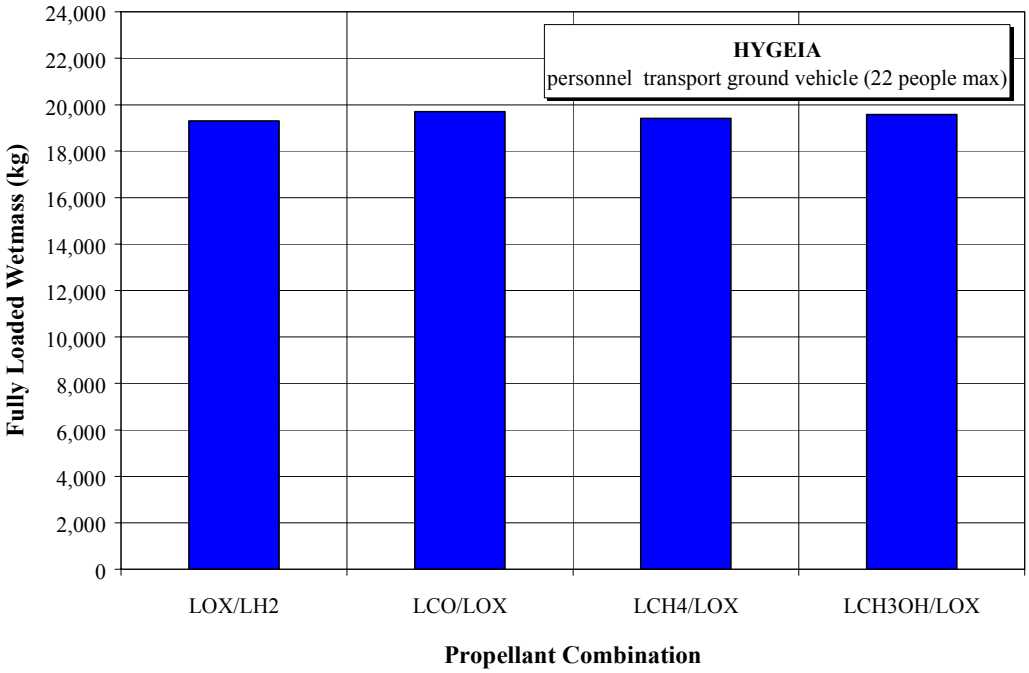

Figure 36. Fully-Loaded Vehicle Wetmass for HYGEIA

A missions analysis model was developed to calculate the total propellant and hydrogen required to complete each mission in the traffic model. It accepted the following as input:

- Mission characteristics (cargo, distance, duration, number of people, road quality, etc.)
- Vehicle drymass for the given propellant combination
- Propellant characteristics (energy density, mixture ratio, percent hydrogen).

The propellant requirements for each mission along with the traffic model were used to establish the total propellant consumption as a function of the colony cycle and propellant family. This information was used to calculate the total propellant processor, hydrogen, and power plant masses required as a function of the colony cycle. Results for all missions in the 10,000-person colony scenario are shown in Figures 37 through 40. Unlike the vehicle wetmass, the propellant mass required for a given mission varies significantly among the propellant combinations. Another factor in propellant use is the road quality, where off-road missions require approximately four times more propellant to travel a given distance than those traveling between the bases on packed roads. The highest propellant consumption is for a long distance, off-road heavy-duty robotic rover mission (Mission 35).

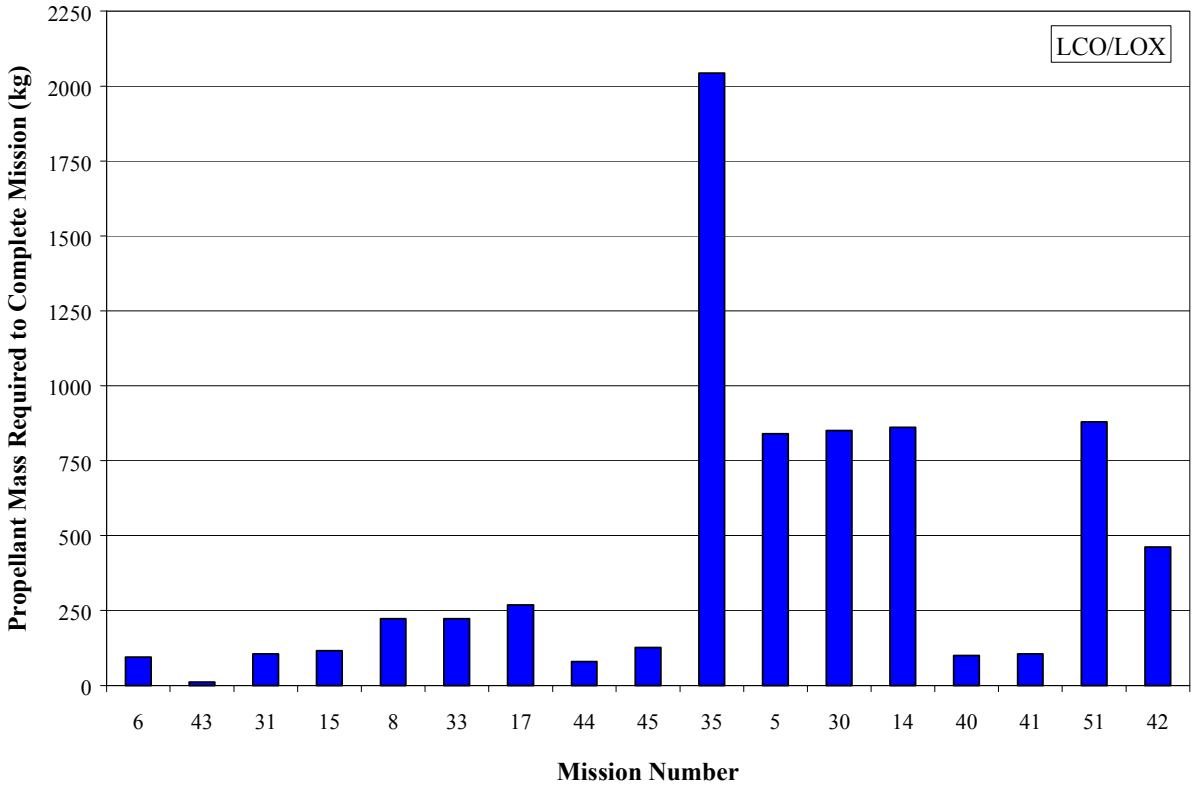

Figure 37. Propellant Requirements for Ground Missions, LCO/LOX

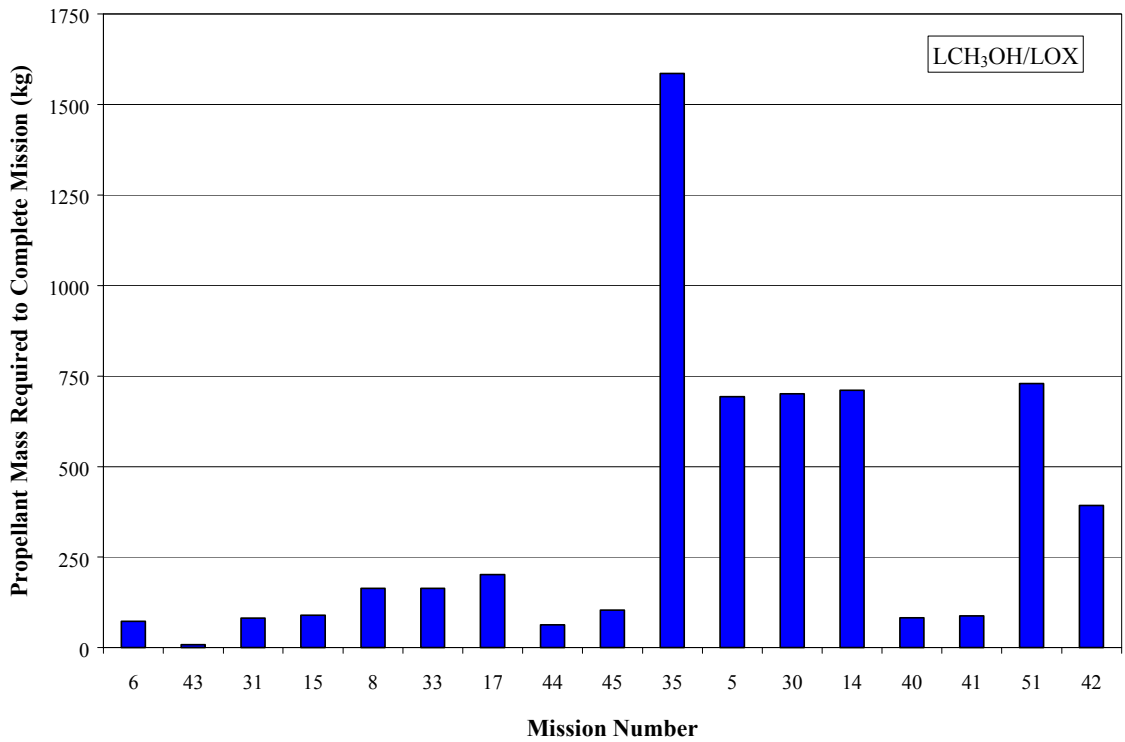

Figure 38. Propellant Requirements for Ground Missions, LCH_3OH/LOX

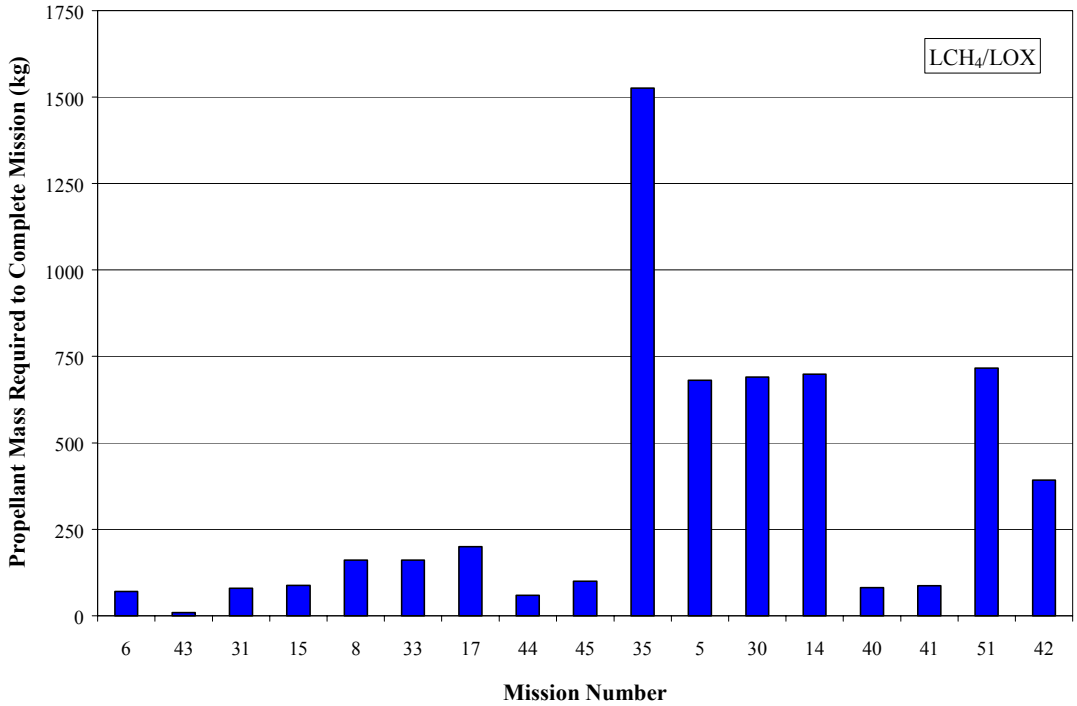

Figure 39. Propellant Requirements for Ground Missions, LCH_4/LOX

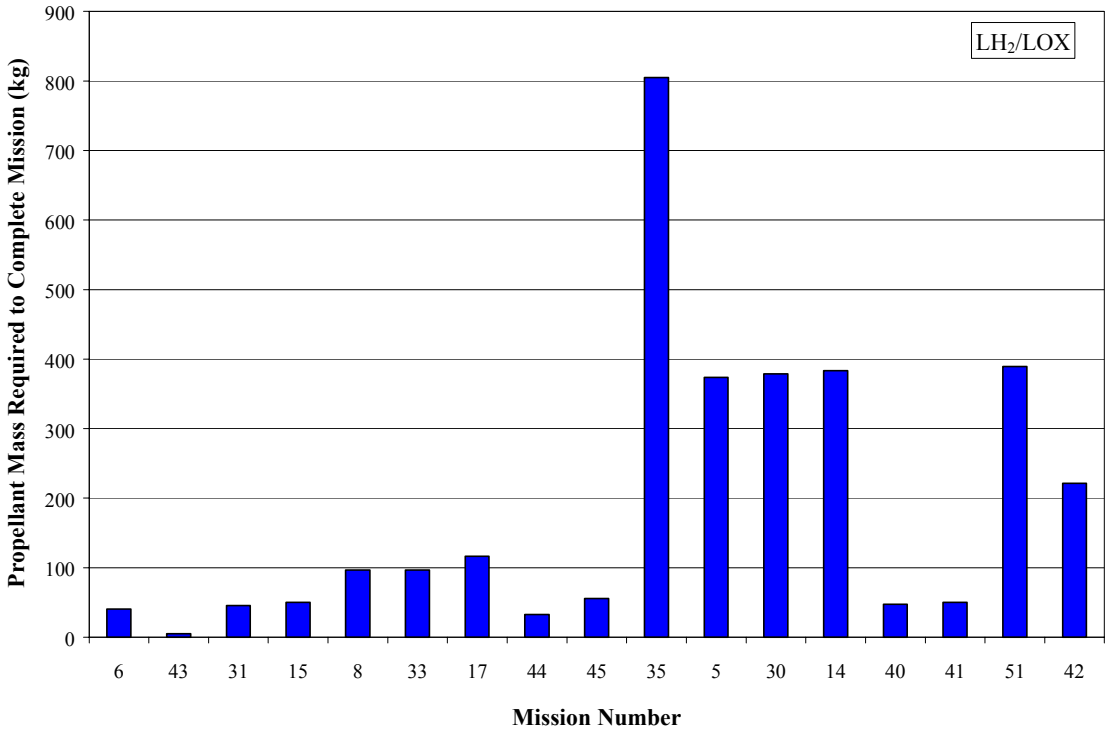

Figure 40. Propellant Requirements for Ground Missions, LH_2/LOX

5.2.4 Ground Vehicle Maintenance and Fleet Efficiency

The ground vehicle traffic model was used to establish the total distance traveled by each vehicle type and the amount of time each vehicle type is in use per colony. This information was used to complete the ground vehicle maintenance and replacement model. Assuming that each vehicle has a useful life of 160,000 km and that it is unavailable 25% of the time due to maintenance and logistics issues, Tables 18 and 19 list the vehicle delivery requirements as a function of colony cycle to meet the demand dictated by the traffic model. The majority of these vehicles are replacements for those that have worn out.

Table 18. Ground Vehicle Shipment Requirements; 100-Person Colony

Colony Cycle	Ground Vehicle Type			
	TYCHE	SELENE	ZEPHYRUS	GAMMA
1	2	2	1	1
2	0	1	0	1
3	1	1	0	1
4	0	1	0	2
5	0	1	0	1
6	1	1	0	1
7	0	0	0	1
8	0	1	0	2
9	1	1	0	1
10	0	0	0	1
11	0	1	0	2
12	1	0	0	1
13	0	1	0	1
14	0	0	0	1
15	0	1	0	2
16	0	0	0	1
17	1	1	0	1
18	0	0	0	2
19	0	0	0	1
20	0	1	0	1
21	0	0	0	1
22	0	0	0	2
23	1	0	0	1
Totals	**8**	**14**	**1**	**29**

Table 19. Ground Vehicle Shipment Requirements; 10,000-Person Colony

Colony Cycle	Ground Vehicle Type			
	TYCHE	ZEPHYRUS	SELENE	HYGEIA
1	2	2	2	0
2	0	0	1	2
3	1	1	2	0
4	1	2	1	0
5	1	2	1	0
6	1	3	1	1
7	1	4	2	0
8	2	3	1	1
9	1	5	2	1
10	2	5	2	0
11	2	6	2	1
12	2	6	1	1
13	2	7	2	1
14	3	7	2	1
15	3	7	3	2
16	3	9	2	1
17	2	9	2	1
18	3	9	2	2
19	3	9	3	1
20	4	11	2	2
21	3	11	3	2
22	3	11	3	1
23	4	12	3	2
Totals	**49**	**141**	**45**	**23**

5.3 Sounding Rockets

Sounding rockets were analyzed and included in the 100-person colony results. Propellant consumption for the sounding rocket is trivial relative to the rest of colony operations. In this vein, the type of propellant used for the sounding rocket would have little effect on the total colony cost. A representative SCO/LOX sounding rocket was designed for the 100-person colony scenario and added to the total cost. The sounding rocket climbs to a height of 60 km above the surface, assuming an angle of attack of up to 45 degrees. LOX is pressure fed into the grain case using a high-pressure helium source. A top-level mass breakdown for the system is shown in Table 20. Four expendable sounding rockets are launched per year for the 100-person colony, resulting in a total requirement of 92 over the colony lifetime. It was clear that sounding rockets would have a negligible cost for the 10,000-person colony, so they were not integrated in to the 10,000-person colony results.

Table 20. Sounding Rocket Mass Summary

Component	Mass (kg)
Dry Mass	3.67
Propellant	2.89
Payload	2.00
Total:	8.56

5.4 Mars Aeroplanes (Aerocraft)

Unmanned Mars aeroplanes were analyzed and incorporated into the 100-person colony results. Twenty-three unmanned aeroplane missions are required for each colony cycle in the 100-person colony scenario. The aeroplane design is summarized in Table 21 and is loosely based on a detailed Mars aeroplane design study conducted by David Hall Consulting (Hall, et. al., 1997). This study provided estimates for the coefficient of lift, wing mass per surface area, and structure mass ratio. An electric motor is powered by a fuel cell and an onboard cryocooler prevents propellant boiloff (using the same correlations developed for the ground vehicles, discussed in the Vehicle Design Ground Rules Document, Appendix D). The planes are designed to refuel at the main base and have a maximum sortie range of 5000 km from the base. A mass summary for the different propellant combinations is shown in Figure 41. It was clear that Mars aeroplanes would have a negligible cost for the 10,000-person colony, so they were not integrated in to the 10,000-person colony results.

Table 21. Mars Aeroplane Characteristics

Power Supply	Fuel cell
Payload Mass	4 kg
Cruising Speed	110 m/s
Cruising Altitude	5 km
Maximum Roundtrip Range	10,000 km
Propeller Efficiency	80 %
Electric Motor Efficiency	95 %
Full-Range Trip Time	25.3 hours

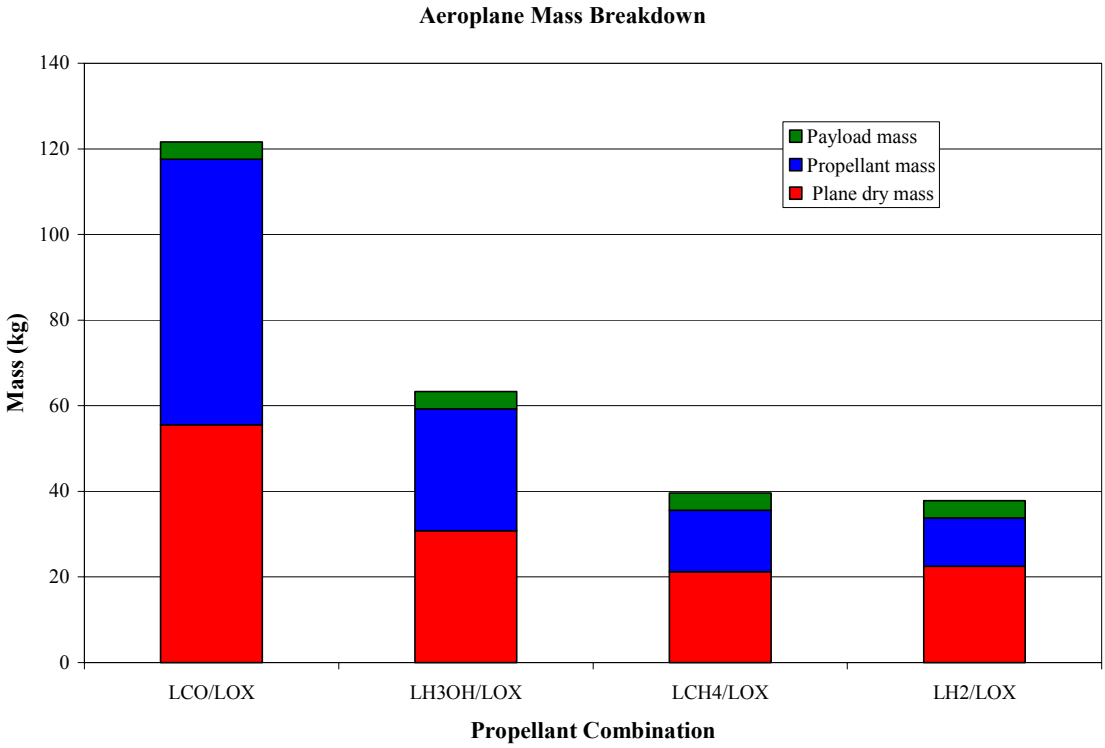

Figure 41. Unmanned Aeroplane Mass Summary for Different Propellant Combinations

5.5 Balloons

Weather balloons were analyzed and incorporated into the 100-person colony results. The traffic model for the 100-person colony calls for a total of 93 weather and atmospheric probe balloon missions per colony cycle. The balloons are assumed to have a mass of 4 kg and are expendable. The balloons design is not specific to any propellant family, but is included as a part of the overall cost of the 100-person colony. It was clear that balloons would have a negligible cost for the 10,000-person colony, so they were not integrated in to the 10,000-person colony results.

6.0 PROPELLANT PRODUCTION REQUIREMENTS

Propellant production/requirements were calculated using the vehicle traffic model and resulting propellant use requirements. These calculations include sufficient storage capability for refueling given the traffic model. Propellant production plants were designed or taken from existing literature and scaled to a pre-determined unit size. Power requirements were included in this analysis in addition to a spare parts contingency and the continuous loss of some propellants through fugitive emissions. Combining these factors generates a per-cycle requirement of propellant production units, power units, propellant storage tanks, and replacement parts to be delivered from orbit. Further calculations are then required for the orbital download vehicle to include the additional propellant load for these orbital download missions. This results in an iterative process until a final solution is obtained for the total propellant requirements of the colony.

6.1 Propellant and Power Plant Correlations

Propellant plants were defined using both in-house estimates and information available in published sources. For each propellant family, existing production processes were researched to determine the lowest mass and most energy efficient system capable of producing the propellants in a reasonable O/F ratio. A finite modular unit size of 6000 kg was set to provide a baseline for shipping requirements and to allow for a stepwise expansion in production capability. Since existing plant design concepts were for demonstration-sized units or for small colony scenarios, these systems had to be scaled up to produce a 6000-kg baseline unit and provide the production rates necessary for this study's colony operations. A parametric scaling factor was developed to account for the mass savings inherent in the use of larger chemical equipment. The scaling factor was calculated by examining existing process equipment and the mass savings associated with the increases in production rate due to scale-up. The parametric equation used is given in Equation 1. For example, assume the production rate is doubled (I=2). Then, the new plant mass would be 1.61 times the production plant mass. The scaling factor results in a nearly 20% reduction in the mass of the plant.

$$M = pI^{0.6871} \qquad (1)$$

M – New Plant Mass
p – Production Plant Mass
I – Production Increase

Cryocooler subsystem estimates were developed from industry data. A comparison of flight-weight cryocoolers determined that, on a Watt/kg basis, the most efficient cooler is the Brayton Cycle, followed by the Stirling Cycle and the pulse tube cooler, for the required production rates. A parametric equation was developed for Brayton cooler sizing and is included in the 6000-kg propellant production unit. The parametric equation used to scale the Brayton Cycle cryocooler is given in Equation 2.

$$M = 0.4817\, Q^{0.8} \qquad (2)$$

M = Cryocooler Mass
Q = Energy Required to Cool Propellant

A breakdown of each propellant production system is given in Table 22. These systems are for propellant production only, and are scaled-up to the 6000-kg unit size including the cryocooler masses.

Table 22. Propellant Production Systems and Their Sources

Propellant Family	Oxidizer/Fuel	Process Selected	Reference
1	Oxygen/Hydrogen	Water from Earth/Electrolysis	Green, et.al, 1999
2 & 3	Oxygen/Hydrogen	Zirconia Electrolysis/Hydrogen	Green, et.al, 1999
6	Oxygen/Carbon Monoxide	Zirconia Electrolysis	Green, et.al, 1999
9 & 10	Oxygen/Ethylene	Fischer-Tropsch Direct Reduction	Rosenberg, et.al, 1999
11 & 12	Oxygen/Methane	Sabatier with Methane Pyrolysis	Green, et.al, 1999

A sample spreadsheet calculation for a baseline methane production unit is given in Figure 41. This spreadsheet includes the propellant processor, cryocooler, and compressor masses in addition to the total power requirements for constant operation. Compressor masses and power requirements needed to compress the Martian atmosphere to the one-atmosphere inlet pressure were developed using data from Green, et. al., (1999). These mass and power requirements were included in the production plant mass and were then scaled with the unit to the 6000-kg baseline size. The process information for the small-scale flight system is given in the right-most columns. This information is then used in addition to the cryo-cooler correlation and physical property data to scale-up the entire production system. The left columns give the fuel and oxidizer production and surplus amounts in addition to the energy requirements for the large-scale system. The assumptions on operational parameters including downtime, propellant cooling energy requirements, and fugitive emissions are added later in the propellant production model.

Sabatier with Methane Pyrolysis Process						Small-Scale Process Data		
Oxidizer Produced:	Oxygen							
Fuel Produced:	Methane					Reactor Mass:	30.1	kg
						Energy Consumption:	2.26	kW
Combustion Process and Requirements						Operational Hours/Day:	24.0	hrs/dy
Process:	Sabatier with Methane Pyrolysis					Power Consumption/Day:	54.3	kWh/dy
Required O/F Ratio:	3.7							
Fuel Required:	2961	kg/dy				Oxidizer Type:	Oxygen	
Oxidizer Required:	10954	kg/dy				Mass Oxidizer/Day:	6.02	kg/dy
						Oxidizer Liquefaction:	4.74	W/kg
Required Production Values						Oxidizer Cryocooler Mass:	821	kg
Plant and Cooling Mass:	6000	kg				Oxidizer Cryocooler η:	11%	
Production Energy:	4119	kW				Oxidizer T_b:	90.2	K
Operational Hours:	24.0	hrs/dy						
Power Consumption:	98849	kWh/dy				Fuel Type:	Methane	
						Mass Fuel/Day:	1.63	kg/dy
Fuel Produced:	2961	kg/dy	Fuel Surplus:	0.1	kg/dy	%Fuel Mass Hydrogen:	25.0%	
Oxidizer Produced:	10954	kg/dy	Oxidizer Surplus:	-0.0	kg/dy	Fuel Liquefaction:	23.7	W/kg
						Fuel Cryocooler Mass:	288	kg
						Fuel Cryocooler η:	17%	
						Fuel T_b:	112	K
						O/F Production Ratio:	3.70	
						Multiplier:	1821	
						Mass Offset:	0.6781	

Figure 41. Scale-up Spreadsheet Calculations for Methane Production

A conceptual drawing of propellant processing plants in the Mars base installation is shown in Figure 42. The spherical storage tanks can be seen in the background behind protective burms.

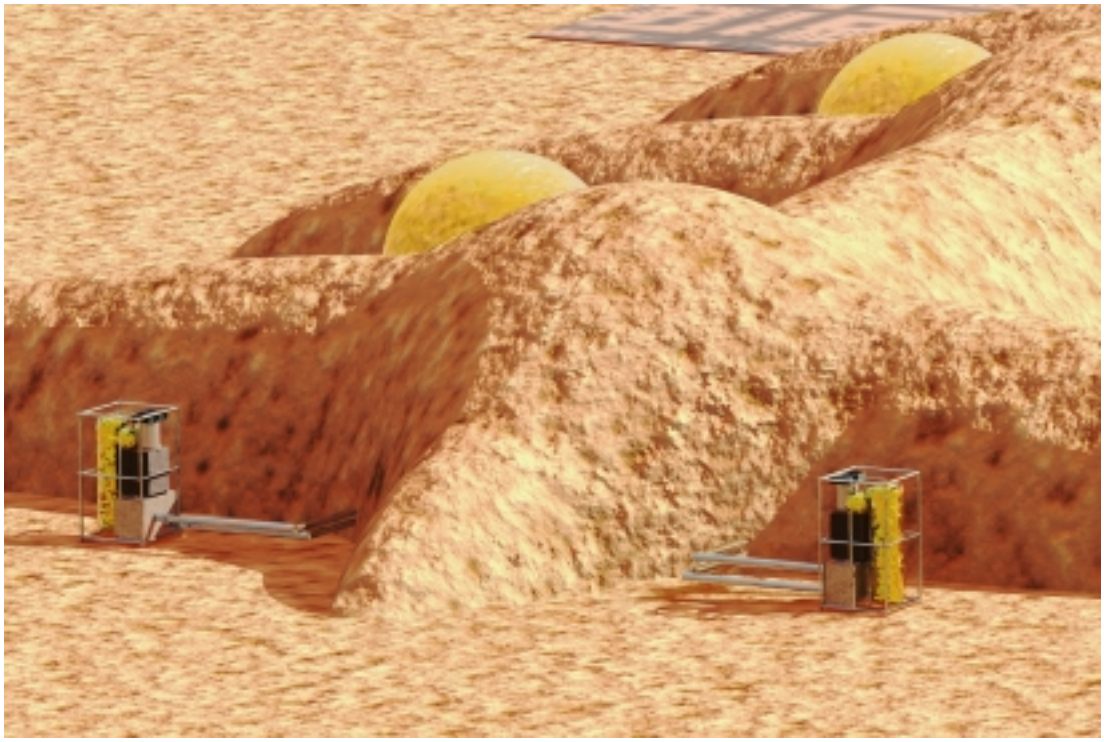

Figure 42. Propellant Production Units and Storage Tanks on the Mars Base

6.2 Requirements Analysis

The propellant processing requirements for all the propellant families defined in Section 4.1 were calculated using the 6000-kg baseline production plant and the minimum number of propellant storage tanks. Power requirements were included into the total power requirements of the colony for determination of the total number of nuclear reactors. Flight vehicles were analyzed separately from the rovers using different sets of calculations. Rovers were found to have a very small influence on total propellant production requirements. *In-situ* hydrogen production was used as an option for all propellant families requiring it and was provided by the WAVAR system, an atmospheric water extraction unit (Grover, et. al., 1998).

6.2.1 Flight Vehicle Requirements

Based upon our analysis, the flight vehicle propellant requirements dominate the total propellant requirements of the colony in both the 100 and 10,000 person colony scenarios. The propellant requirements are calculated using separate spreadsheets containing inputs from the vehicle traffic model, the propellant requirements, and the propellant plant correlations. Each spreadsheet builds off of calculations made in the previous sheets to determine the total propellant requirements for each propellant family. The propellant production model takes the propellant requirements from the vehicle traffic model to determine the number of 6000-kg production plants required for the demand. This number includes the necessary additional plants for covering plant downtime during repairs. Tanks are provided for the processing units capable of holding enough propellant for any mission requirement. Hydrogen tanks will be recycled for storage and transport of hydrogen from the cargo shuttle. Given the propellant demands over the study period, the model gives the shipment schedule of plants from Earth to meet the demand. Hydrogen requirements and replacement parts mass are calculated per period based on scheduled use. Storage tank mass and shipment schedules are also generated for the storage of propellants during over-

production periods, and energy requirements of re-liquefying the boil-off are calculated. Total energy requirements for production, liquefaction/solidification of propellants, and boil-off reprocessing are given on a steady-state basis per cycle for calculation of the required electrical plant mass. The total propellant production plant, tank, and parts mass is given for integration into the traffic model with the required electrical requirements. These requirements are then used to calculate the number of additional orbital download missions needed to bring the propellant processing systems from Earth, and these missions are added to the vehicle traffic model in the first spreadsheet. These calculations are repeated until the system converges to a solution. In the large-scale scenario colonization, some of the download missions of Cycle 6 are spread out over the previous cycles to remove the abrupt spike in propellant requirements associated with the rapid expansion of colony size after the initial ten-year period. This greatly reduces the overall propellant production requirements by effectively increasing the window available for orbital downloads. If this were not done, far more propellant production units and power plants would be required to produce propellants at a sufficient rate to provide the download capability necessary during rapid colony expansion. These units would only be required for orbital download missions at the beginning of each cycle, and would add unnecessary mass during the remainder of the cycle. Under this study's scenario, equipment shipments from Earth would be parked in low Martian orbit and brought down to the surface (downloaded) over the course of each cycle before they are needed to minimize the required production rate of propellants.

The following example calculations use Propellant Family 11, LCH_4/LOX, for the 10,000 person colony scenario. The propellant requirements spreadsheet calculates the total propellant mass for a propellant family using both the given flight vehicle traffic model and the given mission propellant requirements. This spreadsheet allows for the manual distribution of orbital download trips to other cycles to minimize the necessary propellant production rate for orbital downloads. Orbital download missions required for the transport of propellant production plants, tanks, parts, and terrestrial hydrogen are also entered into this sheet for the iteration process. The output from these calculations is a vehicle-by-vehicle breakdown of fuel and hydrogen requirements for each cycle for input into the next spreadsheet. The total fuel and hydrogen requirements for all vehicles is also calculated for use in a one-propellant family scenario. Oxidizer requirements in all cases are calculated in subsequent sheets using the required O/F ratio. Hydrogen requirements for vehicles that produce their own return propellants and must carry their own hydrogen are also calculated in this spreadsheet. A summary sheet from the propellant requirements spreadsheet for Propellant Family 11, LCH_4/LOX, is shown in Figure 43. The case shown is for the total fuel and hydrogen requirements of all vehicles. Note that the chart included in Figure 43 does not spread out the spike in propellant requirements in Cycle 6.

Cycle	Mass Fuel	Mass Oxidizer
1	5.60E+05	1.51E+05
2	3.18E+05	8.58E+04
3	3.45E+05	9.32E+04
4	3.72E+05	1.01E+05
5	3.84E+05	1.04E+05
6	1.68E+06	4.53E+05
7	1.70E+06	4.58E+05
8	1.72E+06	4.65E+05
9	1.92E+06	5.19E+05
10	1.83E+06	4.95E+05
11	1.95E+06	5.26E+05
12	1.98E+06	5.35E+05
13	2.04E+06	5.52E+05
14	1.97E+06	5.33E+05
15	2.22E+06	6.01E+05
16	2.15E+06	5.81E+05
17	2.21E+06	5.98E+05
18	2.26E+06	6.10E+05
19	2.27E+06	6.15E+05
20	2.29E+06	6.20E+05
21	2.38E+06	6.44E+05
22	2.43E+06	6.58E+05
23	2.46E+06	6.66E+05

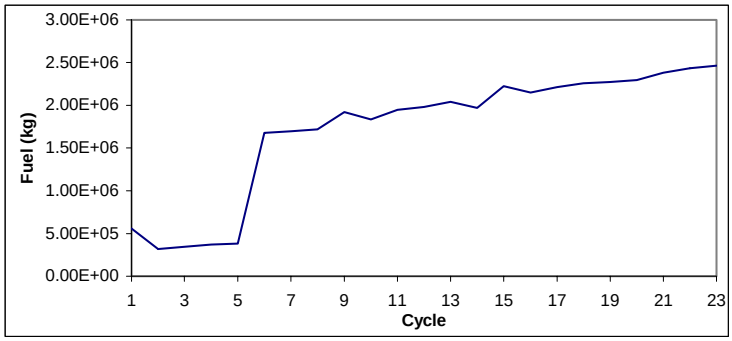

Figure 43. Total Methane and Hydrogen Fuel Requirements for Propellant Family 11, 10,000-Person Colony Scenario

After the total fuel and hydrogen masses are calculated, they are imported into a spreadsheet to calculate the required number of propellant production plants, storage tanks, and power requirements. This sheet includes provisions for fugitive emissions and their necessary make-up and for downtime for plant modifications and repairs. A boil-off provision is included; however, all vapors are recondensed into liquid fuel. The overall plant specifications and storage tank calculations are shown in Figure 44**,** where Yr^E = Earth year, again for Propellant Family 11 in the 10,000 person colony scenario.

Process:	**Sabatier/Methane Pyrol.**	
Production per 6000 kg Plant		
Methane:	2960.6	kg/dy
Oxygen:	10954	kg/dy
Process Energy:	4118.7	kW
Hydrogen Fuel %:	25	%
H2 Upload Mass:	270335	kg/yr^E
Fuel Cooling:	23.72	W/kg (liq)
Oxygen Cooling:	4.737	W/kg (liq)
Boil-off:	0.3	%/dy
Downtime:	2	wks/yr^E
Parts Requirement:	10	% kg/yr^E
Fugitive Emissions:	0.5	% /yr^E
Tank Parameters		
Tank Type:	Cylinder	
No. Tanks per Unit:	2	initially
Processing Sites:	1	
Minimum Tanks:	2	
Tank Length:	7.0	m
Tank Radius:	5.0	m
Tank Material:	Aluminum	
Density:	2710	kg/m^3
Thickness:	1	mm
Aerogel Thickness:	1.0094	m
Tank Volume:	248.98	m^3
Hydrogen Tanks:	33.36	
Propellant Properties		
Fuel Density:	415	kg/m^3
Oxidizer Density:	1141.2	kg/m^3
Vehicle Model Specifications		
O/F Ratio:	3.7	
Formula:		
Max Fuel Load:	16414	kg
Max Oxidizer Load:	60732	kg

Figure 44. Propellant Production Plant Specifications for PF 11

Boil-off, fugitive emissions, and annual downtime were all derived from generally accepted values. Replacement parts were determined from ORBITEC's own estimates and are likely high.

After these parameters are entered into the spreadsheet along with the fuel and/or hydrogen requirements from the Propellant Requirements spreadsheet, a per-cycle list is generated for the required download of propellant plants, tanks, replacement parts, and/or hydrogen. A total energy requirement is calculated for the production of the propellants in addition to their liquefaction and the re-liquefaction of the propellant boil-off. The summary table of this information for Propellant Family 11 in the 10,000 person colony scenario is given in Table 23.

Table 23. Summary Information for Propellant Family 11 Production Requirements

Mars Window	Plants	Tanks	Uplift Masses (tonnes)				Total Mass (tonnes)	Energy Req'd (kW)	Total Plant Uplift Mass (tonnes)	Plant Uplift Mass each Year (tonnes)
			Plants	Parts	Hydrogen	Tanks				
1	1	10	6	0.3	188	10.9	205	2240	6	6
2	0	0	0	0.2	129	0.00	129	1480	6	0
3	0	0	0	0.2	140	0.00	140	1610	6	0
4	0	1	0	0.2	150	1.09	151	1720	6	0
5	0	0	0	0.2	152	0.00	153	1760	6	0
6	0	18	0	1.0	484	19.7	505	5960	6	0
7	0	1	0	1.0	490	1.09	492	6030	6	0
8	0	0	0	1.0	504	0.00	505	6180	6	0
9	0	3	0	1.1	562	3.28	566	6890	6	0
10	0	0	0	1.1	540	0.00	541	6620	6	0
11	0	1	0	1.1	569	1.09	571	6980	6	0
12	0	1	0	1.1	586	1.09	588	7170	6	0
13	0	1	0	1.2	602	1.09	605	7380	6	0
14	0	0	0	1.1	585	0.00	586	7150	6	0
15	0	3	0	1.3	664	3.28	668	8100	6	0
16	0	0	0	1.2	645	0.00	647	7870	6	0
17	0	1	0	1.3	662	1.09	664	8080	6	0
18	1	3	6	1.3	682	3.28	692	8310	12	6
19	0	0	0	1.3	686	0.00	688	8360	12	0
20	0	0	0	1.3	693	0.00	695	8450	12	0
21	0	1	0	1.4	721	1.09	724	8780	12	0
22	0	1	0	1.4	745	1.09	747	9040	12	0
23	0	1	0	1.4	757	1.09	759	9180	12	0

Once the propellant production requirements have been calculated for each cycle, they are imported into a summary sheet for placement into a summary table and calculation of the required number of orbital download missions. The required download missions are then entered into the propellant requirements spreadsheet and added to the existing missions in the traffic model to include the propellant requirements of downloading the necessary production equipment. The entire process is then repeated with the three spreadsheets until the system converges to a solution.

For propellant families requiring hydrogen from Earth, the hydrogen requirements are used as the necessary shipment requirements from Earth and are also added to the orbital download requirements. For families using in-situ hydrogen, the WAVAR system (Grover, et. al., 1998) was selected for production of the required oxygen. The Water Vapor Adsorption Reactor (WAVAR) is a system to adsorb Martian atmospheric water in molecular sieves. Water is adsorbed in a Zeolite bed from filtered air pulled through the bed with a high-efficiency fan. Water is removed from the bed in a cyclic manner using a microwave drier. This system was then paired with an electrolysis unit, taken from Green, et. al., (1999) literature for consistency, to produce the hydrogen feed for select propellant families. The oxygen by-product from the electrolysis is used for colony operations including life support. Although several water levels are examined in the WAVAR papers, the published value of 0.03% atmospheric water was selected for our calculations.

An alternative to the WAVAR system was investigated. The Mars Atmosphere Resource Recovery System (MARRS) is another candidate for the production of water from the Martian atmosphere in addition to other trace elements including nitrogen, argon, and neon (England, 2001). While the MARRS is 58% more efficient at producing hydrogen than the WAVAR system, its mass is 15.4 times greater, making it a less attractive candidate on a total mass basis for our analysis.

Using the WAVAR system and an electrolysis unit, the hydrogen requirements from Earth are removed at the cost of higher power and plant mass requirements. Table 24 shows the total download requirements

for methane/oxygen Propellant Family 12, using in-situ hydrogen. The production plant and power system masses include the WAVAR system and electrolysis units for the production of ISRU hydrogen from the Martian atmosphere. Table 25 shows these download requirements for the methane/oxygen Propellant Family 11, using terrestrial hydrogen. The mass savings in using ISRU hydrogen are apparent when the two tables are compared.

Table 24. Total Propellant Production System Masses For Propellant Family 12

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	315392	199245	0
2	183	0	0
3	199	0	0
4	1307	0	0
5	221	0	0
6	455100	295402	0
7	9978	6076	0
8	23703	14154	0
9	96822	62340	0
10	1007	0	0
11	14843	7852	0
12	1042	0	0
13	20309	11595	0
14	7951	4642	0
15	130421	83760	0
16	1139	0	0
17	2268	0	0
18	1202	0	0
19	2762	749	0
20	13690	7075	0
21	90762	53376	0
22	3413	1019	0
23	20515	12289	0
TOTAL:	1214231	759575	0
		GRAND TOTAL (kg):	1973806

Table 25. Total Propellant Production System Masses For Propellant Family 11

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	17248	55190	188
2	183	0	129
3	199	0	140
4	1307	0	150
5	221	0	152
6	20632	91787	484
7	2071	1703	490
8	993	3685	504
9	4385	17653	562
10	1057	0	540
11	2216	2255	569
12	2235	4674	586
13	2271	5017	602
14	1137	0	585
15	4560	17916	664
16	1240	0	645
17	2368	0	662
18	10580	4994	682
19	1312	1370	686
20	1324	2075	693
21	2467	8312	721
22	2497	6451	745
23	2514	3425	757
TOTAL:	85019	226506	11937
		GRAND TOTAL (kg):	12248413

6.2.2 Ground Vehicle Requirements

The ground vehicle propellant requirements were calculated using a similar method to that of the flight vehicles; however, no iteration was necessary since they are not involved in the transport of materials from orbit to the colony. The vehicle model, traffic model, and maintenance model are all used to determine the propellant requirements of the vehicles. First, the vehicle model and traffic models are combined to give the total propellant requirements per cycle. Using the O/F ratio and hydrogen percentage of the fuel, the hydrogen requirements are calculated. These propellant requirements are calculated on a per cycle basis, and the required increase in production capacity is determined for each cycle. Propellants used in the rovers are recycled in storage tanks and recycled into fresh propellant to minimize hydrogen requirements and the energy requirements of processing the bulk atmosphere. The WAVAR system is again used for those propellant families using in-situ hydrogen, and the power requirements of the propellant production system and WAVAR system are calculated. Figure 45 shows these calculations for the methane/oxygen propellant family in the 10,000 person colony scenario.

LCH4/LOX
Total Cumulative Vehicle Propellant Requirements (kg)

Vehicle Type	Propellant Use (kg)	Colony Cycle (one cycle is ~26 Earth months) 1	2	3	4	5	6	7	8	9	10	11	12
G1	145	290	290	435	580	725	870	1015	1305	1450	1740	2030	2320
G2	1387	2774	2774	4161	6935	9709	13870	19418	23579	30514	37449	45771	54093
G3	549	1098	1647	2745	3294	3843	4392	5490	6039	7137	8235	9333	9882
G4	296.4	0	592.8	592.8	592.8	592.8	889.2	889.2	1185.6	1482	1482	1778.4	2074.8
	Sum:	4162	5304	7934	11402	14870	20021	26812	32109	40583	48906	58912	68370
	Increase:	4162	1142	2630	3468	3468	5151	6791	5296	8474	8323	10006	9457
	Days to Produce:	0.30	0.08	0.19	0.25	0.25	0.38	0.50	0.39	0.62	0.61	0.73	0.69
	Sum:	113647	135712	154992	173920	196813	215010	238009	258262	279629	299607	320967	342316
	Increase:	113647	22066	19279	18928	22893	18197	22999	20253	21367	19978	21361	21349
	Max Propellant:	566510											
	Max Cycle Increase:	113647											
	Hydrogen Required kg/cy:	5682	1103	964	946	1145	910	1150	1013	1068	999	1068	1067
WAVAR	Plants Required/cy:	9.45	1.83	1.60	1.57	1.90	1.51	1.91	1.68	1.78	1.66	1.78	1.77
	Plants/cy:	10	2	2	2	2	2	2	2	2	2	2	2
	Required on Surface/cy:	10	10	10	10	10	10	10	10	10	10	10	10
	Shipment Schedule:	10	0	0	0	0	0	0	0	0	0	0	0
	Mass Schedule:	9607	0	0	0	0	0	0	0	0	0	0	0
	Power Plants Req'd/cy:	0.237	0.0460	0.0402	0.0394	0.0477	0.0379	0.0479	0.0422	0.0445	0.0416	0.0445	0.0445
Production	Plants Required/cy:	0.0105	0.0125	0.0143	0.0161	0.0182	0.0198	0.0220	0.0238	0.0258	0.0276	0.0296	0.0316
	Plants/cy:	1	1	1	1	1	1	1	1	1	1	1	1
	Required on Surface/cy:	1	1	1	1	1	1	1	1	1	1	1	1
	Shipment Schedule:	1	0	0	0	0	0	0	0	0	0	0	0
	Mass Schedule:	6000	0	0	0	0	0	0	0	0	0	0	0
	Power Plants Req'd/cy:	0.058	0.069	0.079	0.088	0.100	0.109	0.121	0.131	0.142	0.152	0.163	0.173
	Mass Schedule:	18500	0	0	0	0	0	0	0	0	0	0	0
Comb. Powe	Total Plants Req'd/cy:	0.294	0.115	0.119	0.128	0.147	0.147	0.169	0.173	0.186	0.193	0.207	0.218
	Total Plants/cy:	1	1	1	1	1	1	1	1	1	1	1	1
	Required on Surface/cy:	1	1	1	1	1	1	1	1	1	1	1	1
	Shipment Schedule:	1	0	0	0	0	0	0	0	0	0	0	0
	Mass Schedule:	18500	0	0	0	0	0	0	0	0	0	0	0
	Total Production Mass kg/cy:	15607	0	0	0	0	0	0	0	0	0	0	0

LCH4/LOX
Total Cumulative Vehicle Propellant Requirements (kg) - Continued

Vehicle Type	Propellant Use (kg)	13	14	15	16	17	18	19	20	21	22	23
G1	145	2610	3045	3480	3915	4205	4640	5075	5655	6090	6525	7105
G2	1387	63802	73511	83220	95703	108186	120669	133152	148409	163666	178923	195567
G3	549	10980	12078	13725	14823	15921	17019	18666	19764	21411	23058	24705
G4	296.4	2371.2	2667.6	3260.4	3556.8	3853.2	4446	4742.4	5335.2	5928	6224.4	6817.2
	Sum:	79763	91302	103685	117998	132165	146774	161635	179163	197095	214730	234194
	Increase:	11393	11538	12384	14312	14167	14609	14861	17528	17932	17635	19464
	Days to Produce:	0.83	0.84	0.90	1.05	1.03	1.07	1.09	1.28	1.31	1.29	1.42
	Sum:	361972	382622	404126	423761	443170	463802	483631	504910	525526	546893	566510
	Increase:	19655	20650	21504	19635	19409	20632	19829	21279	20616	21367	19617
	Max Propellant:											
	Max Cycle Increase:											
	Hydrogen Required kg/cy:	983	1033	1075	982	970	1032	991	1064	1031	1068	981
WAVAR	Plants Required/cy:	1.63	1.72	1.79	1.63	1.61	1.72	1.65	1.77	1.71	1.78	1.63
	Plants/cy:	2	2	2	2	2	2	2	2	2	2	2
	Required on Surface/cy:	10	10	10	10	10	10	10	10	10	10	10
	Shipment Schedule:	0	0	0	0	0	0	0	0	0	0	0
	Mass Schedule:	0	0	0	0	0	0	0	0	0	0	0
	Power Plants Req'd/cy:	0.0410	0.0430	0.0448	0.0409	0.0404	0.0430	0.0413	0.0443	0.0430	0.0445	0.0409
Production	Plants Required/cy:	0.0334	0.0353	0.0373	0.0391	0.0409	0.0428	0.0446	0.0466	0.0485	0.0505	0.0523
	Plants/cy:	1	1	1	1	1	1	1	1	1	1	1
	Required on Surface/cy:	1	1	1	1	1	1	1	1	1	1	1
	Shipment Schedule:	0	0	0	0	0	0	0	0	0	0	0
	Mass Schedule:	0	0	0	0	0	0	0	0	0	0	0
	Power Plants Req'd/cy:	0.183	0.194	0.205	0.215	0.225	0.235	0.245	0.256	0.266	0.277	0.287
	Mass Schedule:	0	0	0	0	0	0	0	0	0	0	0
Comb. Powe	Total Plants Req'd/cy:	0.224	0.237	0.250	0.256	0.265	0.278	0.286	0.300	0.309	0.322	0.328
	Total Plants/cy:	1	1	1	1	1	1	1	1	1	1	1
	Required on Surface/cy:	1	1	1	1	1	1	1	1	1	1	1
	Shipment Schedule:	0	0	0	0	0	0	0	0	0	0	0
	Mass Schedule:	0	0	0	0	0	0	0	0	0	0	0
	Total Production Mass kg/cy:	0	0	0	0	0	0	0	0	0	0	0

Figure 45. Ground Vehicle Calculations for the Methane/Oxygen Propellant Family

After calculation of the required production masses, replacement rover parts are included in the total mass requirements for the ground vehicle family. Table 26 shows the total mass requirements for the methane/oxygen propellant family using in-situ hydrogen. Table 27 shows the same propellant family using terrestrial hydrogen. In both cases, it is apparent that the mass costs of operating the ground vehicles are far smaller than the mass requirements for the flight vehicles. Due to the small influence of the ground vehicle propellant requirements on the overall system, it is advisable to use the same propellants for the ground vehicles as are used in the flight vehicles. Furthermore, mass savings due to the WAVAR system are minimal due to the low production requirements. As a stand alone system, the ground vehicle propellant production system would probably not justify the use of in-situ hydrogen generation due to the added complexity; however, when combined with the larger requirements of the flight vehicles, the WAVAR system yields a large mass savings.

Table 26. Mass Requirements for the Methane/Oxygen Propellant Family Using In-Situ Hydrogen

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Parts (kg/cy)	V6 Missions (/cy)
1	15607	18500	0	25549	0.156
2	0	0	0	38142	0.100
3	0	0	0	20056	0.052
4	0	0	0	17586	0.046
5	0	0	0	17586	0.046
6	0	0	0	37828	0.099
7	0	0	0	34492	0.090
8	0	0	0	38509	0.101
9	0	0	0	54734	0.143
10	0	0	0	39985	0.104
11	0	0	0	60227	0.157
12	0	0	0	52945	0.138
13	0	0	0	65039	0.170
14	0	0	0	65719	0.172
15	0	0	0	88431	0.231
16	0	0	0	75343	0.197
17	0	0	0	74663	0.195
18	0	0	0	90773	0.237
19	0	0	0	82625	0.216
20	0	0	0	101078	0.264
21	0	0	0	107679	0.281
22	0	0	0	92249	0.241
23	0	0	0	113172	0.295
TOTAL:	15607	18500	0	1394412	
			GRAND TOTAL:	1428519	

Table 27. Mass Requirements for the Methane/Oxygen Propellant Family Using Terrestrial Hydrogen

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Parts (kg/cy)	V6 Missions (/cy)
1	6000	18500	208	25549	0.131
2	0	0	57	38142	0.100
3	0	0	132	20056	0.053
4	0	0	173	17586	0.046
5	0	0	173	17586	0.046
6	0	0	258	37828	0.099
7	0	0	340	34492	0.091
8	0	0	265	38509	0.101
9	0	0	424	54734	0.144
10	0	0	416	39985	0.105
11	0	0	500	60227	0.159
12	0	0	473	52945	0.139
13	0	0	570	65039	0.171
14	0	0	577	65719	0.173
15	0	0	619	88431	0.233
16	0	0	716	75343	0.199
17	0	0	708	74663	0.197
18	0	0	730	90773	0.239
19	0	0	743	82625	0.218
20	0	0	876	101078	0.266
21	0	0	897	107679	0.283
22	0	0	882	92249	0.243
23	0	0	973	113172	0.298
TOTAL:	6000	18500	11710	1394412	
			GRAND TOTAL:	1430622	

7.0 COST MODELING

This section discusses the cost modeling approach for the build up of the 100-person and 10,000-person colonies, and the results obtained.

7.1 Cost Model and Estimating Relationships

The cost estimating relationships, their source models, and the integrated program cost models are included in this section.

7.1.1 CER Models

Cost Estimating Relationship (CER) sources included both internal estimates and established cost models. The Advanced Missions Cost Model and the Spacecraft/Vehicle Level Cost Model are both available online at http://www.jsc.nasa.gov/bu2/AMCM.html and http://www.jsc.nasa.gov/bu2/SVLCM.html, respectively. Both of them are made available by the NASA Johnson Space Center Cost Estimating Group. ORBITEC ran these models parametrically online and produced curve fits of the data for input into the program study cost models. Brief descriptions of the two models are given below. All CER's are mass-based.

7.1.1.1 Advanced Missions Cost Model

The Advanced Missions Cost Model was used as the basis for the majority of the study CER's. It accepts the following parameters as input (descriptions are taken directly from the JSC website):

Quantity: The quantity is the total number of units to be produced. This includes prototypes, test articles, operational units, and spares.

Dry Mass: The dry weight is the total empty weight of the system in pounds, not including fuel, payload, crew, or passengers.

Mission Type: The mission type classifies the type of system by the operating environment and the type of mission to be performed. Nineteen different space-related categories are available.

IOC Year: The IOC is the year of Initial Operating Capability. For space systems, this is the year in which the spacecraft or vehicle is first launched. Analysis in this study assumed an IOC year of 2000, and as such, the results are presented in year 2000 dollars.

Block Number: The Block Number represents the level of design inheritance in the system. If the system is a new design, then the Block Number is 1. If the estimate represents a modification to an existing design, then a Block Number of 2 or more may be used. For example. Block 5 means that this is the 5th in a series of major modifications to an existing system.

Difficulty: The difficulty factor represents the level of programmatic and technical difficulty anticipated for the new system. This difficulty should be assessed relative to other similar systems that have been developed in the past. For example, if the new system is significantly more complex than previous similar systems, then a difficulty of high or very high should be selected.

The model output is the total cost required to produce the input quantity, including all development and production.

7.1.1.2 Spacecraft/Vehicle Level Model

The Spacecraft/Vehicle Level Model was used to estimate the cost to replace components that have worn out. It accepts the following as input: (mission) type, dry mass, quantity, and learning curve. With the exception of the learning curve, the definition of these parameters are the same as those listed for the

Advanced Missions Model. The learning curve indicates the degree of increased efficiency resulting from larger production runs and only affects the production portion of the total cost. One hundred percent represents no cost benefit from increased quantities. A value of 85% was used for all Spacecraft/Vehicle Level Model results presented in this study. The output of the model includes both the individual development and production costs for the total input quantity.

7.1.2 Earth-to-Mars Orbit Delivery

The cost of Earth-to-Mars orbit delivery was analyzed and estimated based on the result of recent NASA planning documents and studies. Projected Earth-to-LEO (low-Earth-orbit) costs are cited in many NASA documents ("Space Transportation Day '99 – Creating a Highway to Space," NASA, 1999) containing plans for the development of future launch vehicle systems. These plans cite the following goals for future launch systems:

Program	**LEO Cost Goal ($/KG)**	**By Year**
Space Launch Initiative (SLI) [aka Generation Two (Gen 2) Reusable Launch Vehicle (RLV)]	2200	2010
Advanced Space Transportation Program (ASTP) [aka Generation Three (Gen 3) RLV]	220	2025
Generation Four (Gen 4) RLV	22	2040

Both Earth-to-LEO and LEO-to-Mars surface transportation costs have been studied by Science Application International Corporation (SAIC). The results were reported in two papers by Stancati (Stancati et al 2000). One purpose of their studies was to investigate the benefits of a "LOX Augmented Nuclear Thermal Rocket (NTR)," or "LANTR" that has been proposed by NASA. SAIC studied the use of LANTR as a LEO-based LEO to Mars orbit reusable transportation vehicle, or "MTV." As part of the study SAIC baselined Earth-to-LEO a cost that corresponds to the SLI Gen 2 class RLV. The study examined a 20 year, 20 mission Mars manned program scenario and included the use of In-Situ Propellant Production (ISPP). In the case analyzed of most relevance to our study, SAIC determined that payload delivery costs to the Mars surface were about $16,000/kg. Of the $16,000, approximately $11,000 was attributable to the Earth launch system, and $5,000 to the combination of the LANTR MTV and Mars Ascent/Descent Vehicle (MAV). This assumes the LANTR MTV is based in Earth orbits and that Mars Ascent/Descent Vehicle (MAV) is based on the surface of Mars. Based on the data in the papers, ORBITEC estimates that LANTR cost for the Earth orbit to Mars orbit transfer should represent about 3,700/kg.

The SAIC study was based on the use of ISPP in the LANTR MTV for Mars to Earth return. The baseline for our study does not include the use of ISPP for Mars orbit to Earth orbit return. In addition it examines a much longer term Mars scenario or with a much broader scope (including colonization). Therefore, it was necessary to adjust the SAIC results to fit out scenario. First, the mission profile was altered to eliminate Mars landing/ascent and the use of ISPP. Propellant requirements for the LANTR were recalculated based on its Specific Impulse of 597 seconds (and an estimated dry mass of 30,000 kg). The result was a propellant requirement of about 215,000 kg for delivery of a 40,0000 kg payload to Mars orbit and return of the LANTR to Earth orbit where it is based. All of the LANTR propellant must be brought from the Earth's surface. As a result, for each kg of payload delivered to Mars orbit, 6.4 kilograms must be launched from Earth to LEO (i.e., 6.4 x 40,000 = 255,000 = 40,000 + 215,000).

Assuming an SLI Gen 2 RLV with launch costs of $2,200 per kg, then Earth-to-LEO launch cost would

be 6.4 x $2,200 = $14,100/kg. Previously we estimated LANTR cost at $3,700/kg, to give an Earth-to-Mars orbit total of approximately $18,000/kg. This is based on Gen 2 level technology and limited use of LANTR. If Gen 3 technology and cost reduction is assumed to apply to both transportation system elements then this cost would drop to $1,600/kg. ORBITEC believes this value to be highly optimistic and established $5,000/kg as the baseline Earth-to-Mars-orbit payload delivery cost for the purpose of this study.

It is recognized that the above result is only an estimate; however, it provides a reasonable starting point for a parameter that is treated as a variable in the costing analysis that follow. In approaching those analyses it should also be noted that "payload" can be anything, including hardware, fluids/propellants, or humans – all with their unique support system requirements that must be included in the payload mass total.

7.1.3 General Infrastructure

General infrastructure encompasses everything that is assumed to be independent of the propellant family used: habitats, life support, food generation, manufacturing, etc. Both the 10,000-person and 100-person colonies utilize nuclear power systems to support the general infrastructure. However, because these systems are also affected by the energy required for ISRU propellant processing, their cost is calculated separately for each propellant family.

The general infrastructure CER is based on the JSC Advanced Missions Model. It is recognized that the general infrastructure encompases a diverse array of hardware and systems working together. However, the mass of individual types of general infrastructure was not broken down in our analysis (it was based on detailed analysis completed by others), and by definition, it does not affect the competition among the individual propellant combinations. For this reason, the cost of these components were assumed to be, at least on the average, similar to that of a "Spacecraft-Manned Habitat", the most appropriate of the available mission types in the Advanced Missions Model.

Model input for the 10,000-person colony is shown in Table 28. One thousand units of each component were assumed, equivalent to 1 for every 10 people. The Block Number of 2 was selected because the early manned exploration period (up to 20 people living on Mars) generated heritage for these systems.

Table 28. Model Input For General Infrastructure CER, 10,000-Person Colony

Quantity	1000
Unit Dry Mass (lb_m)	174,472
Mission Type	Spacecraft-Manned Habitat
IOC Year	2000
Block Number	2
Difficulty	very low
Total Cost ($M)	105,837
CER	**Cost($M) =1.33E-3*Mass(kg)**

Model input for the 100-person colony is shown in Table 29. Ten units of each component were assumed, again equivalent to 1 for every 10 people. Note the economies of production scale where the 1000 unit run costs 6.5 times less than the 10 unit run on a mass basis.

Table 29. Model Input For General Infrastructure CER, 100-Person Colony

Quantity	10
Unit Dry Mass (lb_m)	174,472
Mission Type	Spacecraft-Manned Habitat
IOC Year	2000
Block Number	2
Difficulty	very low
Total Cost ($M)	6859
CER	**Cost($M) =8.67E-3*Mass(kg)**

7.1.4 Power Systems

Both the 100-person and 10,000-person colonies utilized power systems having a mass of 18,500 kg each. The power system CER is an internal estimate, where the total cost was parametrically calculated as a function of the total production quantity required, shown in Figure 46. The production quantity scaling exponent (-0.4058) is based on the Advanced Missions Cost Model scaling law, established by parametrically running the model and fitting a curve to the results.

The combined general infrastructure and propellant processing needs were integrated to establish the total number of propellant processors required for implementation of a given propellant family. This was then used in conjunction with Figure 46 within the Integrated Program Cost Model to calculate the CER for each propellant family. The very low number of propellant processors required for the 100-person scale colony caused them to cost significantly more than for the 10,000-person colony. As an example, 6 power systems were required for the 100-Person PF12-LCO/LOX case, resulting in a cost of over $350M per unit.

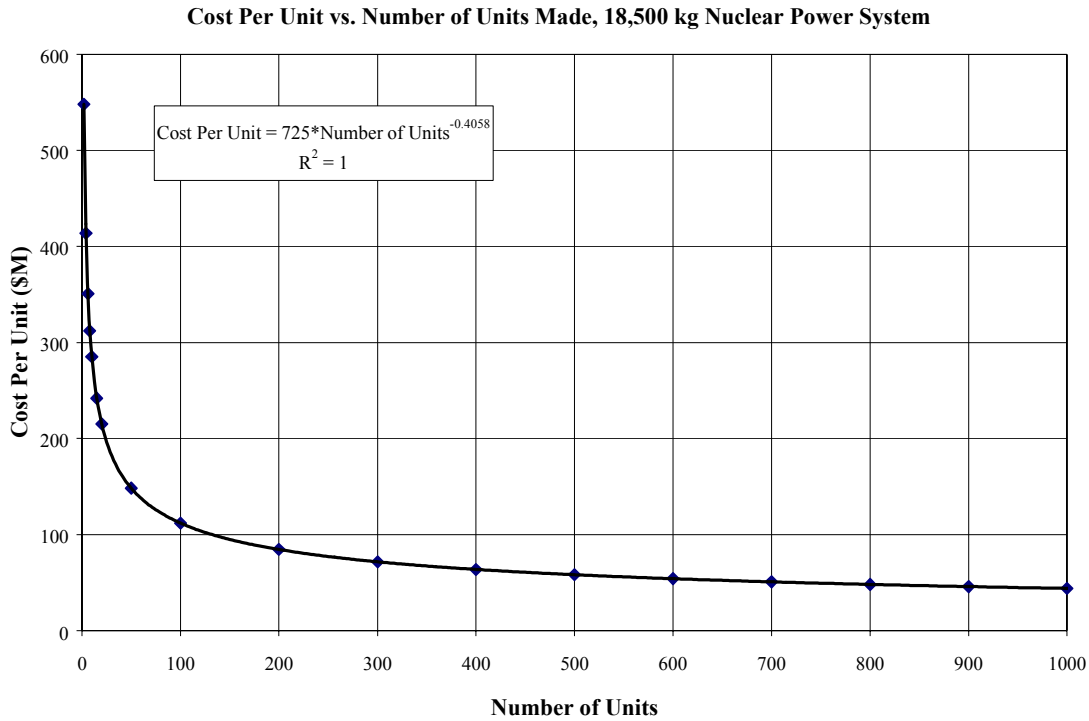

Figure 46. Parametric Power System CER

7.1.5 Propellant Processors

Both the 100-person and 10,000-person colonies utilized propellant processor units having a mass of 6000-kg each. While some systems are more efficient than others, all of the propellant family processors share similar components, functions, and complexity. They extract gasses from the atmosphere, break them down into their individual constituents, liquefy, and store them. For these reasons, the same mass-based CER was used for all of them. The CER for these units is an internal estimate, where the total cost was parametrically calculated as a function of the total production quantity required, shown in Figure 47. The production quantity scaling exponent used (-0.4058) is also based on the Advanced Missions Cost Model scaling law.

The 6000-kg units have a specific power consumption and propellant processing rate associated with them for each propellant family. Thus, propellants requiring more massive processing hardware have a lower propellant production rate per unit. This factor along with the total amount of propellant required for a given propellant family, which can vary significantly, decides the number or units required, and ultimately, the cost per processing unit.

The propellant processors onboard the ISRU vehicles were assumed to be included in the cost of the vehicle itself. They are only used to manufacture the propellant for the return trip to allow more efficient vehicle use (the vehicle can immediately fill up for another trip after it returns to a base).

Replacement parts for processor maintenance were also included in the system analysis, and were assumed to cost the same as the processors themselves on a mass basis, based on the total number or processors required for that propellant family and scenario.

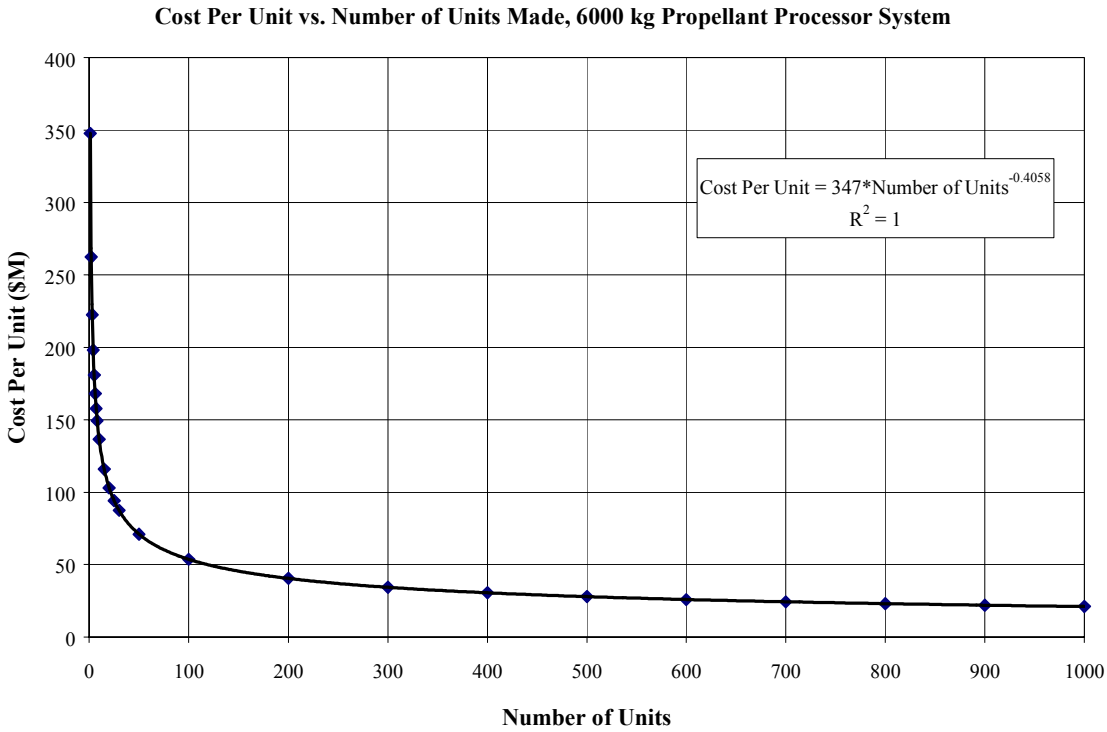

Figure 47. Parametric Propellant Processor System CER

7.1.6 Hopper Vehicles

The hopper vehicle CER was calculated using the Advanced Missions Cost Model; model input is shown in Table 30. The model was parametrically run as a function of the total quantity required and the dry mass of the vehicle. The resulting CER's are show in Figure 48. The CER for a production run of three vehicles was assumed for all six vehicles in the 10,000-person colony. In the 100-person colony, all missions were completed by only three of the six hopper vehicles, varying the total number of required vehicles from two to eight, shown in Table 31 by vehicle type. The CER's do not distinguish between the hybrid and bi-propellant systems.

Table 30. Model Input For Hopper Vehicle CER

Quantity	varies
Dry Mass (lb_m)	varies
Mission Type	Space Transport – launch vehicle stage
IOC Year	2000
Block Number	1
Difficulty	average
Total Cost ($M)	varies

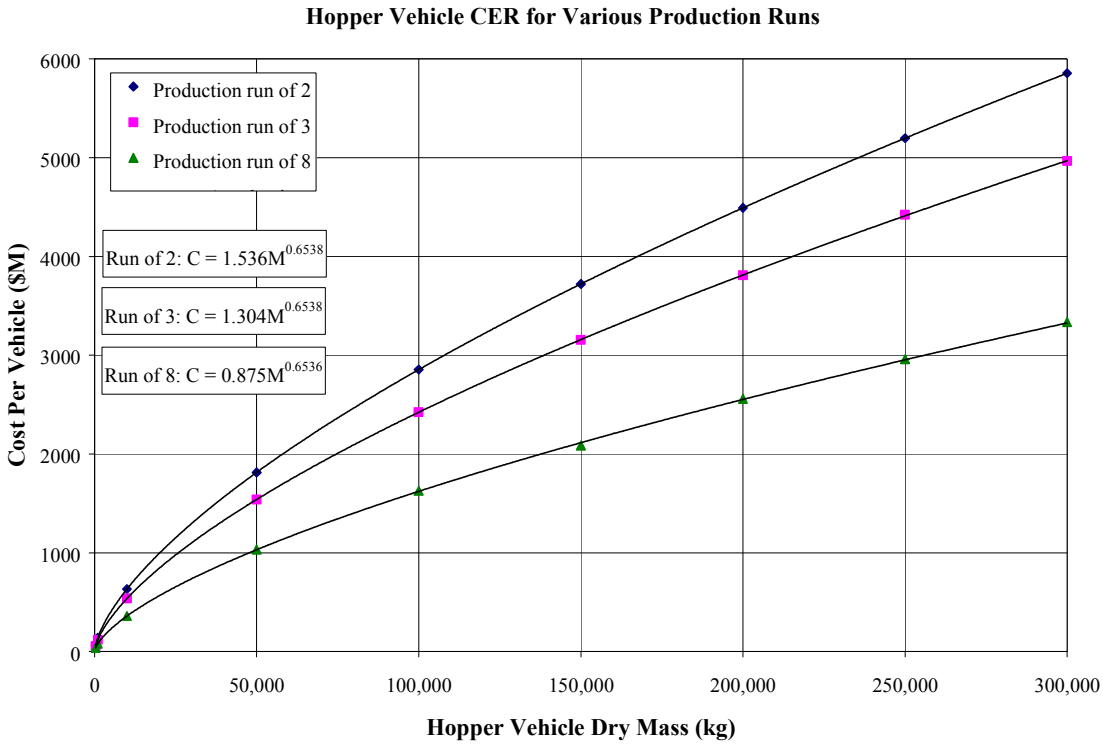

Figure 48. Hopper Vehicle CER for Various Production Runs

Table 31. Total Vehicles Required for 100-Person Colony

Vehicle Type	Number Required
IRIS	8
ARES	2
HYPERION	2

The hopper vehicle engines were replaced after every 50 flights. The initial goal was to develop two CER's, one each for hybrid and bipropellant systems that would factor in the potentially lower cost of the hybrid system due to it's reduced complexity (only half of the turbomachinery is required). However, we could not find any relevant cost data in the public domain or obtain it directly from companies that manufacture turobmachinery. We used the Spacecraft/Vehicle Level Model for both liquid and hybrid replacement engines, without distinguishing between the two. The model input is shown in Table 32 and the CER is displayed in Figure 49. This particular CER does not include engine development costs, as they are already factored into the original vehicle cost.

Table 32. Model Input for Replacement Engine CER

Quantity	20
Dry Mass (lb_m)	varies
Type	Liquid Rocket Engine
IOC Year	2000
Learning Curve (%)	85
Total Cost ($M)	varies

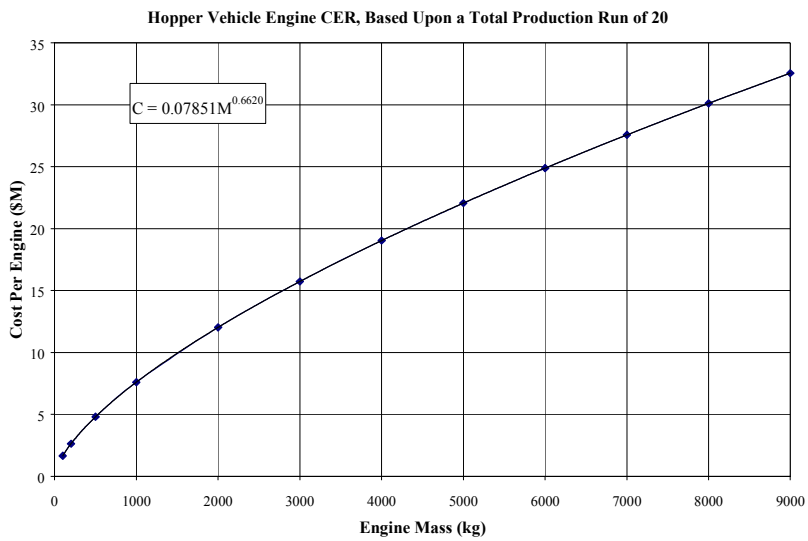

Figure 49. Hopper Vehicle Engine CER

Hopper vehicle maintenance costs were based on the Transcost Model (Dietrich, 1991), frequency of the flights, and internal estimates. The maintenance cost was assumed to be 0.25% of the total vehicle cost for each flight. This includes vehicle maintenance only, and does not factor in any launch operations or vehicle program/management costs.

7.1.7 Ground Vehicles

The ground vehicle CER's were generated using the Advanced Missions Cost Model with the inputs shown in Table 33. A block number of 2 was selected to account for the high degree of commonality among the different rover types. Figure 50 displays the CER's for several levels of production. A total run of 75 was assumed for each vehicle type for the 10,000-person colony. The 100-person colony was broken down into three levels, as displayed in Table 34.

Table 33. Model Input For Ground Vehicle CER

Quantity	varies
Dry Mass (lb_m)	varies
Mission Type	Lunar rover
IOC Year	2000
Block Number	2
Difficulty	average
Total Cost ($M)	varies

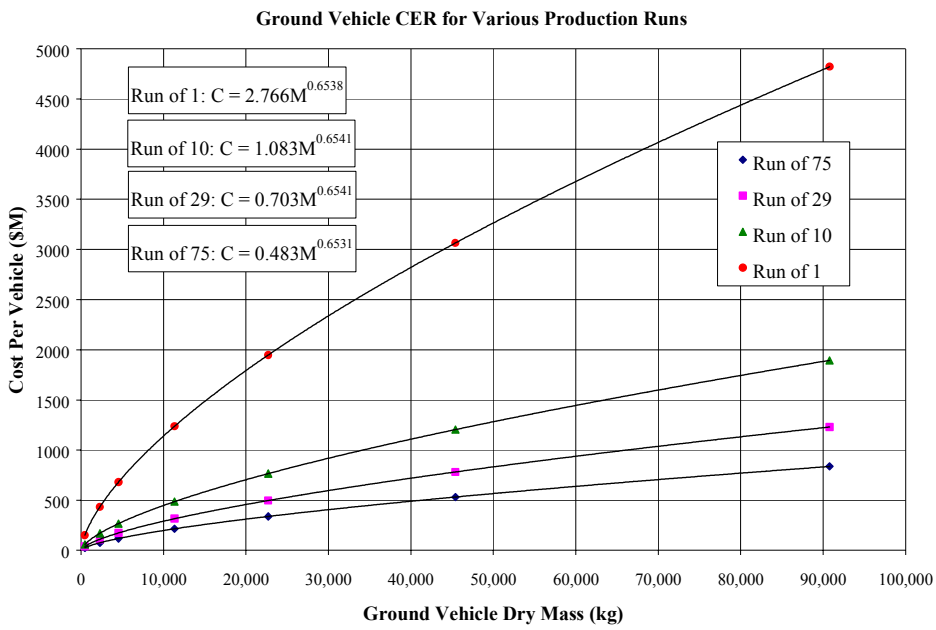

Figure 50. Ground Vehicle CER for Various Production Runs

Table 34. Total Ground Vehicles Required for 100-Person Colony

Vehicle Type	Production CER Implemented
TYCHE	10
SELENE	10
ZEPHYRUS	1
GAMMA	29

A parametric correlation for terrestrial vehicle maintenance, based on a publication by the Department of Transportation (Battelle Team, 1995), was generated to predict the average vehicle maintenance cost as a function of the distance traveled and the vehicle wetmass. This CER was then inflated to account for the small number of ground vehicles produced, the increased cost of space hardware, and operating in space by comparing the cost of a 2002 Chevey Suburban (www.chevrolet.com/suburban) with that of an equivalent mass Mars ground vehicle (assuming a production run of 75). The net result was an increase in the terrestrial based CER by a factor of 1490 for the Mars ground vehicles, shown below:

$$\text{Maintenance Cost} = 9.25\text{x}10^{-5} + 1.97\text{x}10^{-9}(\text{Mass} - 26{,}332)$$

Where:

Maintenance Cost ($M/km): total maintenance cost per distance traveled by the vehicle

Mass (kg): fully loaded vehicle wetmass

The total distance traveled by each class of ground vehicle was then used to establish the total maintenance cost.

7.1.8 Sounding Rocket

Propellant consumption for the sounding rocket is trivial relative to the rest of the 100-person colony operations. In this vein, the type of propellant used for the sounding rocket would have little effect on the total colony cost. A representative SCO/LOX sounding rocket was conceptualized for the 100-person colony scenario and added to the total cost.

Costing for the sounding rocket was only completed for the 100-person colony to provide an estimate of its relative cost. The cost for the 10,000-person colony was expected to be insignificant compared to the rest of the colony elements.

The Advanced Missions Cost Model was used to calculate the sounding rocket cost per the model input shown in Table 35. The total cost is assumed to include the development and production of all the different instrumentation payloads that would be required.

Table 35. Model Input for Sounding Rocket CER

Quantity	92
Dry Mass (lb_m)	8.09
Mission Type	Space Transport –launch vehicle stage
IOC Year	2000
Block Number	1
Difficulty	low
Total Cost ($M)	44
CER	**Cost =$478,000 each**

7.1.9 Mars Aeroplane

The Mars Aeroplane CER was calculated using the Advanced Missions Cost Model with the inputs shown in Table 36. The corresponding CER is shown as Figure 51. Costing for the airplane was only completed for the 100-person colony to provide am estimate of its relative cost. The cost for the 10,000-person colony is insignificant compared to the rest of the colony elements.

Table 36. Model Input for Ground Vehicle CER

Quantity	23
Dry Mass (lb_m)	varies
Mission Type	Spacecraft – weather
IOC Year	2000
Block Number	1
Difficulty	average
Total Cost ($M)	varies

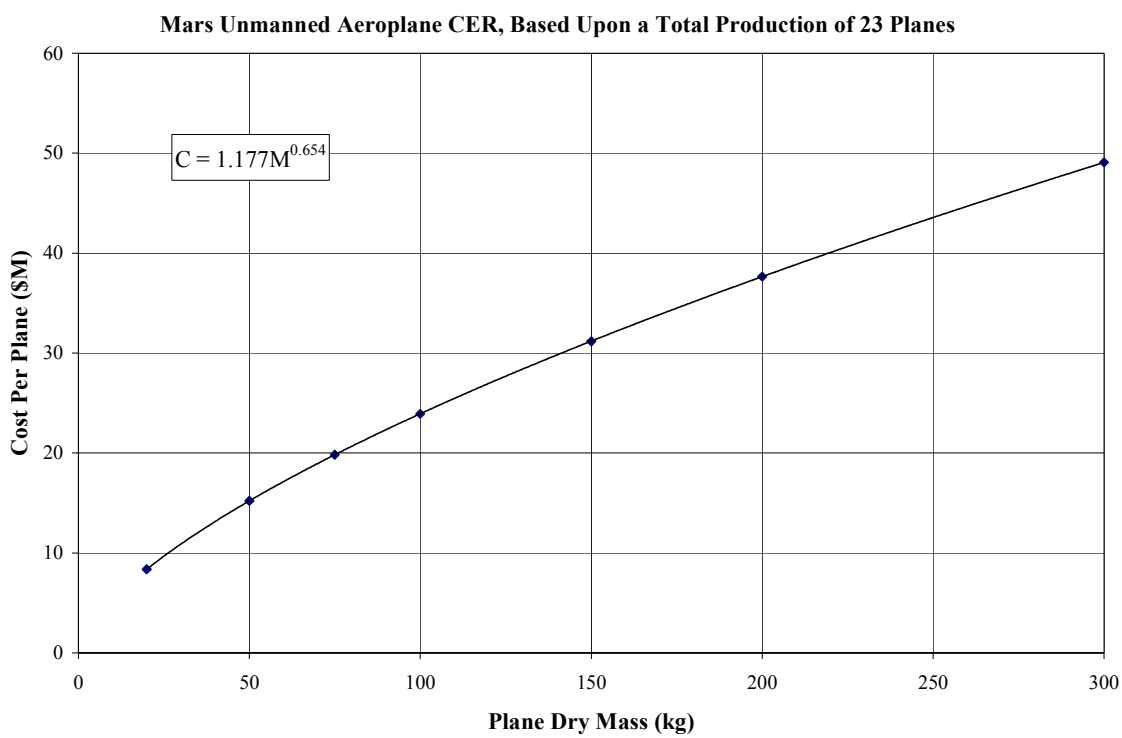

Figure 51. Unmanned Mars Aeroplane CER

7.1.10 Mars Balloon

The Mars balloon does not depend on the propellant family used, and is included in the cost of the 100-person colony only. The CER was developed using the Advanced Missions Cost model with the inputs shown in Table 37. The resulting CER includes the development of all onboard instrumentation.

Table 37. Model Input for Mars Balloon CER

Quantity	2139
Dry Mass (lb_m)	8.81
Mission Type	Spacecraft - weather
IOC Year	2000
Block Number	1
Difficulty	very low
Total Cost ($M)	409
CER	**Cost =$191,000 each**

7.1.11 Terrestrial Liquid Hydrogen

A quote for the cost of terrestrial liquid hydrogen was obtained from BOC Gasses as $3.78/kg.

7.1.12 Integrated Program Cost Models

Cost models integrated the appropriate CER's to establish the cost of each vehicle type for every propellant combination, and for the general infrastructure. The cost models accepted input from several other program study models, including: vehicle design, vehicle maintenance, propellant requirements and processing, traffic, and infrastructure. All of the cost models were implemented in the "Engineering Equation Solver (EES)" software package.

Each cost model walks through the 50-year colony life one cycle at a time, keeping record of the incremental cost for a given colony cycle and the total cumulative cost. All results are in 2000 year dollars; discounting and inflation were not represented in the model. The cost is broken down into three main areas: (1) production, (2) delivery, and (3) maintenance. Definitions of these three parameters are given at the beginning of the cost analysis results.

As an example, the hopper vehicle cost model accepted the following parameters as input:

- Dry mass for each vehicle type
- Engine mass for each vehicle type
- Total number of flights for each vehicle type as a function of the colony cycle
- Number of flight vehicles required of each type as a function of the colony cycle
- Replacement engines required for each vehicle type as a function of the colony cycle
- Propellant processor requirements as a function of the colony cycle

- Power system requirements as a function of the colony cycle
- Terrestrial hydrogen requirements as a function of the colony cycle.

7.2 100-Person Colony Analysis Results

The results are broken down by six major categories: (1) ground vehicles, (2) hopper vehicles, (3) sounding rockets, (4) aeroplanes, (5) balloons, and (6) non-transportation related costs (general infrastructure: habitats, life support, and all other required facilities/equipment unrelated to transportation). These cost categories are further divided into production, delivery, and maintenance. Production includes both development and manufacturing costs, delivery is defined as shipping items from the surface of the Earth to Mars orbit, and maintenance is keeping equipment running properly. Replacement parts for the maintenance of propellant processors and nuclear power systems were factored into the analysis; however, the costs associated with them are not included in the "Maintenance" cost category. Rather, they were included in the "Production" cost to streamline our analysis process.

The only operations costs associated with human labor included in the results presented here are for flight and ground vehicle maintenance. Results do not include the cost for any terrestrial or Martian management/operations to support the colony activities, or the salary for any of the colony Martians. Labor costs are also included in the hardware production cost.

The results presented here assume an Earth to Mars orbit delivery cost of $5000/kg. It does not directly factor in the cost to develop the Earth to Mars orbit transportation system, or distinguish between the cost to deliver people and hardware. If the delivery cost was significantly higher, it would have a direct impact on the total colony cost. Nevertheless, this analysis captures the relative cost of the various propellant families, and the effects of other delivery costs (both higher and lower) are explored in the sensitivity analysis section of this report.

Figure 52 displays the total relative 100-person colony cost for the different propellant families, shown as a percentage of the lowest cost family: PF6-LCO/LOX (ISRU carbon and oxygen). These results include the costs for: (1) ground vehicles, (2) hopper vehicles, (3) sounding rockets, (4) airplanes, (5) balloons, and (6) non-transportation related costs. The propellant combinations considered in this study for the hopper and ground vehicles are different. However, the cost differential among the ground vehicle propellant families is small, and as such, Figure 52 was generated under the assumption that PF6-LCO/LOX was used for all the ground vehicles. Similarly, the total cost for the sounding rockets, airplanes, balloons, and non-transportation costs are not dependant on the propellant family. Therefore, the cost ranking shown in Figure 52 is solely attributed to the difference in hopper vehicle costs (discussed in detail under Section 7.2.2).

The most striking aspect of Figure 52 is the cost of PF1 relative to the other propellant families. PF1 is the only propellant family that uses all terrestrial propellants. The total cost for this scenario is over 36 times more expensive than the lowest cost propellant family (PF6), using all ISRU propellants. These results clearly illustrate the enormous benefits of ISRU. Similarly, increasing the amount of ISRU implementation decreases the total cost for every propellant family. These results assume a total Earth to Mars orbit delivery cost of $5000/kg. If the delivery cost were higher, this would further increase the benefits of ISRU, and substantially increase the total colony cost. The effects of other delivery costs (both higher and lower) are discussed in the sensitivity analysis section of this report.

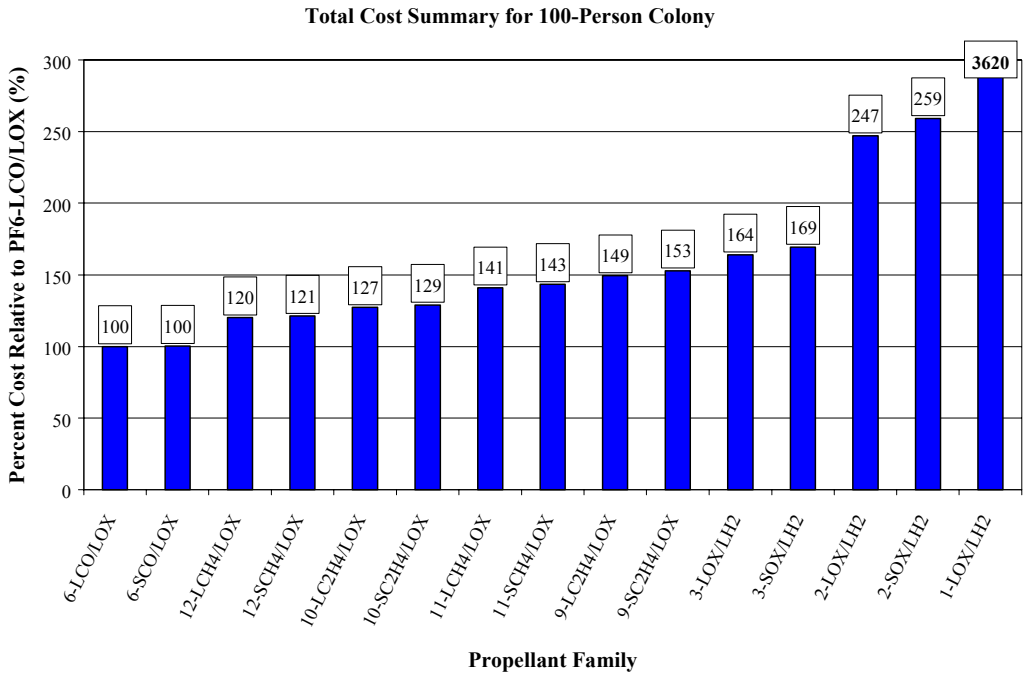

Figure 52. Total Cost Summary for 100-Persson Colony

The lowest total cost is achieved by using the CO/LOX propellant family, where the results for the hybrid and bi-propellant liquid cases are nearly identical. Table 37 summarizes the results for the use of PF6-LCO/LOX which has a total cost of $32.6B. The three highest price items (non-transportation, ground vehicles, and hopper vehicles) all have a comparable total cost. The smaller amount of infrastructure required by the 100-person scenario greatly diminishes the dominance of the non-transportation cost, compared to the 10,000-person colony scenario. That is, the costs associated with transportation are much more significant for the 100-person scenario.

The sounding rocket was only analyzed for PF6, and the balloon cost is independent of the propellant combination used.

Table 37. Total 50-Year Cost Summary for 100-Person Colony Using LCO/LOX

	Production ($B)	Delivery ($B)	Maintenance ($B)	Subtotal ($B)
General Infrastructure	7.81	4.93	N/A[1]	**12.74**
Ground Vehicles	8.21	0.78	0.37	**9.36**
Hopper Vehicles	7.17	0.94	1.48	**9.59**
Sounding Rockets	0.04	~0	N/A[1]	**0.04**
Airplanes	0.40	~0	N/A[1]	**0.40**
Balloons	0.41	0.04	N/A[1]	**0.45**
Subtotal	**24.04**	**6.69**	**1.85**	**Total: 32.58**

[1]Maintenance costs were integrated into the production cost

7.2.1 Ground Vehicles

The total ground vehicle cost for the 50-year 100-person colony is summarized in Figure 53 and Table 38 for each propellant family. The cost span among all propellant families is only $325M or 3.6%. Increasing the amount of ISRU implementation does not provide a cost savings for the ground vehicles. This is a direct result of recycling the spent propellants for re-use, including terrestrial supplied propellants; the total propellant production/shipping requirements are low. Another significant factor that diminishes the influence of ISRU is the high cost of the vehicles themselves, accounting for over 80% of the total cost.

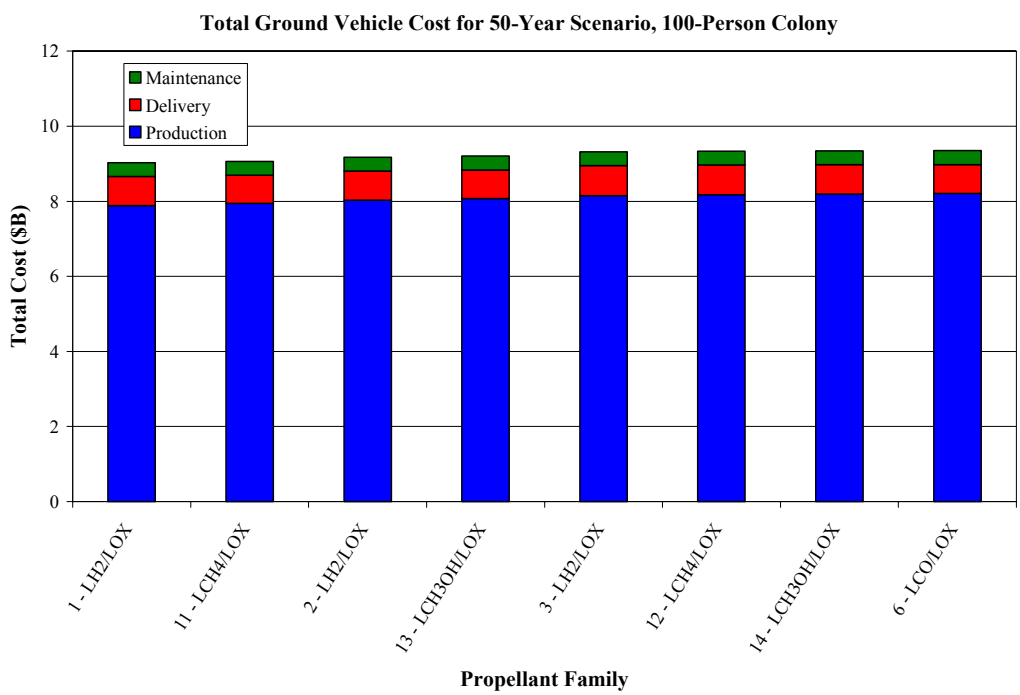

Figure 53. Total Ground Vehicle Cost for 50-Year Scenario; 100-Person Colony

Table 38. Ground Vehicle Cost Breakdown for 50-Year Scenario; 100-Person Colony

Propellant Family	Propellant	Production ($B)	Delivery ($B)	Maintenance ($B)	Total ($B)
1	LH2/LOX	7.88	0.78	0.37	9.03
11	LCH4/LOX	7.94	0.75	0.37	9.06
2	LH2/LOX	8.03	0.78	0.37	9.17
13	LCH3OH/LOX	8.07	0.76	0.37	9.20
3	LH2/LOX	8.15	0.80	0.37	9.32
13	LCH4/LOX	8.17	0.80	0.37	9.34
14	LCH3OH/LOX	8.19	0.79	0.37	9.34
6	LCO/LOX	8.21	0.78	0.37	9.35

7.2.2 Hopper Vehicles

The total hopper vehicle cost for the 50-year 100-person colony life is summarized in Figure 54 and Table 39 for each propellant family. There are six distinct cost groupings for the propellant families, displayed in Table 40. The cost range among the propellant families is striking, with the lowest total cost (PF6-CO/O_2) coming in 120 times lower than the total terrestrial propellant case (PF1-LOX/LH_2). Increasing the amount of ISRU implementation significantly reduces the total cost for every propellant combination. The price tag for the propellant families that implement terrestrial hydrogen are dominated by the hydrogen delivery costs. Alternatively, the cost for the total ISRU propellant families are driven by the production of the propellant processing and power systems (along with the vehicle production costs).

Table 39. Hopper Vehicle Cost Breakdown for 50-Year Scenario; 100-Person Colony

Propellant Family	Propellant	Production ($B)	Delivery ($B)	Maintenance ($B)	Total ($B)
6	LCO/LOX	7.17	0.94	1.48	9.59
6	SCO/LOX	7.20	0.97	1.49	9.66
12	LCH4/LOX	11.48	3.31	1.37	16.15
12	SCH4/LOX	11.69	3.46	1.38	16.52
10	LC2H4/LOX	12.91	3.76	1.81	18.47
10	SC2H4/LOX	13.21	3.95	1.85	19.02
11	LCH4/LOX	6.96	14.35	1.64	22.95
11	SCH4/LOX	7.02	15.05	1.66	23.73
9	LC2H4/LOX	9.15	14.52	2.03	25.71
9	SC2H4/LOX	9.34	15.40	2.09	26.83
3	LOX/LH2	19.13	9.57	1.76	30.46
3	SOX/LH2	19.98	10.38	1.81	32.18
2	LOX/LH2	9.09	45.87	2.57	57.53
2	SOX/LH2	9.68	49.12	2.66	61.46
1	LOX/LH2	28.03	1093	36.58	1158

Table 40. Flight Vehicle Cost Groupings for 100-Person Colony

Cost Group	Propellant Family	Propellant	Total Cost ($B)	Group Characteristics
1	6	LCO/LOX	9.59	Complete ISRU production of propellants that do not contain any hydrogen
	6	SCO/LOX	9.66	
2	12	LCH_4/LOX	16.15	Complete ISRU production of propellants that contain a relatively small percentage of hydrogen (3.76% and 5.32% of total propellant mass for C_2H_4/LOX and CH_4/LOX, respectively)
	12	SCH_4/LOX	16.52	
	10	LC_2H_4/LOX	18.47	
	10	SC_2H_4/LOX	19.02	
3	11	LCH_4/LOX	22.95	ISRU O_2 and terrestrial H_2 propellants that contain a relatively small percentage of hydrogen (C_2H_4/LOX and CH_4/LOX)
	11	SCH_4/LOX	23.73	
	9	LC_2H_4/LOX	25.71	
	9	SC_2H_4/LOX	26.83	
4	3	LOX/LH_2	30.46	Complete ISRU production of propellants that contain a high percentage of hydrogen (H_2/LOX, 15.38% H_2 by mass)
	3	SOX/LH_2	32.18	
5	2	LOX/LH_2	57.53	ISRU O_2 and terrestrial H_2 propellants that contain a high percentage of hydrogen (H_2/LOX, 15.38% H_2 by mass)
	2	SOX/LH_2	61.46	
6	1	LOX/LH_2	1,158	All terrestrial propellants (no ISRU)

The CO/O_2 families are the clear winners for the 100-person colony vehicles. The ease of extracting CO and O_2 from the largely CO_2 Martian atmosphere leads to relatively power efficient and small processing systems. The water extraction systems used for the total ISRU propellant families requiring hydrogen are comparably massive, and have to move enormous volumes of the Martian atmosphere through the processor to collect a sufficient amount of water. The use of CO/O_2 provides a savings of $6.6B compared to the next least expensive propellant combination, or a savings of 68%.

In almost every case, the hybrid version of a propellant family has a nearly identical cost to its bi-propellant counterpart. The spread between the hybrids and bi-propellant systems seen in the 10,000-person colony scenario is not present here because the 100-person colony uses a higher percentage of smaller vehicles, which tend to be more competitive for the hybrids.

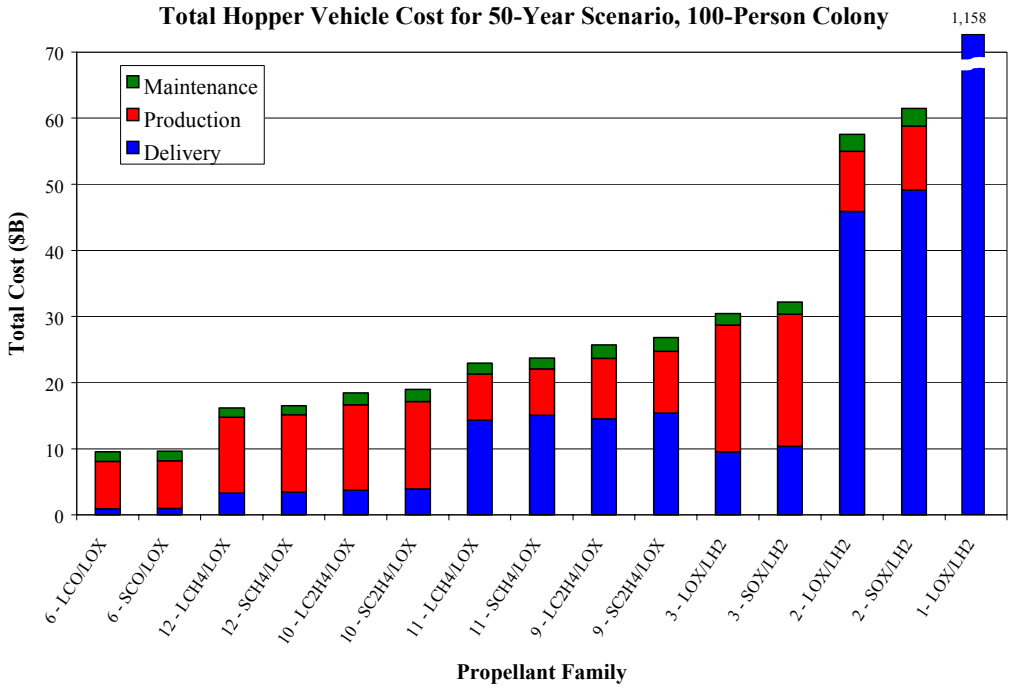

Figure 54. Total Flight Vehicle Cost for 50-Year Scenario; 100-Person Colony

7.2.3 Mars Aeroplane

The Mars aeroplane cost analysis considered the propellant type, development and production, and delivery from Earth to Mars. The total propellant requirements for this vehicle type are very small, so the cost of the propellant production and associated power systems were not included. Their contribution to the total cost is negligible assuming the propellant production/delivery capability already exists to support the hopper vehicles. For these reasons, the cost analysis does not distinguish between the propellant source (terrestrial/ISRU), only the propellant type. The results are summarized in Table 41. The differences in cost can be traced back to the propellant energy densities. The lower performance propellants require larger planes, resulting in more expensive hardware. The thermal management needs for LH_2 requires a comparably larger cryocooler, diminishing the benefits of LH_2/LOX's high energy density, and resulting in a tie with LCH_4/LOX for the least expensive propellant type. Delivery expenses were less than $0.01B for all propellant types and maintenance expenses were not considered.

Table 41. Mars Aeroplane Cost Breakdown for 50-Year Scenario; 100-Person Colony

Propellant	Production ($B)	Delivery ($B)	Total ($B)
LCH4/LOX	0.23	~0	0.23
LH2/LOX	0.23	~0	0.23
LCH3OH/LOX	0.28	~0	0.28
LCO/LOX	0.40	~0	0.40

7.2.4 General Infrastructure

The general infrastructure costs are defined as those which are considered to be independent of the propellant family used. This includes personnel transport to Mars orbit and the general infrastructure to support life (habitats, power systems, life support, etc.). A cumulative cost summary is shown in Figure 55. In contrast to the high scenario, the total general infrastructure production cost is higher than the delivery cost, assuming 61% of the non-transportation price tag. The smaller production runs for the 100-person colony significantly drive up the hardware costs on a per part basis. Much of this increase can be attributed to the development expense being absorbed over a smaller number of units. The baseline $5000/kg delivery cost is assumed to be the same as the 10,000-person colony case. The delivery cost is broken down in Figure 56. There are five major delivery cycles at the beginning of the colony life and the remaining cycles only require the transport of people and hardware associated with maintenance.

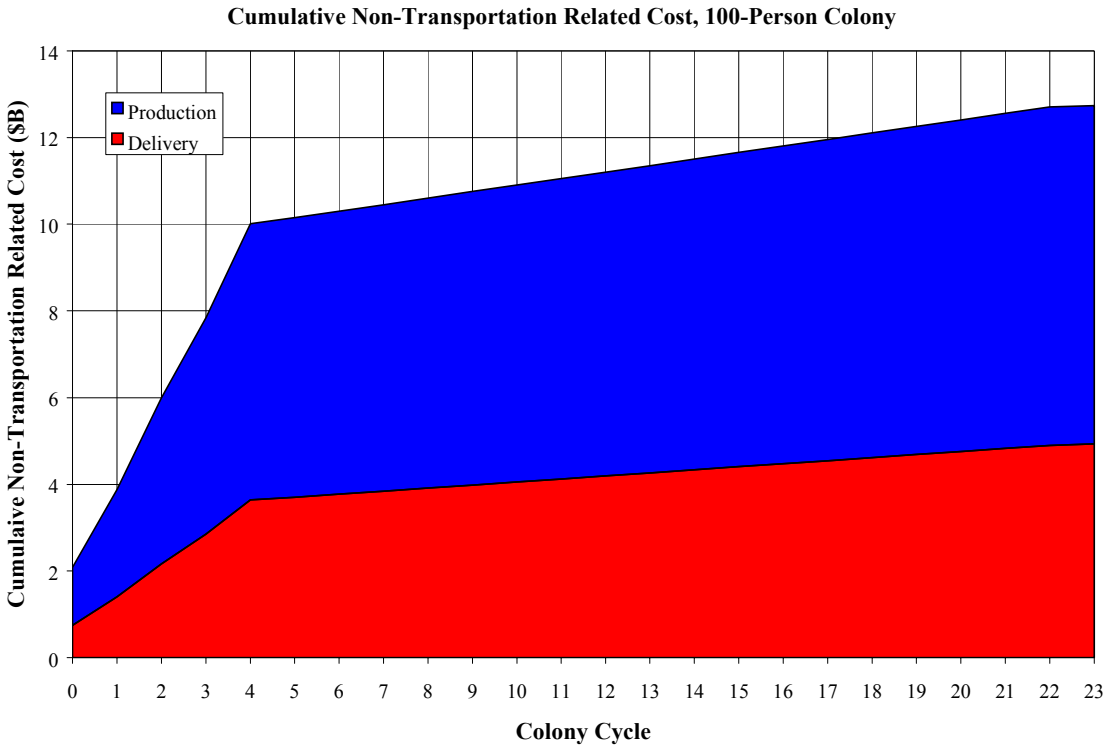

Figure 55. Total Cumulative General Infrastructure Cost; 100-Person Colony Cycle

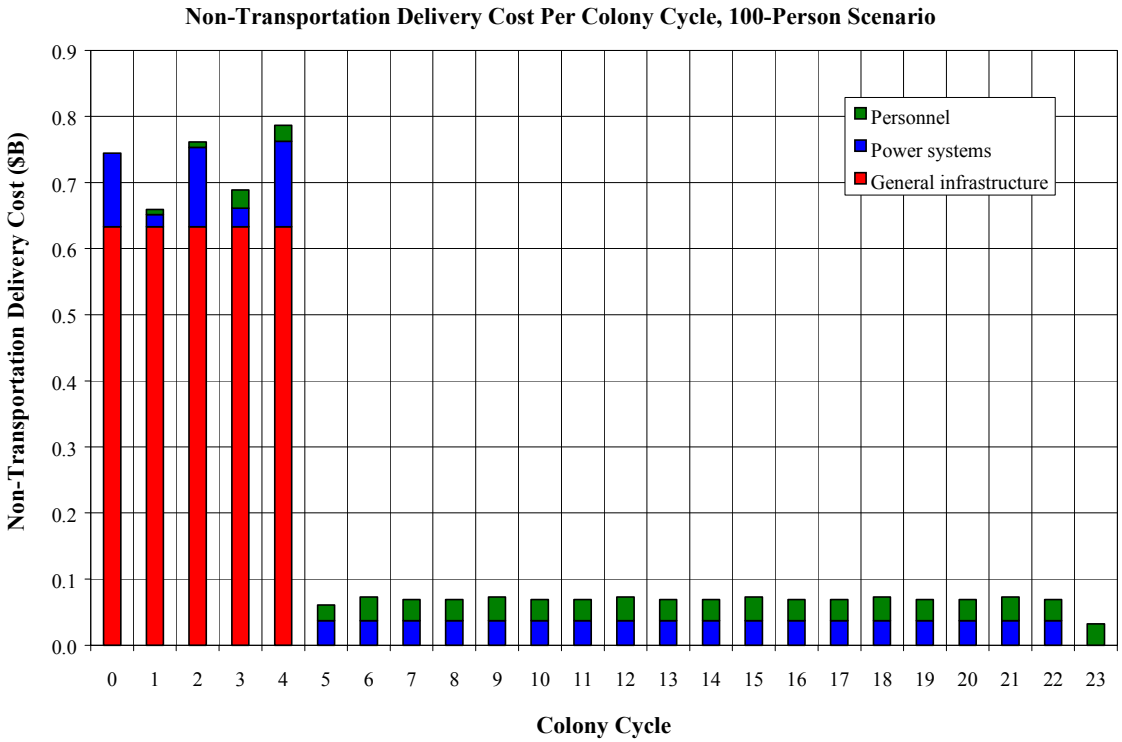

Figure 56. General Infrastructure Delivery Cost Per Colony Cycle; 100-Person Colony

7.3 10,000-Person Colony Analysis Results

The results are broken down into three major areas: ground vehicles, flight vehicles, and non-transportation related costs (general infrastructure: habitats, life support, and all other required facilities/equipment unrelated to transportation). These cost categories are further divided into production, delivery, and maintenance. Production includes both development and manufacturing costs, delivery is defined as shipping items from the surface of the Earth to Mars orbit, and maintenance is keeping equipment running properly. Replacement parts for the maintenance of propellant processors and nuclear power systems were factored into the analysis, however, the costs associated with them are not included in the "Maintenance" cost category. Rather, they were included in the "Production" cost to streamline our analysis process.

The only operations costs associated with human labor included in the results presented here are for flight and ground vehicle maintenance. Results do not include the cost for any terrestrial or Martian management/operations to support the colony activities, or the salary for any of the colony Martians. Labor costs are also included in the hardware production cost.

The results presented here assume an Earth-to-Mars orbit delivery cost of $5000/kg. It does not directly factor in the cost to develop the Earth-to-Mars orbit transportation system, or distinguish between the cost to deliver people and hardware. If the delivery cost was significantly higher, it would have a direct impact on the total colony cost. Nevertheless, this analysis captures the relative cost of the various propellant families, and the effects of other delivery costs (both higher and lower) are explored in the sensitivity analysis section of this report.

Figure 57 displays the total relative 10,000-person colony cost for the different propellant families, shown as a percentage of the lowest cost family: PF6-LCO/LOX (ISRU carbon and oxygen). These results

include the costs for: (1) ground vehicles, (2) hopper vehicles, and (3) non-transportation related costs. The propellant combinations considered in this study for the hopper and ground vehicles are different. However, the cost differential among the ground vehicle propellant families is relatively small, and as such, Figure 57 was generated under the assumption that PF6-LCO/LOX was used for all the ground vehicles. Similarly, the total cost for non-transportation costs are not dependant on the propellant family. Therefore, the cost ranking shown in Figure 57 is solely attributed to the difference in hopper vehicle costs (discussed in detail under Section 7.3.2).

The most striking aspect of Figure 57 is the cost of PF1 relative to the other propellant families. PF1 is the only propellant family that uses all terrestrial propellants. The total cost for this scenario is over 49 times more expensive than the lowest cost propellant family (PF6), using all ISRU propellants. These results clearly illustrate the enormous benefits of ISRU. Similarly, increasing the amount of ISRU implementation decreases the total cost for every propellant family.

The non-transportation related costs represents 88% of the total cost in Figure 57 for PF6-LCO/LOX. This is a result of an aggressively growing population over the 50-year, 10,000-person colony scenario which requires continuous infrastructure buildup. The dominance of the non-transportation related costs diminishes the relative influence of the propellant family implemented.

These results assume a total Earth-to-Mars orbit delivery cost of $5000/kg. If the delivery cost were higher, this would further increase the benefits of ISRU, and substantially increase the total colony cost. The effects of other delivery costs (both higher and lower) are discussed in the sensitivity analysis section of this report.

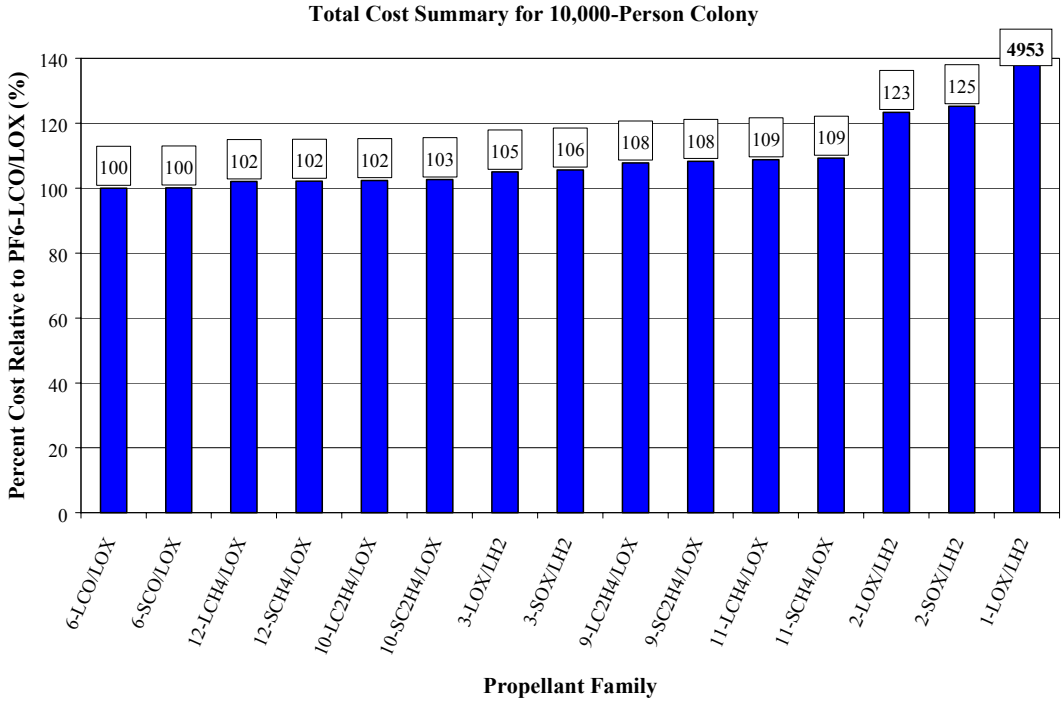

Figure 57. Total Cost Summary for 10,000-Person Colony

The lowest total cost is achieved by using CO/LOX, where the results for the hybrid and bi-propellant case are nearly identical (within 0.1%). Table 42 summarizes the results for the use of PF6-LCO/LOX.

The ground vehicles are less expensive to manufacture than the flight vehicles; however, the large number of them required for colony life pushes their total cost 41% higher than the flight vehicles. The total price for the 50-year scenario is dominated by the delivery of non-transportation related materials (68% of total cost).

Because the propellants are recycled, ISRU does not generate significant savings for the ground vehicles. Increasing the amount of ISRU implementation for the flight vehicles significantly reduces their cost for every propellant combination considered.

Table 42. Total 50-Year Cost Summary for 10,000-Person Colony Using LCO/LOX

	Production ($B)	Delivery ($B)	Maintenance ($B)	Subtotal ($B)
General Infrastructure	128.1	435.8	NA[1]	**563.9**
Ground Vehicles	35.0	7.8	2.4	**45.2**
Hopper Vehicles	20.6	4.9	6.0	**31.5**
Subtotal	**183.7**	**448.5**	**8.4**	**Total: 640.6**

[1]Maintenance costs were integrated into the production cost

7.3.1 Ground Vehicles

Ground vehicles are the backbone of the Martian colony transportation system. They use significantly less propellant than the flight vehicles to travel a given distance on the planet, and are therefore utilized to meet the majority of the colony's mobility requirements. The ground vehicles store their spent propellant and later recycle it via electrolysis for re-use, resulting in extremely low propellant manufacturing requirements. However, the vast distances traveled by the ground vehicles during the 50-year colony period requires a large number of them (258), primarily to replace the ones that have worn out.

A cost breakdown for all ground vehicle propellant families is shown in Figure 58 and Table 43. Seventy-seven percent of the total cost is associated with the development and manufacturing of the equipment. Approximately 96% of this production cost is attributed to the ground vehicles and the balance is for the power and propellant production systems. The remaining 23% of the total cost is for hardware delivery and ground vehicle maintenance.

The lowest total ground vehicle cost is achieved by propellant families PF3-LH_2/LOX (all ISRU propellant) and PF2-LH_2/LOX (ISRU oxygen and terrestrial hydrogen) at a cost of $41.7B and $41.8B respectively. The cumulative cost as a function of colony cycle for PF3 is shown in Figure 59. In general, the total relative cost for the remaining propellant combinations is established first by propellant energy density (J/kg) and then by amount of ISRU implementation. For example, LCH_4/LOX has the second highest energy density and the two propellant families using this combination are the next least expensive after the LH_2/LOX families (highest energy density). The total ISRU case (PF12) costs slightly more than the partial ISRU case (PF11). The only exception to this ordering is for the only total terrestrial case of LH_2/LOX (PF1), which costs more than the partial ISRU case (PF3). The difference between the two cost extremes for all the propellant families is only 8.4 %, or $3.5B. Based on this small difference and the major savings provided by using CO/LOX for the flight vehicles, CO/LOX may be the appropriate propellant combination for the ground vehicles as well to provide a common propellant.

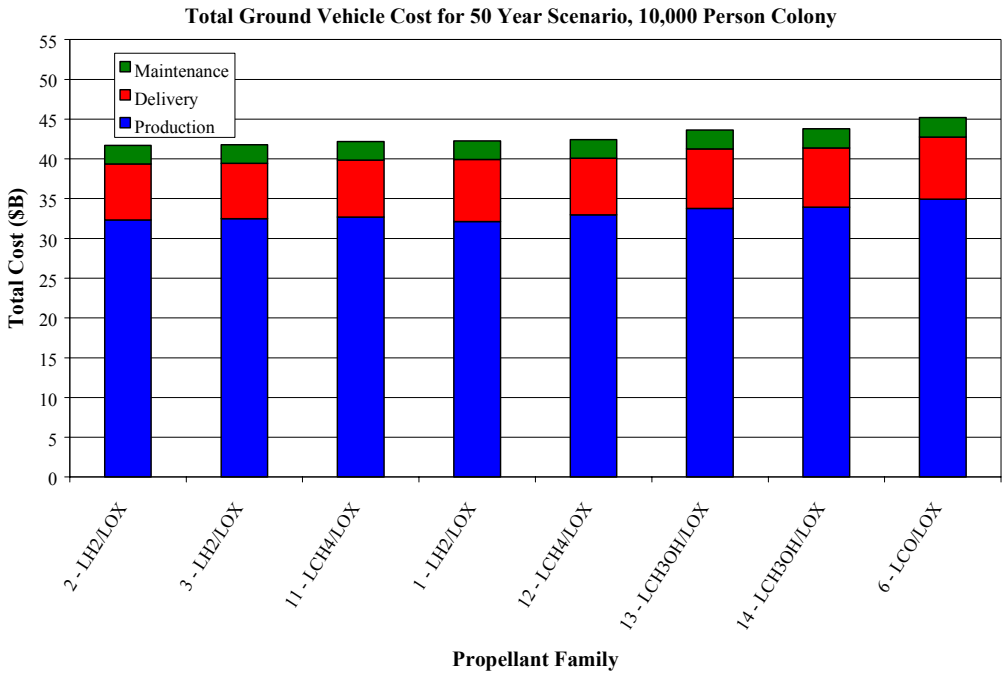

Figure 58. Total Ground Vehicle Cost for 50-Year Scenario; 10,000-Person Colony

Table 43. Ground Vehicle Cost Breakdown for 50-Year Scenario; 10,000-Person Colony

Propellant Family	Propellant	Production ($B)	Delivery ($B)	Maintenance ($B)	Total ($B)
2	LH2/LOX	32.3	7.1	2.3	41.7
3	LH2/LOX	32.5	7.0	2.3	41.8
11	LCH4/LOX	32.7	7.2	2.4	42.2
1	LH2/LOX	32.2	7.8	2.3	42.3
12	LCH4/LOX	33.0	7.1	2.4	42.4
13	LCH3OH/LOX	33.8	7.5	2.4	43.7
14	LCH3OH/LOX	33.9	7.5	2.4	43.8
6	LCO/LOX	35.0	7.8	2.4	45.2

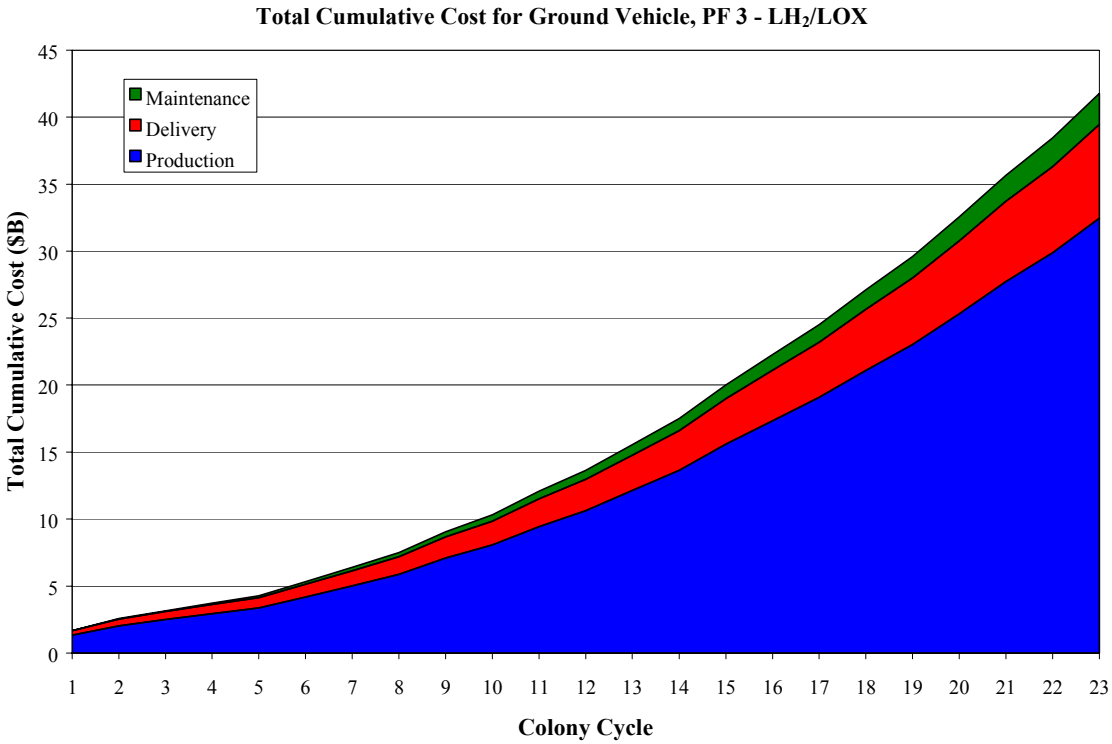

Figure 59. Total Cumulative Cost for Ground Vehicles, PF3 (ISRU LH_2/LOX)

7.3.2 Flight Vehicles

A breakdown of the flight vehicle costs is given in Figure 60 and Table 44. Because the propellants are exhausted to the atmosphere during each flight, the cost ranking is primarily attributed to the expense associated with delivering propellants, propellant production units, and power systems. A total of only 23 flight vehicles are required to meet the needs of the 50-year, 10,000-person colony. The CO/LOX propellant combination costs ~40% less than the next least expensive one (PF12-CH_4/LOX), with very little difference between the hybrid and bi-propellant cases. The cost spread among the different propellant families is enormous, with the total cost of the most expensive case coming in almost 1000 times more than the CO/LOX case. Not surprisingly, the ISRU propellant families tend to have higher equipment production costs and the families that utilize terrestrial propellants are driven by the delivery cost. With the exception of the huge vehicles required for PF1, the vehicle maintenance cost for all propellant families is comparable.

There are six distinct cost groupings for the flight vehicles, summarized in Table 45. The lowest cost group includes complete ISRU production of propellants that do not contain any hydrogen. The next least expensive group is comprised of complete ISRU propellants that contain a small percentage of hydrogen. The third cost grouping consists of total ISRU H_2/LOX which requires massive and expensive hardware to produce the hydrogen. The fourth cost group includes partial ISRU C_2H_4/LOX and CH_4/LOX which have high delivery costs associated with shipping terrestrial hydrogen. The fifth group is H_2/O_2 using terrestrial H_2, where the costs of shipping hydrogen are even higher. The last group is for the use of all terrestrial propellants, where the propellant delivery costs dwarf all other expenses. It should be noted that the extreme cost of this family (PF1) is partially a result of enormous roundtrip vehicles that are on the fringe of what can be accomplished without ISRU for H_2/LOX (per the roundtrip missions defined in the traffic model).

The fundamental finding of the flight vehicle study is that the superior propulsive performance offered by increasing amounts of hydrogen does not offset the high cost associated with either shipping hydrogen or making it in-situ (for the 10,000 person colony scenario). A second important result is that increasing the amount of ISRU implementation significantly reduces the total cost for every propellant combination considered.

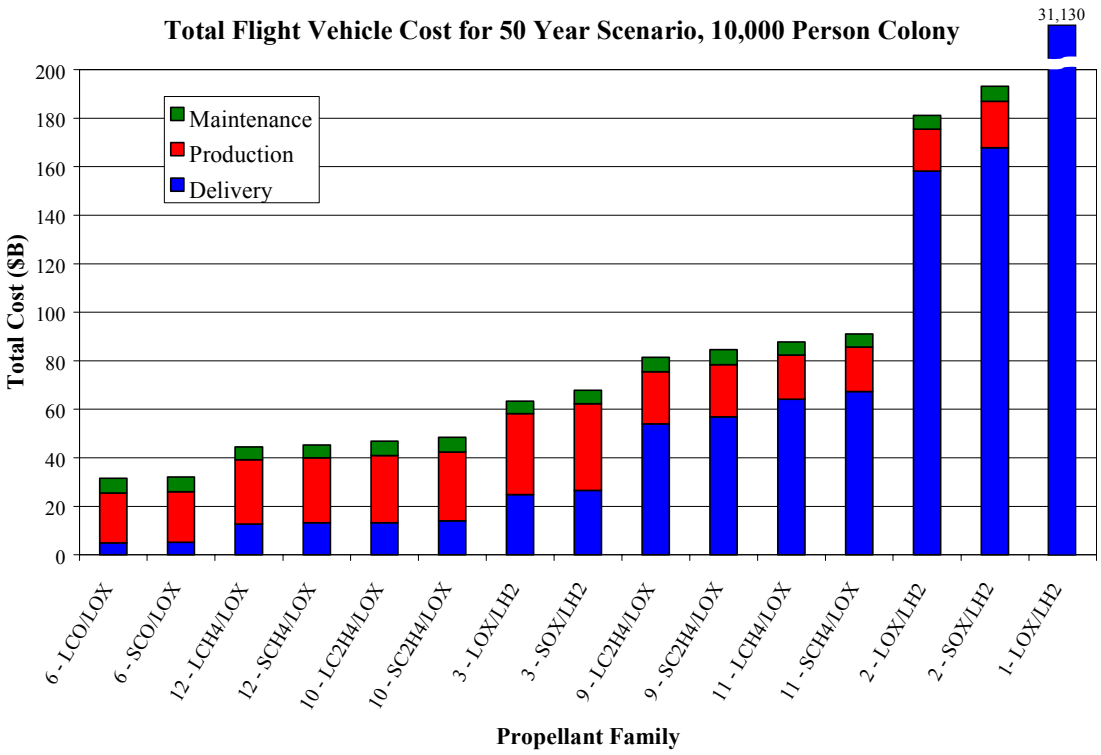

Figure 60. Total Flight Vehicle Cost for 50-Year Scenario; 10,000-Person Colony

Table 44. Flight Vehicle Cost Breakdown for 50-Year Scenario; 10,000-Person Colony

Propellant Family	Propellant	Production ($B)	Delivery ($B)	Maintenance ($B)	Total ($B)
6	LCO/LOX	20.6	4.9	6.0	31.5
6	SCO/LOX	20.8	5.2	6.1	32.2
12	LCH_4/LOX	26.5	12.7	5.3	44.5
12	SCH_4/LOX	26.8	13.2	5.3	45.3
10	LC_2H_4/LOX	27.7	13.2	5.9	46.8
10	SC_2H_4/LOX	28.4	14.0	6.0	48.4
3	LOX/LH_2	33.3	24.9	5.2	63.4
3	SOX/LH_2	35.7	26.5	5.6	67.8
9	LC_2H_4/LOX	21.4	54.0	6.1	81.5
9	SC_2H_4/LOX	21.5	56.9	6.2	84.6
11	LCH_4/LOX	18.2	64.1	5.5	87.8
11	SCH_4/LOX	18.3	67.3	5.5	91.1
2	LOX/LH_2	17.2	158.2	5.8	181.2
2	SOX/LH_2	19.1	167.8	6.3	193.1
1	LOX/LH_2	71.5	30,982	76.7	31,130

Table 45. Flight Vehicle Cost Groupings for 10,000-Person Colony

Cost Group	Propellant Family	Propellant	Total Cost ($B)	Group Characteristics
1	6	LCO/LOX	31.6	Complete ISRU production of propellants that do not contain any hydrogen
	6	SCO/LOX	32.2	
2	12	LCH_4/LOX	44.5	Complete ISRU production of propellants that contain a relatively small percentage of hydrogen (3.76% and 5.32% of total propellant mass for C_2H_4/LOX and CH_4/LOX, respectively)
	12	SCH_4/LOX	45.3	
	10	LC_2H_4/LOX	46.8	
	10	SC_2H_4/LOX	48.4	
3	3	LOX/LH_2	63.4	Complete ISRU production of propellants that contain a high percentage of hydrogen (H_2/LOX, 15.38% H_2 by mass)
	3	SOX/LH_2	67.8	
4	9	LC_2H_4/LOX	81.5	ISRU O_2 and terrestrial H_2 propellants that contain a relatively small percentage of hydrogen (C_2H_4/LOX and CH_4/LOX)
	9	SC_2H_4/LOX	84.6	
	11	LCH_4/LOX	87.8	
	11	SCH_4/LOX	91.1	
5	2	LOX/LH_2	181.2	ISRU O_2 and terrestrial H_2 propellants that contain a high percentage of hydrogen (H_2/LOX, 15.38% H_2 by mass)
	2	SOX/LH_2	193.1	
6	1	LOX/LH_2	31,130	All terrestrial propellants (no ISRU)

7.3.3 General Infrastructure

The general infrastructure costs are defined as those which are considered to be independent of the propellant family used. This includes personnel transport to Mars orbit and the general infrastructure to support life (habitats, power systems, life support, etc.). A cumulative cost summary is shown in Figure 61, where the cost is overwhelmed by the delivery of people and equipment. The delivery cost is broken down in Figure 62, illustrating that the delivey of general infrastructure dominates the total cost for the entire 10,000-person colony scenario.

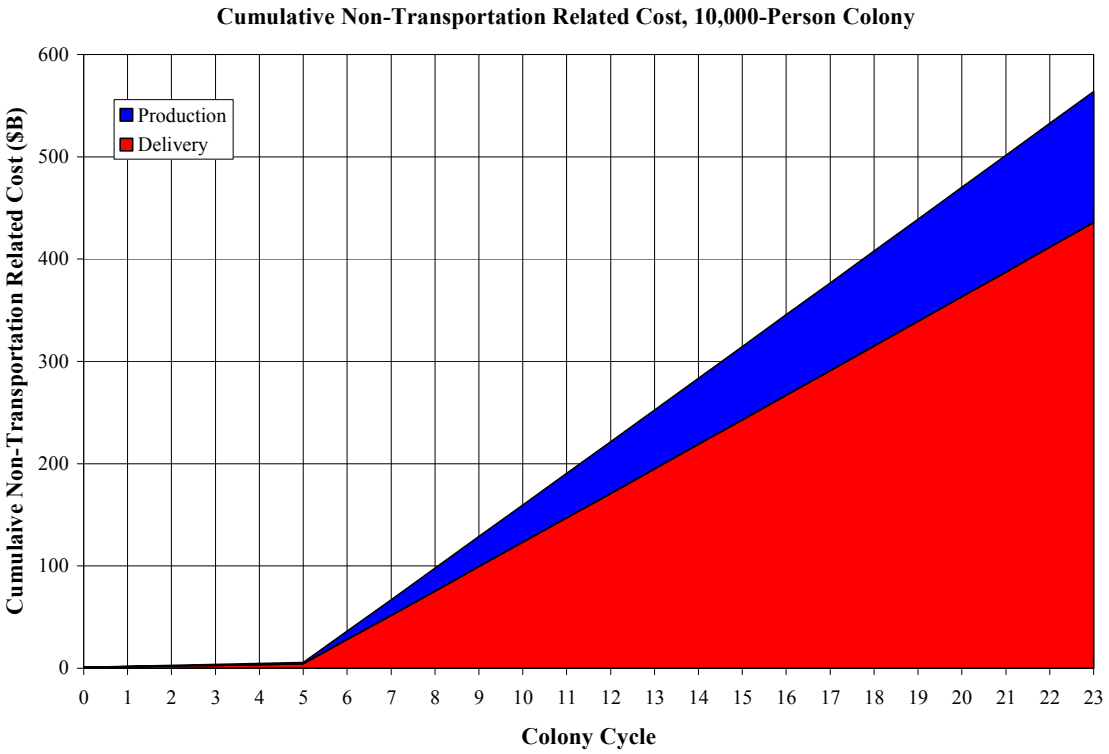

Figure 61. Total Cumulative General Infrastructure Cost; 10,000-Person Colony Cycle

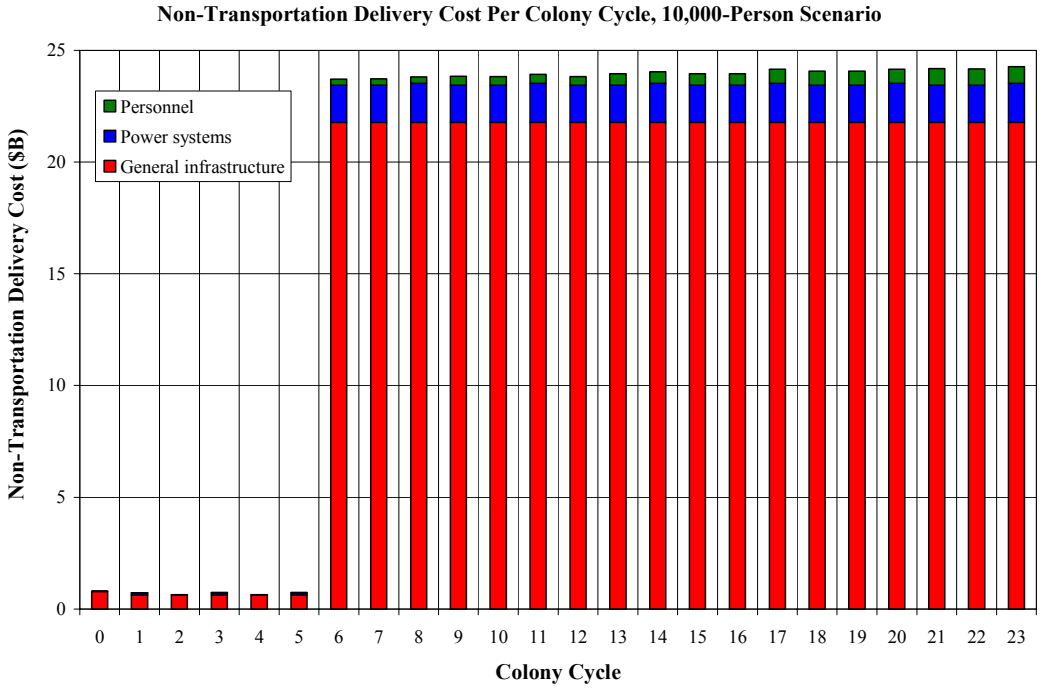

Figure 62. General Infrastructure Delivery Cost Per Colony Cycle; 10,000-Person Colony

8.0 SENSITIVITY ANALYSIS

A sensitivity analysis was conducted to explore the ramifications of uncertainties in the program study. The effects on the ground vehicles were not considered because all the ground vehicle propellant families have similar cost breakdowns (production, delivery, and maintenance) and the cost differential among them is small. This is in contrast to the results for the hopper vehicles, which the sensitivity analysis focuses on. Because the results for the hybrid and liquid hopper vehicles are nearly the same, the liquid systems were analyzed to simplify the task. The effects and trends on hybrid systems will be the same as their liquid counterpart with only a small offset in total cost.

Sensitivity variables include:

- Earth-to-Mars orbit delivery cost
- The use and cost of power beaming
- Production costs
- Combined production and delivery costs
- Hydrogen availability on Mars
- Propellant integration.
- Earth-to-Mars orbit hydrogen delivery cost.

The results indicate that the choice of CO/LOX as the lowest-cost propellant combination is amazingly robust to uncertainty in these variables. Based on these results and the assumption of the study ground rules, CO/LOX is clearly the propellant combination of choice for all vehicles in both the 100-person and 10,000-person colonies.

The only exception to this finding is if subsurface water is readily available at the bases. In this case, ISRU LH_2/LOX would become the lowest cost propellant combination for the 10,000-person colony and cost about the same as PF6-LCO/LOX for the 100-person colony.

8.1 Earth-to-Mars Orbit Delivery Cost

The cost of delivering hardware and supplies from Earth-to-Mars orbit has a direct impact on the study results. The baseline cost set for both the 10,000-person and 100-person colonies were established as $5000 per kg, and is based on an analysis conducted by SAIC. The effects of this cost parameter varying from $100 to $50,000 per kg on the overall study results were investigated for the hopper vehicles and the total scenario cost. The analysis illustrated that PF6-CO/LOX is the propellant combination of choice for almost this entire range, with PF11-LCH4/LOX edging it out by a small margin when the delivery cost is reduced to $100/kg. As expected, decreasing the delivery cost reduces the cost savings provided by the use of ISRU, and vice versa.

100-Person Colony. Figure 63 and Table 45 parametrically display the effects of increasing the delivery cost above $5000 per kg for the 100-person scenario hopper vehicles. Increasing the delivery cost above $5000 does not change the order of the 3 least expensive propellant combinations: PF6, PF10, and PF12. However, CO/LOX is not as sensitive to this cost as PF10 and PF12, and so costs are comparably less as the delivery cost is increased. Decreasing the amount of ISRU implementation inflates the penalty paid for higher delivery costs, as observed by comparing PF1, PF2, and PF3. These results demonstrate that PF6-CO/LOX is still the most economical choice for all delivery costs greater than $5000/kg.

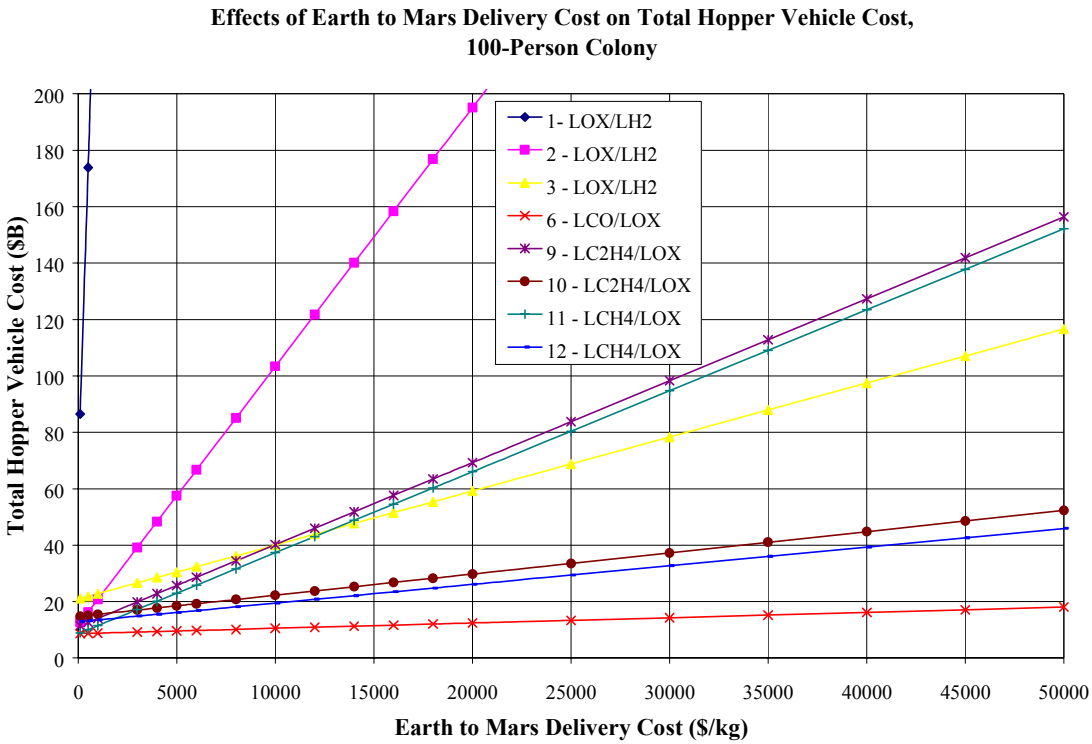

Figure 63. Effects of a Delivery Cost Higher than $5000 Per kg, 100-Person Colony

Table 45. Effects of a Delivery Cost Higher than $5000 Per kg

	Total Cost		
Delivery Cost ($/kg)	**PF6-LCO/LOX ($B)**	**PF12-LCH4/LOX ($B)**	**PF10-LC2H4/LOX ($B)**
5000	9.59	16.16	18.48
10000	10.53	19.47	22.24
30000	14.29	32.71	37.28
50000	18.05	45.95	52.32

Figure 64 parametrically displays the effects of decreasing the delivery cost below $5000 per kg for the 100-person colony hopper vehicles. Note that the results for PF1 do not fall within the scale of Figure 64. There is a unique delivery cost for each propellant type where the use of ISRU hydrogen becomes more expensive than shipping it form Earth. Table 46 summarizes these cross-over points by propellant combination.

Even assuming a delivery cost of zero, the use of all terrestrial propellants (PF1) is never less expensive than the partial ISRU case (PF2). This is a direct result of the very large roundtrip hopper vehicles required for PF1 (because they carry all of their propellant along for the return trip), where the vehicle costs are more expensive than the combined propellant processor and vehicle costs for PF2.

The high sensitivity slope of PF10-LCH4/LOX that renders it unattractive at high delivery costs is the same characteristic that pushes it into a close second place with PF6-LCO/LOX for very low delivery costs. Nevertheless, even assuming a delivery cost as low as $100 per kg, PF6 still represents the least expensive propellant combination.

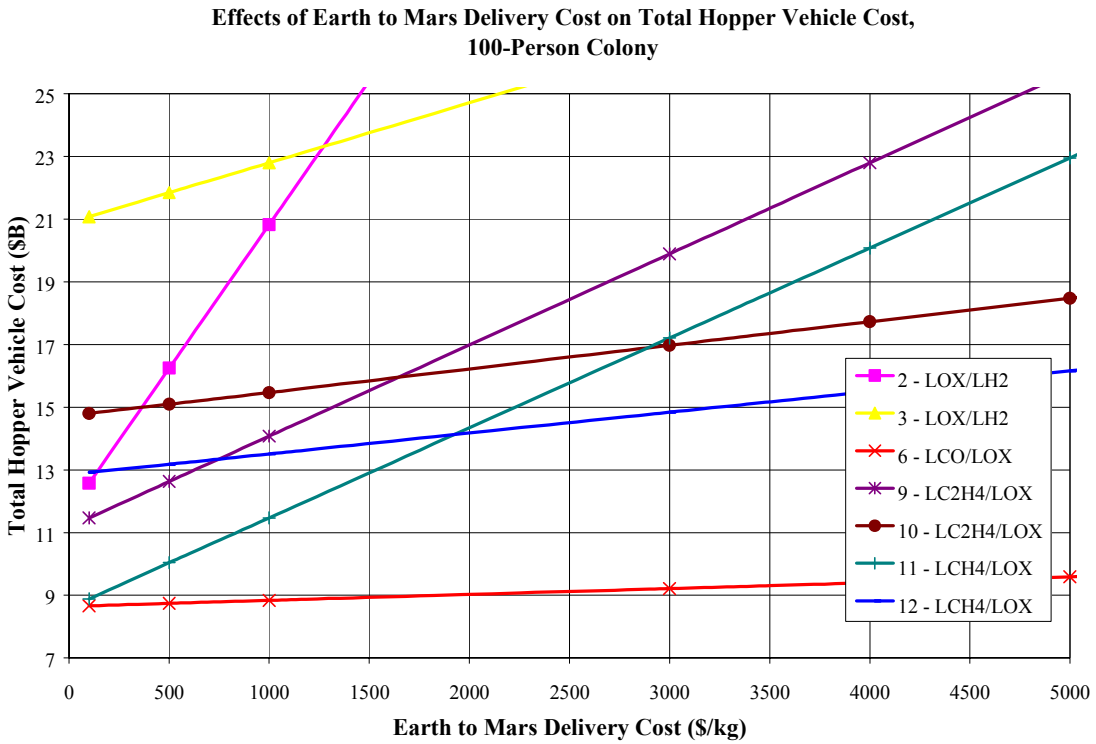

Figure 64. Effects of a Delivery Cost Lower than $5000 Per kg, 100-Person Colony

Table 46. Cross Over Delivery Costs for Hopper Vehicles, 100-Person Colony

Propellant Combination	Cross-Over Delivery Cost ($/kg)
LCH4/LOX	1910
LC2H4/LOX	1640
LOX/LH2	1270

10,000-Person Colony. Figure 65 parametrically displays the effects of increasing the delivery cost above $5000 per kg for the 10,000-person colony hopper vehicles. The results are analogous to the 100-person colony scenario. Increasing the delivery cost above $5000 does not change the cost order of any propellant combinations. Also analogous to the 100-person colony, CO/LOX is not as sensitive to the delivery cost as the rest of the families, so costs comparably less as the delivery cost is increased. Decreasing the amount of ISRU implementation inflates the penalty of higher delivery costs, observed by comparing PF1 (not shown), PF2, and PF3. These results demonstrate that PF6-CO/LOX is still the most economical choice for all delivery costs greater than $5000/kg.

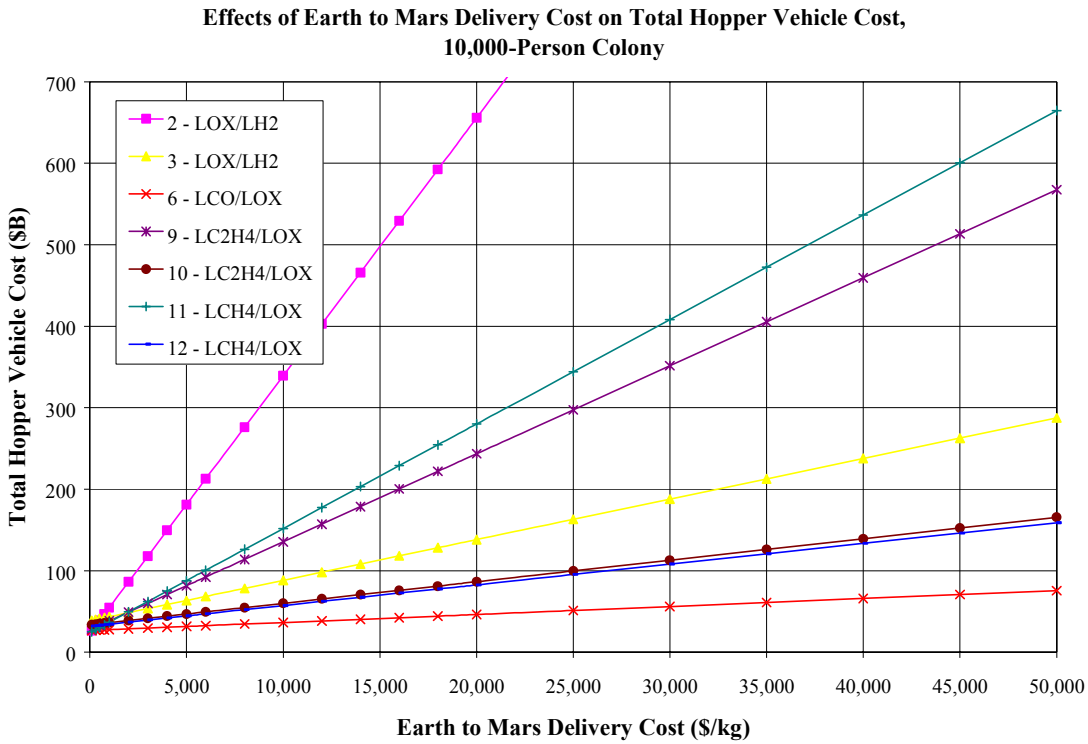

Figure 65. Effects of a Delivery Cost Higher than $5000 Per kg, 10,000-Person Colony

Figure 66 parametrically displays the effects of decreasing the delivery cost below $5000 per kg for the 10,000-person colony hopper vehicles. There is a unique delivery cost for each propellant type where the use of ISRU hydrogen becomes more expensive than shipping it form Earth. Table 47 summarizes these cross-over points by propellant combination. The delivery cost per kg at which terrestrial hydrogen breaks even with ISRU hydrogen is over half as much for the 10,000-person colony, as compared to the 100-person colony. This is likely a result of larger-scale ISRU utilization, where the propellant processor units become less expensive on a per unit basis (due to larger production runs and development costs being absorbed into a higher number of units). For the same reasons as noted for the 100-person colony scenario, even assuming a delivery cost of zero, the use of all terrestrial propellants (PF1) is never less expensive than the partial ISRU case (PF2).

Even at a delivery cost of $500/kg, PF6-LCO/LOX is still the least expensive propellant combination by $3B, with PF11-LCH4/LOX (terrestrial hydrogen) in second place. If the delivery cost per kg can be reduced down to $100, three propellant combinations would be in close proximity: (1) PF11-LCH4/LOX: $25.0B; (2) PF2-LH2/LOX: $26.2; and (3) PF6-LCO/LOX: 26.7.

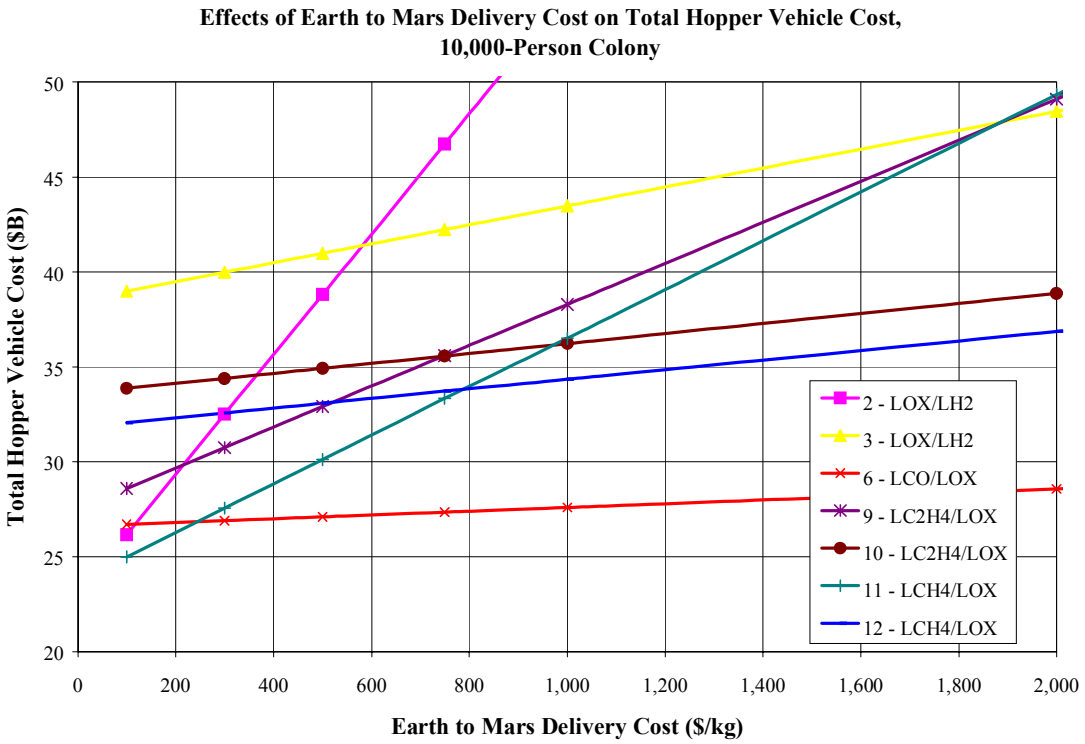

Figure 66. Effects of a Delivery Cost Lower than $5000 Per kg, 10,000-Person Colony

Table 47. Cross Over Delivery Costs for Hopper Vehicles, 10,000-Person Colony

Propellant Combination	Cross-Over Delivery Cost ($/kg)
LCH4/LOX	790
LC2H4/LOX	750
LOX/LH2	580

Total Colony Cost. Figure 67 parametrically displays the total colony cost for both the 100-person and 10,000-person colony scenarios as a function of the Earth-to-Mars delivery cost, assuming PF6-LCO/LOX is used for all vehicles. As would be expected, this cost parameter has a large impact on the total scenario cost.

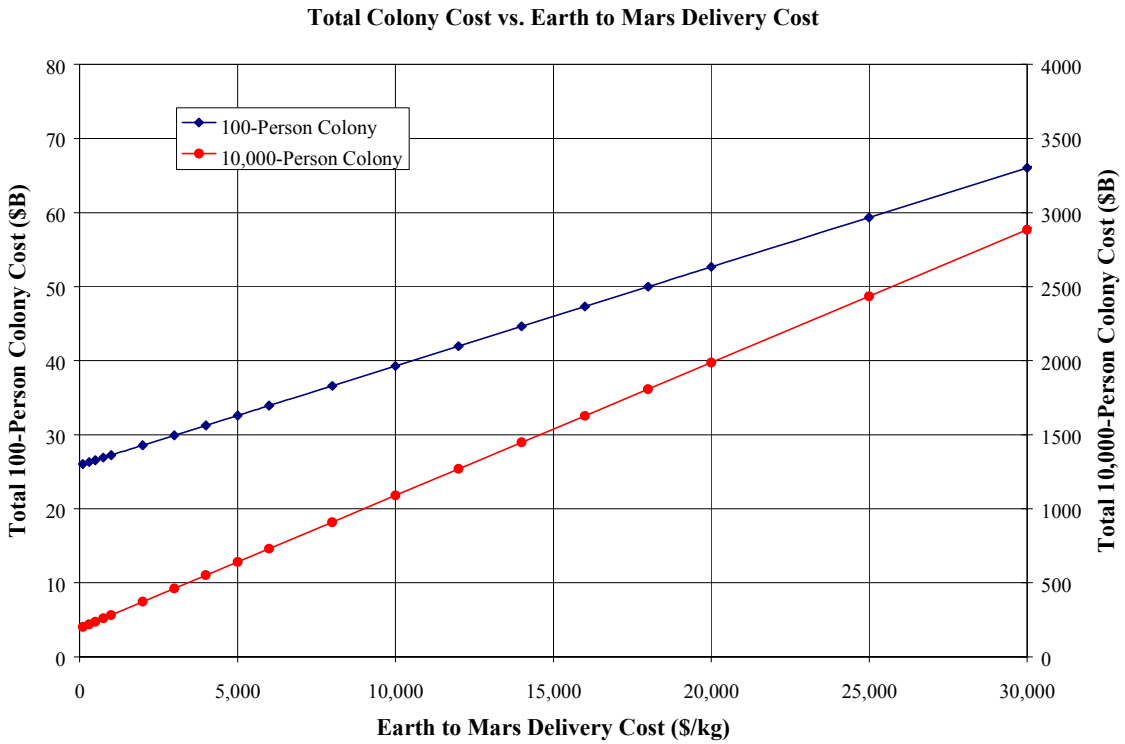

Figure 67. Effects of Delivery Cost on Total Minimum Scenario Cost

8.2 Power Beaming

Both the 10,000-person and 100-person scale colonies utilize power beaming for the roundtrip hopper vehicles (IRIS and ARES), primarily for propellant processing. The vehicles carry large microwave antennas and electronics systems to accept and condition energy beamed to them from a satellite. The satellite generates power via onboard nuclear systems and beams it to the vehicle on the ground. There is a significant amount of uncertainty with respect to the ultimate cost and reliability of this technology.

The only propellant family that does not utilize ISRU during the roundtrip hopper missions (all trips performed by vehicles IRIS and ARES) is PF1-LH2/LOX. This propellant family carries along all its propellant for the return trip, and as a result, the vehicles are enormous. The distances and payloads for these roundtrip missions push PF1-LH2/LOX to the fringe of what it can physically accomplish in a single-stage hop. The energy required for propellant cooling alone is on par with the propellant processing energy required by the other propellant families. Nevertheless, these vehicles could likely carry along small (in comparison to the rest of the vehicle) nuclear systems to supply their required power, rather than accepting it from a satellite.

None of the other propellant combinations can accomplish all of the IRIS or ARES missions if they have to carry along all of their propellant for the return trip, or a nuclear power reactor or RTG for propellant processing. Thus, power beaming enables these two vehicles to use all of the propellant combinations in the study by greatly reducing the mass of the onboard power system (reduced to a receiver, conditioner, and distribution network).

The unwieldy cost of the huge PF1-LH2/LOX vehicles rules them out as a realistic alternative to power

beaming. If power beaming were not used, the following approaches might be employed in its absence:

- Reduce the payload and trip distance demands of the roundtrip missions and carry on-board power systems for propellant processing
- Allow multiple hops to complete the roundtrip missions
- Increase the mission duration to allow more time for propellant processing (reduces the size and mass of the on-board power system)
- The use of an advanced propellant or propulsion system that offers a significantly higher specific impulse than LH2/LOX
- Send out a mobile nuclear powered rover in advance to the landing site to supply power to the vehicles. This may not always be feasible and would largely defeat the purpose of the robotic IRIS missions. However, it could keep the manned ARES missions to a short duration, to the benefit of the crew.

One of the fundamental findings of this study is that shipping hydrogen from Earth or extracting if from the atmosphere does not pay for the increased performance offered by using it. Comparing this result against the list of alternatives to power beaming suggests that the power beaming assumption does not have a major impact on the selection of CO/LOX as the winner. Similarly, the propellant integration analysis (discussed elsewhere in this section) calculated the cost distribution by vehicle type for the highest performing propellant combinations. This analysis demonstrated that CO/LOX is still the least expensive propellant combination for those vehicle types that do not rely on power beaming.

The power requirements for both roundtrip vehicles by propellant combination are listed in Table 48. If the cost of the power beaming system were to be increased and the total cost related to the amount of power required, it would tend to widen the gap between the higher and lower cost propellant combinations. One exception to this trend is for the comparison between CO/O_2 and CH_4/O_2. That is, PF6 has a lower total cost than PF12, however, PF6 requires more beamed energy. Additionally, the power beaming system contributes a larger percentage of the overall cost for the 100-person scale colony, where there is a much smaller amount of hardware required. For these reasons, the most potentially interesting case of increased power beaming costs would be for the 100-person colony, comparing the effects on PF6 and PF12.

Table 48. Power Requirements for Roundtrip Vehicles

Propellant Combination	IRIS Power Requirements (kW)	ARES Power Requirements (kW)
1-LOX/LH2	424	914
2-LOX/LH2	75.7	1679
2-SOX/LH2	109	2415
3-LOX/LH2	75.7	1679
3-SOX/LH2	109	2415
6-LCO/LOX	35.3	1175
6-SCO/LOX	31.8	1246
9-LC2H4/LOX	63.2	2308
9-SC2H4/LOX	67.2	2579
10-LC2H4/LOX	63.2	2308
10-SC2H4/LOX	67.2	2579
11-LCH4/LOX	26.2	784
11-SCH4/LOX	25.4	831
12-LCH4/LOX	26.2	784
12-SCH4/LOX	25.4	831

The baseline beamed power system cost for these two propellant families are as follows:

- Total base cost for PF6-LCO/LOX power beaming: $670M
- Total base cost for PF12-LCH4/LOX power beaming: $500M

These baseline costs do not include development of the nuclear power system itself (several of them are already required for the colony operations).

The total hopper vehicle cost for the liquid cases of PF6 and PF12 are parametrically compared against a multiplier, defined as the factor by which the baseline cost of the power beaming system is multiplied, in Figure 68. The cross-over point for the two propellant families exists at a multiplier of 40 where the power beaming system costs $26.8B for PF6. At this point, the cost of the power beaming system would be approaching the cost of the entire 100-person colony including all hardware, infrastructure, and delivery costs. While it's possible that the total colony cost could be much higher than predicted here, it's unlikely that the power beaming system would share such a disproportionate cost burden.

The uncertainty in the power beaming cost does not appear to bring the cost ordering of the propellants into question for the 100-person scale colony. The effects of increased power beaming system cost for the 10,000-person colony are even less significant.

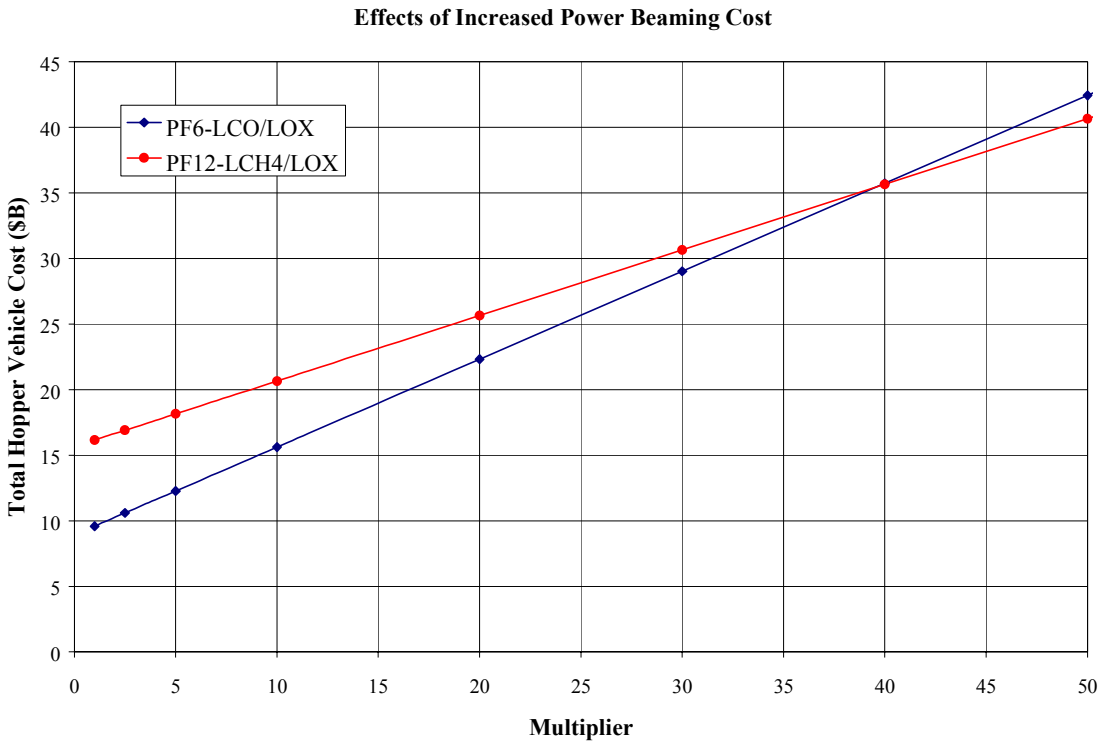

Figure 68. Hopper Vehicle Sensitivity to Power Beaming Cost Multiplier

8.3 Production Costs

The sensitivity of production cost is considered in this section.

100-Person Colony. The total hopper vehicle cost for the 100-person colony is shown in Table 49 for reference. The effects of uncertainty in the hardware costs (development and production) were explored by using a blanket multiplier to inflate or reduce the total cost of the hopper vehicle hardware (vehicles, power systems, and propellant processors). The results are shown in Figure 69, where the production cost was multiplied by the "multiplier" factor shown on the horizontal axis and factored into the total cost. PF1 does not fall within the range of the vertical axis of Figure 69.

PF6-LCO/LOX remains the least expensive propellant family over the entire range of multipliers considered (0.25 to 50). Interestingly, at a multiplier of only 1.7 and 2.5, PF11-LCH4/LOX crosses over PF10-LC2H4/LOX and PF12-LCH4/LOX, respectively, and becomes less expensive as the hardware cost is increased beyond these points. Reducing the hardware cost by a factor of 4 does not affect the order of the three lowest cost propellant families.

Table 49. Hopper Vehicle Cost Breakdown for 50-Year Scenario; 100-Person Colony

Propellant Family	Propellant	Production ($B)	Delivery ($B)	Maintenance ($B)	Total ($B)
6	LCO/LOX	7.17	0.94	1.48	9.59
6	SCO/LOX	7.20	0.97	1.49	9.66
12	LCH4/LOX	11.48	3.31	1.37	16.15
12	SCH4/LOX	11.69	3.46	1.38	16.52
10	LC2H4/LOX	12.91	3.76	1.81	18.47
10	SC2H4/LOX	13.21	3.95	1.85	19.02
11	LCH4/LOX	6.96	14.35	1.64	22.95
11	SCH4/LOX	7.02	15.05	1.66	23.73
9	LC2H4/LOX	9.15	14.52	2.03	25.71
9	SC2H4/LOX	9.34	15.40	2.09	26.83
3	LOX/LH2	19.13	9.57	1.76	30.46
3	SOX/LH2	19.98	10.38	1.81	32.18
2	LOX/LH2	9.09	45.87	2.57	57.53
2	SOX/LH2	9.68	49.12	2.66	61.46
1	LOX/LH2	28.03	1093	36.58	1158

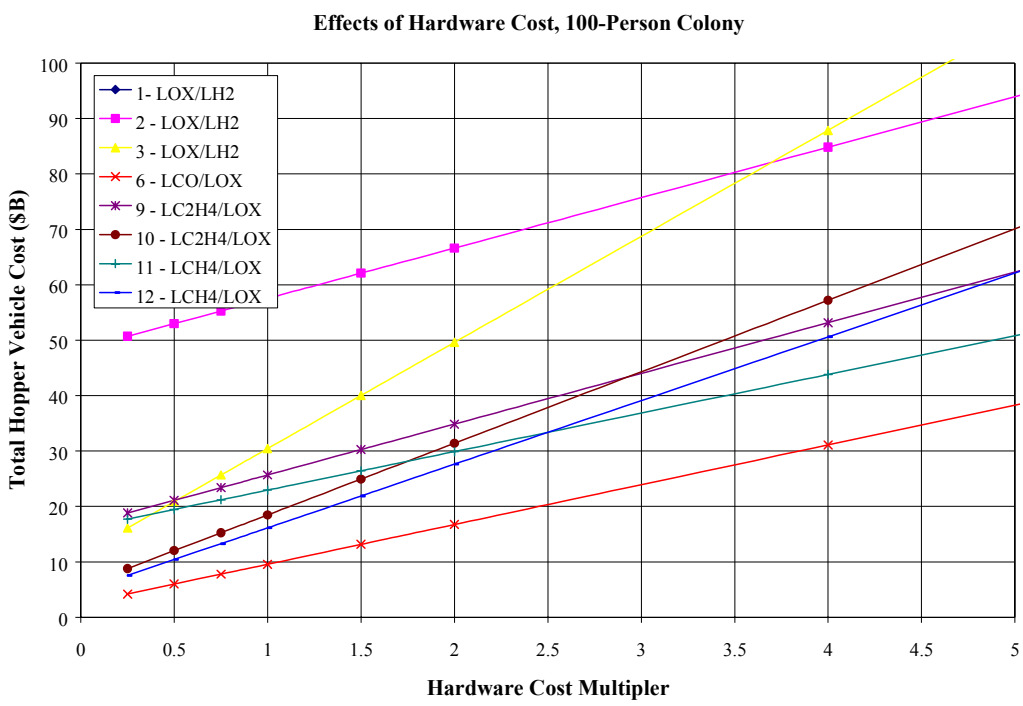

Figure 69. Total Hopper Vehicle Cost vs. Hardware Cost Multiplier, 100-Person Colony

10,000-Person Colony. The same multiplier approach was taken for the 10,000-person colony as well; the results are shown in Figure 70**.** PF6-LCO/LOX remains the least expensive propellant family over the entire range of multipliers considered (0.25 to 50) for the 10,000 person colony. PF11-LCH4/LOX is one of the highest cost propellant combinations at the baseline hardware cost level (multipler = 1). However, as the hardware multiplier is increased it begins to become less expensive than the other combinations at a multiplier of 2.6 and becomes the second lowest cost propellant family at a multiplier of 6.2. Decreasing the hardware cost by a factor of up to 4 does not affect the cost ordering of any of the propellant families.

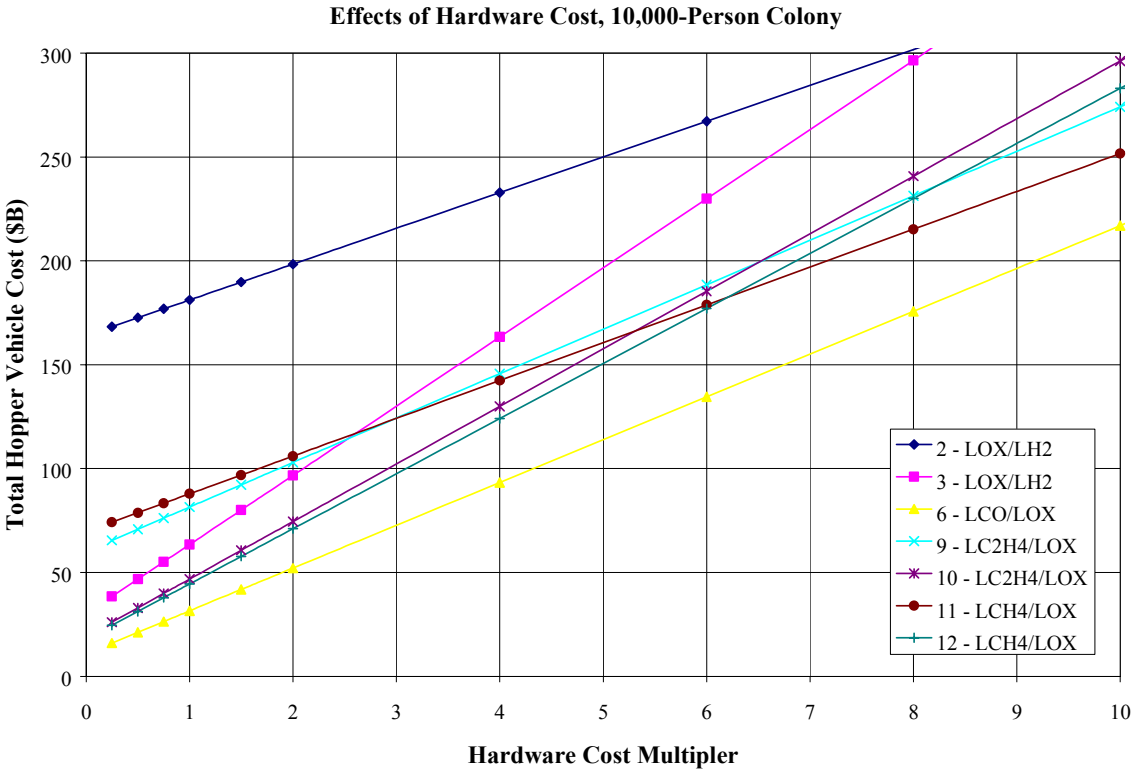

Figure 70. Total Hopper Vehicle Cost vs. Hardware Cost Multiplier, 10,000-Person Colony

8.4 Combined Production and Delivery Costs

The sensitivity analysis of individual variables illustrates that specific propellant combinations are favored by increased hardware costs and decreased delivery costs. Of these, PF11-LCH_4/LOX has been shown to be the most significant contender for the lowest total cost as a result of combined uncertainties in the analysis. This raises the question of what would be the actual costs for the hopper vehicles if the baseline delivery and hardware costs were too high and too low, respectively. This issue was explored by defining and applying a cost factor as follows:

$$Hopper\ Vehicle\ Cost = \frac{Baseline\ Delivery}{Cost\ Factor} + Baseline\ Production \times Cost\ Factor + Baseline\ Maintenance$$

This relationship effectively forces the baseline delivery and production costs in opposite directions as the cost factor is varied. A cost factor less than one is not of great interest here because it doesn't change the cost ordering or reduce the relative costs of the lowest cost propellant families. Figure 71 displays the ramifications of an increasing cost factor for key propellant families.

The inflection in the PF11 curve is a result of the competing effects of the decreased delivery and increased hardware costs. This battle is not prevalent for the other two propellant families because the vast majority of their cost is attributed to production. At a cost factor above 1.6 the use of terrestrial hydrogen becomes more attractive than indigenous sources. As the cost factor increases further, PF11 approaches the cost of PF6 until they are approximately equal when the hardware production cost has been increased by a factor of 8 and the delivery cost has be reduced from $5000/kg to $625/kg.

The same analysis for the 10,000-person colony is presented in Figure 72. The results are analogous to the 100-person colony. At a cost factor above 2.5 the use of terrestrial hydrogen becomes more attractive than making it on Mars. As the cost factor increases further, PF11 approaches the cost of PF6 until they are approximately equal when the hardware production cost has been increased by a factor of 4.8 and the delivery cost has be reduced from $5000/kg to $1042/kg.

The low cost offered by PF6 is quite robust against the combined sensitivity of delivery and production cost even when they are simultaneously varied in directions that do not favor this propellant combination for both the 10,000-person and 100-person colony sizes.

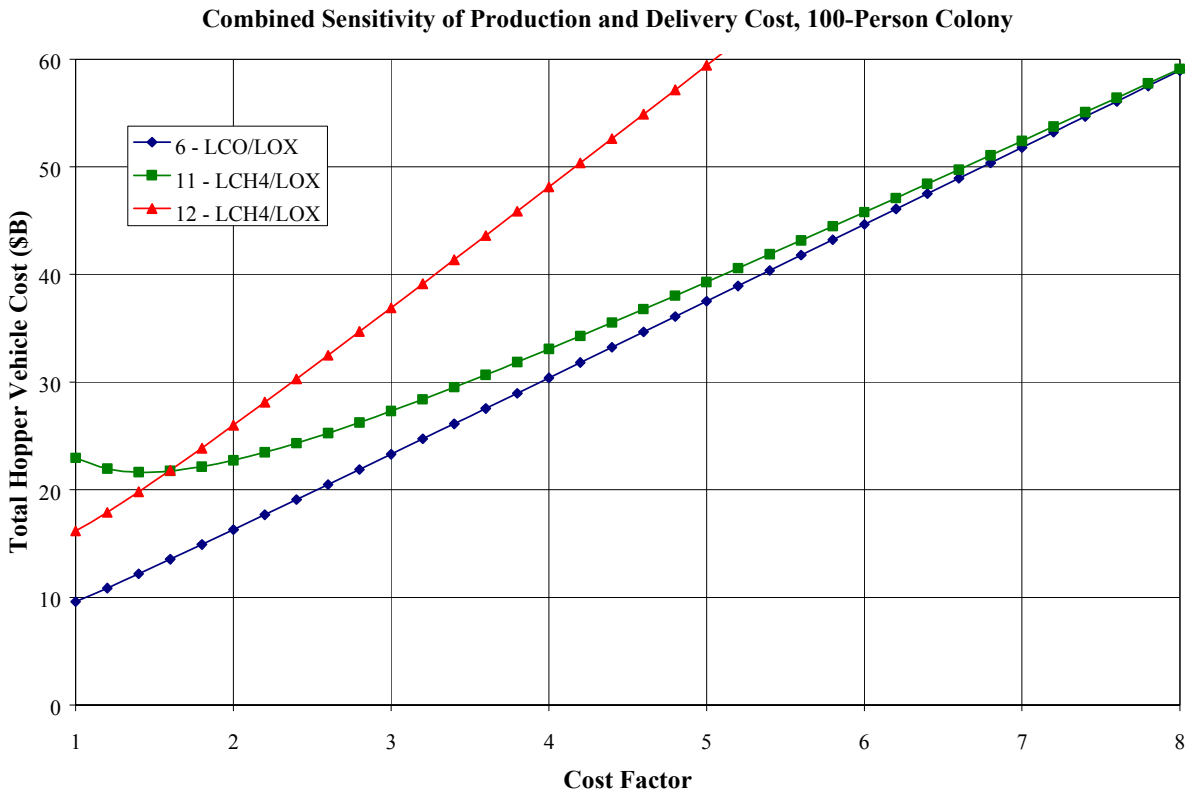

Figure 71. Combined Sensitivity of Production and Delivery Cost, 100-Person Colony

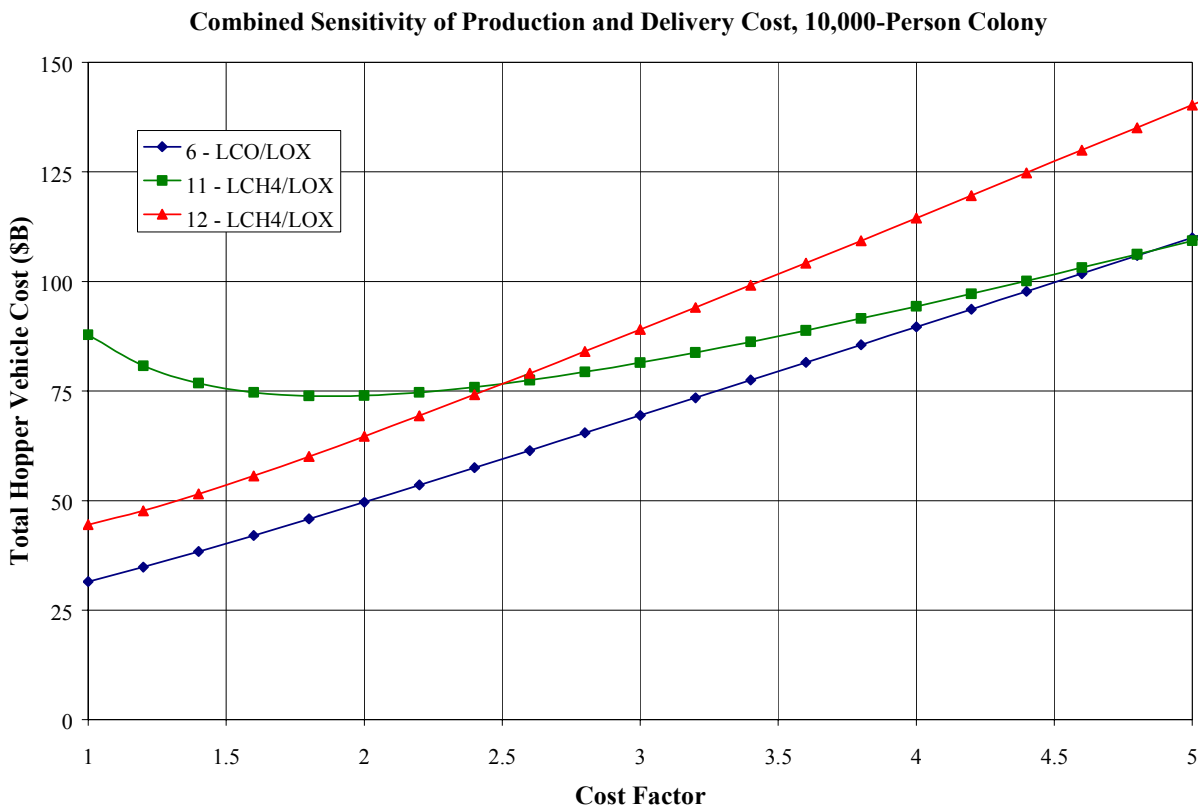

Figure 72. Combined Sensitivity of Production and Delivery Cost, 10,000-Person Colony

8.5 Hydrogen Availability

The baseline assumption for the acquisition of hydrogen on Mars is that it is extracted from the atmosphere. As previously discussed, this involves enormous volumes of gas to be moved through the extraction units, requiring massive equipment and power systems. This section of the sensitivity analysis explores the ramifications of large amounts of liquid water being available below the Martian surface, referred to as PF3a.

We assumed the best case scenario, where water is readily available near the surface, easy to get, and does not require any significantly deep drilling or high pumping power. It was also reasoned that large pools of underground water would not be readily available at all locations over the planet. Therefore, water was only assumed available at the bases, and the roundtrip vehicles that fly to/from remote areas still have to bring along their hydrogen for the return trip. The LH_2/LOX hopper vehicle designs are then identical to those used in PF2 and PF3.

The cost results for both the 100-person and10,000 person are summarized in Table 50 for PF6-LCO/LOX, PF3-LH_2/LOX, and PF3a-LH_2/LOX . Not surprisingly, the total hopper vehicle cost for PF3 is substantially reduced by the availability of subsurface water. However, at first glance it is somewhat surprising that the hopper vehicle cost for PF3a isn't significantly lower that that of PF6, in fact they are almost the same for the 100-person colony.

Table 50. Total Hopper Vehicle Cost

Colony Size	PF6-LCO/LOX atmosphere extraction ($B)	PF3a-LH_2/LOX ground water extraction ($B)	PF3-LH_2/LOX atmosphere extraction ($B)
100-Person	9.6	9.3	30.5
10,000-Person	31.6	24.7	63.4

The specific impulse for LOX/LH_2 is much higher then the performance offered by LCO/LOX. Also, the propellant processing units for electrolyzing the water are less massive than the systems required for extracting CO and O_2 from the atmosphere. In these respects, PF3a is an attractive alternative to PF6. However, the equalizing factor is that the roundtrip vehicles for PF3a have to bring along all their hydrogen for the return trip. Table 51 compares the drymass of the 6 hopper vehicles. The drymass for the roundtrip vehicles (IRIS and ARES) are actually higher for PF3a. While the wetmass for the PF3a vehicles are lower, due to the high I_{SP}, the energy required for processing the propellant is higher too. Also, hydrogen's very low boiling temperature requires larger cryocoolers, larger beamed power systems, and thicker insulation to handle boiloff for PF3a.

The net result from a cost standpoint is that PF6 and PF3a are similar for 100-person colony. There is only one base, requiring a proportionally higher number of sorties to remote areas using IRIS and ARES.

Alternatively, the 10,000-person colony has a total of 8 bases where a larger portion of the colony traffic is between bases, diminishing the relative penalty paid by PF3a for IRIS and ARES. This gives rise to a hopper vehicle cost savings of 22% for the use of PF3a instead of PF6 for the 10,000-person colony.

Table 51. Vehicle Drymass Comparison

Vehicle	PF3a-LH_2/LOX Drymass (kg)	PF6-LCO/LOX Drymass (kg)
Hermes	6360	7461
EOS	426	506.7
IRIS	1893	1377
ARES	20,128	19,023
HYPERION	16,903	24,804
ZEUS	119,321	169,576

8.6 Propellant Integration

This study also sought to explore the possible benefits of simultaneously using several different propellant combinations to arrive at a lower total scenario cost. The cost separation among the ground vehicle propellant families was small, and their missions and operations were all quite similar from a vehicle design standpoint. Based on these observations, an integrated propellant family architecture does not appear to have significant benefit potential for the ground vehicles.

On the other hand, the cost separation among the hopper vehicle propellant families is large. Additionally, these vehicles included a wide array of vehicle types, sizes, and missions including surface-to-orbit, roundtrip ISRU, and base-to-base hops. An analysis was conducted to determine if one or more of the six vehicle types would benefit from the use of a propellant combination other than CO/LOX, which achieved the lowest cost for all 6 vehicles combined.

The next least expensive propellant combination when considering all vehicles together was found to be PF12-LCH4/LOX, suggesting that it would have the best chance for beating out one of the CO/LOX vehicles on an individual vehicle basis. This was studied by completing the entire hopper vehicle analysis process individually for each vehicle type. The first time through the analysis, it was assumed that the cost of propellant processors were identical to those calculated for the use of all one type of propellant (which is specific to each propellant family). Penalties for the development and operation of two or more types of propellant processing systems would then be assessed and added on if there appeared to be any potential benefit to using multiple propellant combinations.

The results for the 100-person colony are shown in Figure 72. The PF12 vehicles were found to be significantly more expensive for all 3 vehicle types used. The ratio of the PF12 and PF6 roundtrip hopper vehicles, IRIS and ARES, were comparably more expensive than the ratio of the two propellant families for HYPERION. This is likely the result of the PF12 round trip vehicles paying a "penalty" for having to carry along their hydrogen for the return trip. The most expensive total cost for both families is associated with the production and operations of ARES.

The results for the 10,000-person colony are shown in Figure 73. With the exception of EOS, the PF6 vehicles are all significantly less expensive than those for PF12. The PF12 EOS vehicle is $0.05B less expensive than the one for PF6. However, as mentioned above, these cost numbers assume high levels of propellant processor productions. The cost associated with the development and operation of one small CH_4/LOX propellant processor for EOS and the logistics of using two types of propellants would not justify a "savings" of $0.05B. The most expensive vehicle for the 10,000-person colony is the heavy orbit downloader, ZEUS, which is responsible for delivering massive amounts of infrastructure every colony cycle to support the continuing population growth.

The net conclusion is that there does not appear to be any real benefit for using several propellant combinations within the framework the study assumptions; however with readily available water, this may not be true.

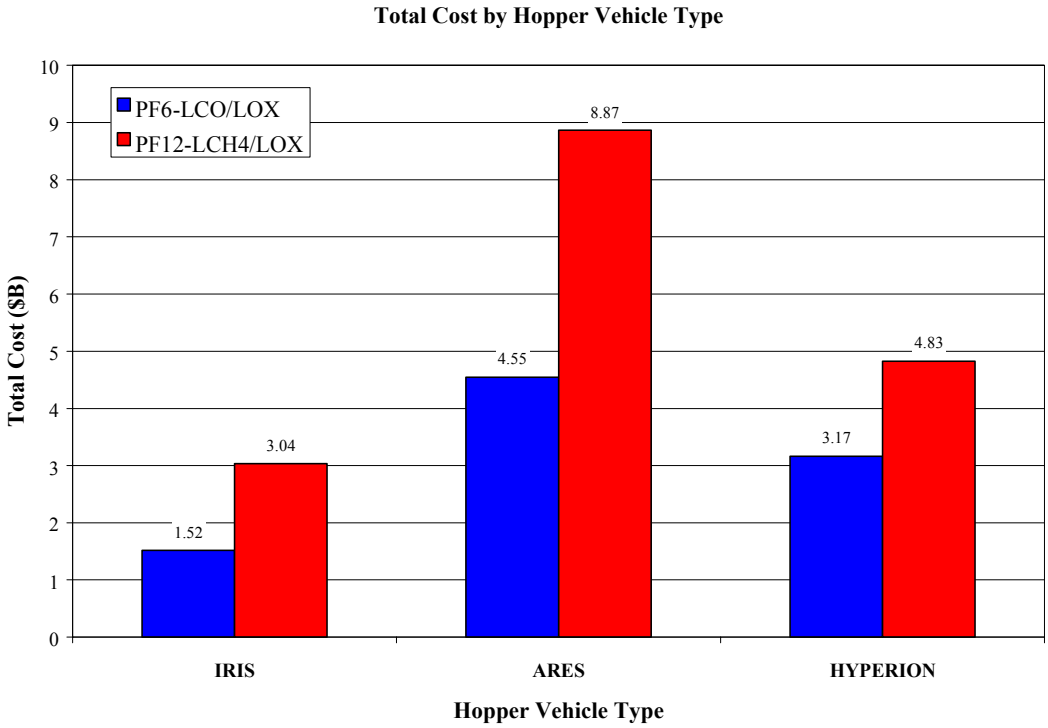

Figure 72. Hopper Vehicle Cost Breakdown, 100-Person Colony

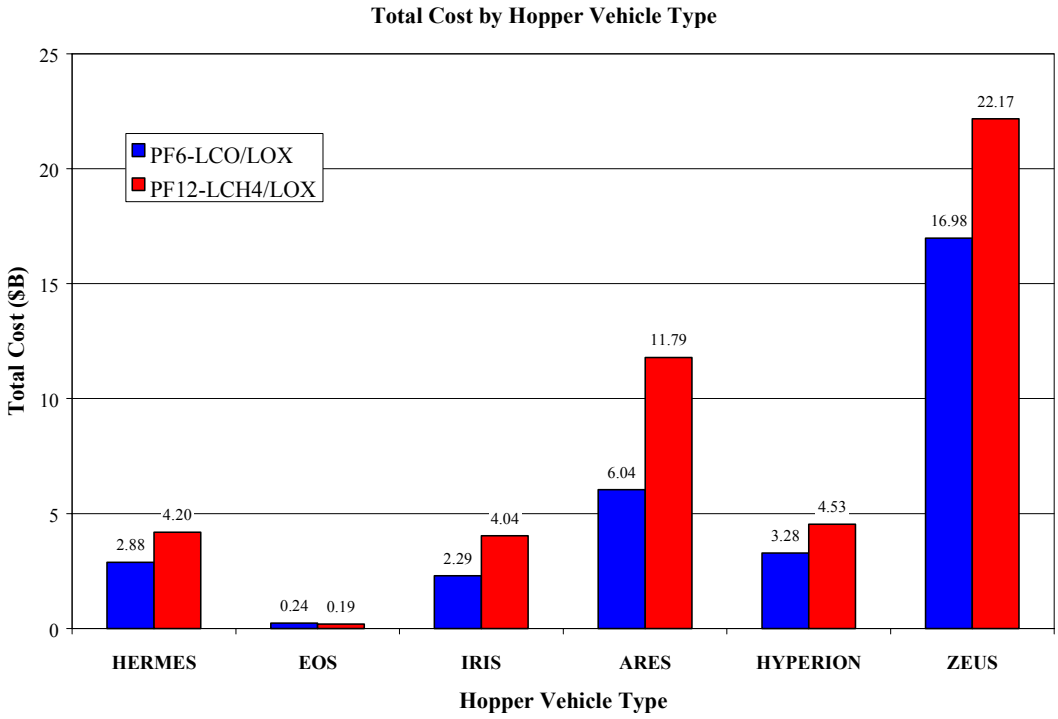

Figure 73. Hopper Vehicle Cost Breakdown, 10,000-Person Colony

8.7 Hydrogen Delivery Cost

The baseline analysis results assumed an Earth-to-Mars orbit delivery cost of $5000/kg, and did not make a distinction between the cost of transporting people, hardware, propellants, etc. This section investigates the effects the expected higher cost of delivering propellants (as compared to inert hardware), resulting from the need for storage tanks and thermal conditioning. The analysis results were adjusted for a propellant delivery cost of $6500, or an increase of 30% over the baseline cost. The delivery of all other supplies and people were charged the baseline $5000/kg.

Figures 74 and 75 display the results as the total relative results for the 100-person and 10,000-person colonies, where the total cost for each propellant family is shown as a percentage of the lowest cost family: PF6-LCO/LOX (ISRU carbon and oxygen). These results include the costs for: (1) ground vehicles, (2) hopper vehicles, (3) sounding rockets (100-person colony only), (4) aeroplanes (100-person colony only), (5) balloons (100-person colony only), and (6) non-transportation related costs. The propellant combinations considered in this study for the hopper and ground vehicles are different. However, the cost differential among the ground vehicle propellant families is small, and as such, Figures 74 and 75 were generated under the assumption that PF6-LCO/LOX was used for all the ground vehicles. Similarly, the total cost for the sounding rockets, aeroplanes, balloons, and non-transportation costs are not dependant on the propellant family. Therefore, the cost ranking shown Figures 74 and 75 are solely attributed to the difference in hopper vehicle costs.

The increased cost of hydrogen delivery has little effect on the cost ranking of the different propellant combinations. The major influence of this sensitivity is to widen the cost gap between ISRU and non-ISRU propellant combinations. This is particularly true for PF1 which increased in relative cost compared to PF6 from 3620% to 4621% for the 100-person colony, and from 4953% to 6404% for the 10,000-person colony.

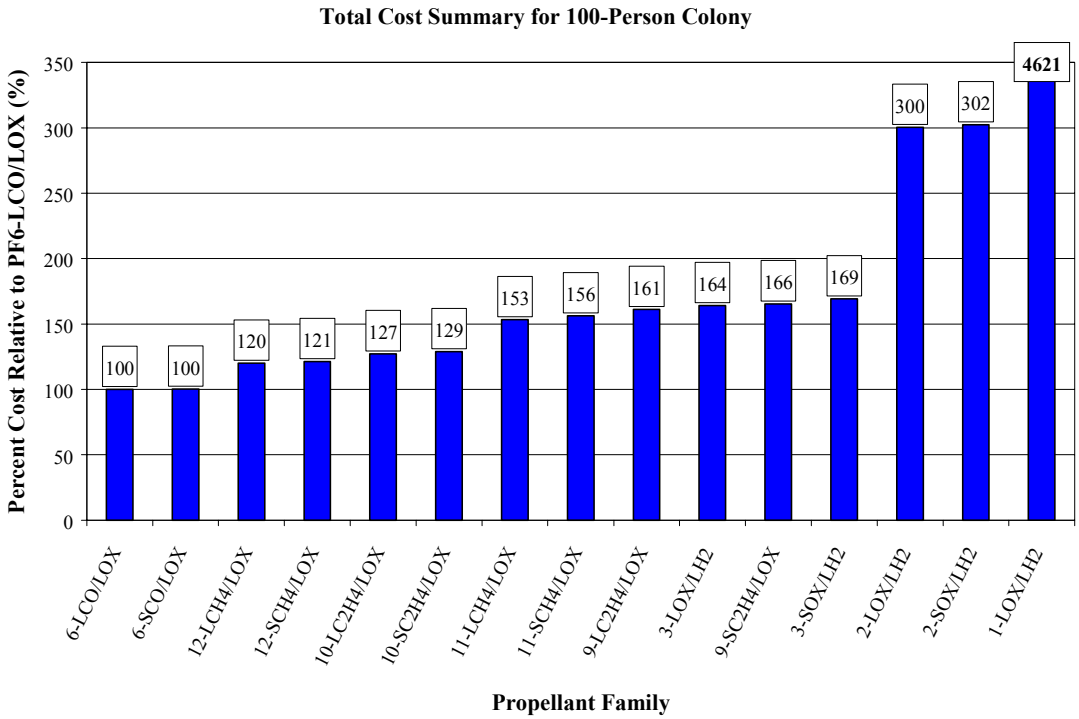

Figure 74. Total Cost Summary for 100-Person Colony; Propellant Delivery Cost Sensitivity

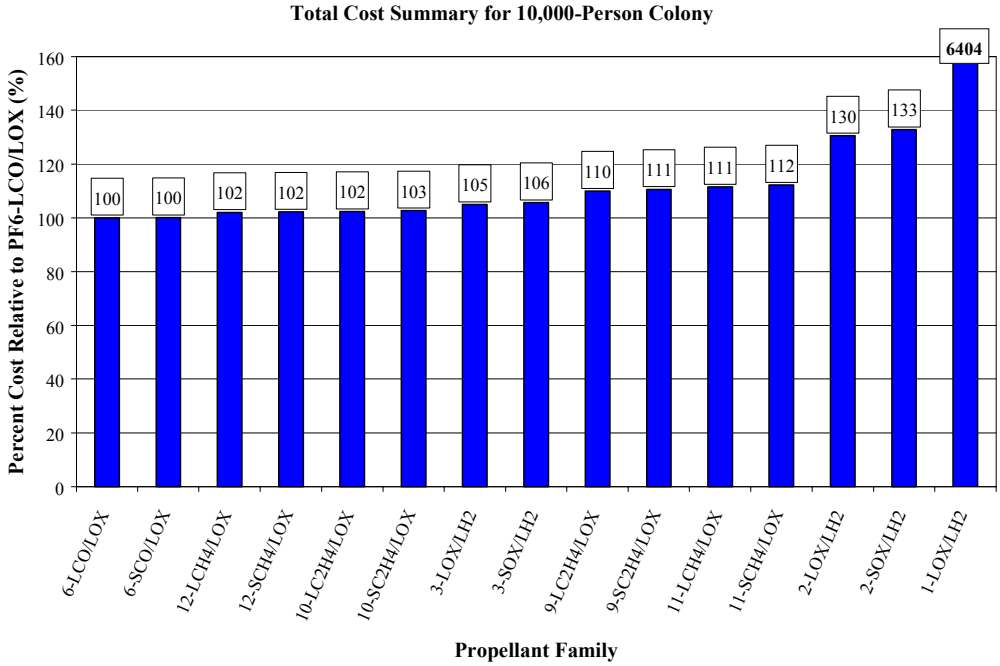

Figure 75. Total Cost Summary for 10,000-Person Colony; Propellant Delivery Cost Sensitivity

9.0 ISRU ASSESSMENT FOR EARLY MANNED MARS EXPLORATION

The early manned Mars exploration period is envisioned to occur from 2020 through 2040. The colonization period immediately follows this manned exploration period. The following sections will discuss the missions that would occur during the manned exploration period. This is followed by an analysis of the potential mass savings afforded by using alternate ISRU propellant combinations.

9.1 Overview of Early Manned Exploration Missions

The missions that occur during the manned Mars exploration period are closely modeled after the NASA Mars Reference Mission 3.0 (Hoffman, 1997; Drake, 1998). The early exploration period consists of three human exploration missions. Two cargo vehicles are launched and delivered to Mars before each crew is launched. One cargo vehicle delivers a fully-fueled Earth Return Vehicle. The other vehicle is a Cargo Lander that delivers an ISRU processing plant, nuclear power reactor and a Mars Ascent Capsule. Each human crew has six members who will stay on the surface of Mars for 18-20 months (nominal stay of 600 days). An ISRU processing plant will produce the propellants required for the Mars Ascent Vehicle and life support consumable water. The crew will use the Mars Ascent Vehicle to rendezvous with the Earth Return Vehicle in Mars orbit.

The objectives of the early exploration period are to:

- Conduct human missions to Mars and verify a way that people can ultimately inhabit Mars
- Conduct applied science research to use Mars resources to augment life-sustaining systems
- Conduct basic science research to gain new knowledge about the solar system's origin and history.

The launch windows to send vehicles from Earth to Mars occur every ~26 months. During the first launch window, two cargo vehicles are launched from Earth orbit. One cargo vehicle delivers an Earth Return Vehicle to Mars orbit. The other cargo vehicle delivers a Cargo Lander to the Mars surface. The cargo vehicles follow a minimum energy (Hohmann) transfer trajectory with transit times around 250 days. The Cargo Lander contains an ISRU processing plant and a nuclear power plant. The ISRU plant will operate remotely and store propellant and life support consumables before the human crew leaves Earth in the second launch window.

A piloted vehicle will transfer the crew and habitat from Earth orbit to the Mars surface during the second launch window. The crew vehicle will follow a fast transit trajectory to Mars (4 to 6 months). The crew will stay on the surface of Mars for 18 to 20 months (600 days nominal surface stay). Two additional cargo vehicles are also launched during the second launch window to support the second crew. The second crew vehicle is launched during the third launch window along with two additional cargo vehicles. The third human crew is launched during the fourth launch window along with two additional cargo vehicles to support future human crews. Each subsequent human mission helps to build up the infrastructure on the Mars surface. This infrastructure will form the basis of the permanent human colony that will follow the early exploration period.

Each vehicle that travels from Earth to Mars requires two launches from the Earth surface to Earth orbit. One launch carries the interplanetary propulsion system of the vehicle into Earth orbit. The other launch carries the cargo portion of the vehicle into Earth orbit. The two components require a rendezvous and docking operation before the completed vehicle can travel to Mars. All launches to Earth orbit use a new Magnum launch vehicle. This Magnum launch vehicle uses liquid hydrogen and oxygen propellants to launch an 80 metric ton payload. The Magnum vehicle consists of a core vehicle with the same diameter as the Shuttle External Tank (8.4 m) attached to two Shuttle boosters.

9.2 ISRU Processing Plant and Nuclear Power System

The ISRU processing plant will produce methane, oxygen and water using hydrogen supplied from Earth and the Mars atmosphere. The ISRU plant uses 5,420 kg of hydrogen feedstock to produce ~39 metric tons of propellant for the Mars Ascent Vehicle and 23 metric tons of water for life support consumables in ~1 year. The ISRU plant will have a mass of ~3,941 kg. A nuclear power system with a mass of 11,425 kg and an electrical power output of 160 kW will supply energy to operate the ISRU plant.

9.3 Mars Ascent Vehicle

The baseline Mars Ascent Vehicle will use ISRU propellants (liquid methane and liquid oxygen) to carry the crew from the surface of Mars up to the Earth Return Vehicle in Mars orbit. Approximately 5,625 m/sec of ΔV is required for single stage ascent to orbit and rendezvous with the Earth Return Vehicle.

The baseline Mars Ascent Vehicle has the following specifications:

- Dry mass is 4,829 kg
- ~39 metric tons of propellant is required for ascent
- Engines on vehicle burn LOX/CH_4
  -Specific impulse of 379 seconds
  -Mixture ratio of 3.5
  -Chamber pressure of 600 psi
  -Nozzle area of ~400
  -Thrust level of 15,000 lbf.

9.4 Earth-to-Mars Transport Vehicles

Mass information for the various interplanetary vehicles are given below. Earth to Mars transport propulsion is supplied by a Thermal Nuclear Rocket (TNR).

- Cargo Lander
  -Mass in Earth Orbit = 134,743 kg
  -Mars Entry Mass = 66,043 kg
  -Landed Mars Surface Mass = 44,440 kg
  -Total Cargo Mass = 40,236 kg
- Crew Lander
  -Mass in Earth Orbit = 137,406 kg
  -Mars Entry Mass = 60,806 kg
  -Landed Mars Surface Mass = 35,145 kg
  -Total Payload Mass = 30,941 kg
- Earth Return Vehicle
  -Mass in Earth Orbit = 147,472 kg
  -Mars Orbit Injection Mass = 74,072 kg
  -Trans Earth Injection (TEI) Mass = 61,829 kg
  -Mass of Earth Return Capsule @ TEI = 27,042 kg

9.5 Analysis of Alternate Propellant Families

The NASA Mars Reference Mission was designed to use LCH_4/LOX for the following operations:

- Cargo lander vehicle orbital maneuvers and descent to the Martian surface
- Crew lander orbital maneuvers and descent to the Martian surface
- Crew ascent stage from the Martian surface (brought by the cargo lander)
- Crew Earth return propulsion from Mars orbit.

Of these four applications, the only one which uses propellants manufactured on Mars is the Crew ascent stage. The Reference Mission dictates that all hydrogen required for water (for life support) and propulsion be brought from Earth, and carbon and oxygen be made via ISRU on Mars. Analysis was conducted to evaluate the impact of other propellant combinations and sources. Table 52 lists the scenarios under consideration. Note that the Reference Mission and PF11 are identical in both propellant type and source. The motivation for analyzing PF11 ourselves was to generate self-consistent results for comparison against the other families. The scenario for PF6-LCO/LOX does not require any hydrogen for propulsion; however, hydrogen is still required to make water for life support, and so must be included as part of the analysis. In the case of PF6, the hydrogen required for life support is assumed to be brought from Earth. PF11 and PF12 investigate the effects of using terrestrial and ISRU hydrogen, respectively, for LCH_4/LOX.

Table 52. Scenarios Considered

Propellant Family	Reference Mission- LCH_4/LOX	PF11 - LCH_4/LOX	PF3- LH_2/LOX	PF6- LCO/LOX	PF12 - LCH_4/LOX
Source of H_2	terrestrial	terrestrial	ISRU	terrestrial	ISRU
Source of C and/or O_2	ISRU	ISRU	ISRU	ISRU	ISRU

The main driver for the analysis is the ascent stage, as it is the only portion that utilizes ISRU propellants. The total cargo mass for the ascent stage was not specifically listed in the Reference Mission Publication, so it was calculated to be 2115 kg using the listed vehicle stage mass, crew capsule mass, ΔV requirement, propellant mass, and I_{SP}. The HYPERION vehicle code was adapted for the ascent vehicle analysis, with the most major modifications being elimination of the aerobraking system and re-sizing of the crew capsule.

Results of the ascent vehicle analysis are shown in Table 53**.** The low I_{SP} of LCO/LOX gives rise to a vehicle weighing over three times the one using LCH_4/LOX. The amount of propellant and hydrogen required for the mission are also listed. The water produced using the 2556 kg of hydrogen is required for life support only. This information was used to size the ISRU-related systems for each propellant combination, including:

- Nuclear power system
- ISRU propellant processors
- Water production system.

The power system capability includes 119 kW of power for life support and other non-ISRU operations (per the Reference Mission specifications). The incremental amount of power required for manufacture of ascent vehicle propellants and water was calculated and factored into the required power system size. The total mass of these three components is listed in Table 54 as "ISRU related cargo".

Table 53. Mars Ascent Vehicle Mass Breakdown (in kg)

Vehicle Component	PF6-LCO/LOX (kg)	PF11&PF12 - LCH_4/LOX (kg)	PF3- LH_2/LOX (kg)
Vehicle dry mass	8692	2470	1809
Crew capsule mass	4829	4829	4829
Payload mass	2115	2115	2115
Oxidizer mass	48,939	32,015	21,437
Fuel mass	85,856	8653	3898
Wet mass	150,431	50,082	34,088
Hydrogen for propellants	0	2163	3898
Hydrogen for H_2O	2556	2556	2556
Total H_2 required	2556	4719	6454

The cargo lander is responsible for bringing several components to the Martian surface, including the ascent stage and ISRU processing hardware. The final step of the analysis was to resize the cargo lander for each propellant family. The results are shown in Table 54 and Figure 76. Data for the Reference Mission are also included for comparison with PF11. The base cargo comprises all non-ISRU related components on the lander which are delivered to the surface. ISRU related cargo includes the nuclear power system, propellant processor, and water production unit.

The lander descent vehicle for the cargo lander was re-sized for each propellant family. The descent stage propulsion system serves multiple propulsive applications (station keeping, orbit circularization, and descent). The total ΔV requirement for these operations was calculated to be 676.2 m/sec using information in the Reference Mission document. As an approximate check, the Reference Mission document specifies 632 m/sec alone for the descent maneuver. The lander vehicle structure was calculated as 5% of the vehicle wetmass. The propulsion system, parachutes and mechanisms, and forward aeroshell were all assumed to be the same as the reference mission value. The total propellant required was calculated using the propellant family specific impulse along with the aforementioned assumptions. The results are summarized in Table 54.

The cargo lander descent vehicle is delivered to Mars orbit by a Nuclear Thermal Rocket (NTR). This system was also resized for each propellant family based on the total mass of the cargo lander descent vehicle. The NTR propulsion system drymass/wetmass ratio for the Reference Mission is 0.341. This ratio was assumed for all propellant families. The total ΔV required for the Reference Mission cargo lander NTR was calculated to be 3818 m/sec using the given I_{SP} of 950 sec. Collectively, this information was used to determine the NTR propulsion system and propellant masses shown in Table 54 for each propellant family.
Our analysis for PF11 is in relatively good agreement with the Reference Mission results; the difference in total cargo lander mass is less than 10%. The three main drivers which separate the different propellant combinations are: (1) the ISRU related cargo mass, (2) the terrestrial hydrogen mass, and (3) specific impulse. The lowest ISRU related cargo mass is achieved by PF11. The combinations which use ISRU hydrogen, PF3 and PF12, suffer from the heavy water production units and high power requirements (to extract water from the atmosphere). PF6 has the second lowest ISRU cargo mass, which is still relatively

heavy due to the large amount of propellant required to compensate for the lower I_{SP}. These differences translate through the lander vehicle and NTR propulsion systems to establish the total cargo lander mass shown in Figure 76. The cargo lander for PF11 is 16.9% lighter than the next lightest family, PF3.

Table 54. Cargo Lander Vehicle Mass Summary for Different Propellant Families

Component	Reference Mission (kg)	PF11 - LCH_4/LOX (kg)	PF3- LH_2/LOX (kg)	PF6- LCO/LOX (kg)	PF12 - LCH_4/LOX (kg)
H_2 source	terrestrial	terrestrial	ISRU	terrestrial	ISRU
O_2 and/or C source	ISRU	ISRU	ISRU	ISRU	ISRU
Base cargo	15,381	15,381	15,381	15,381	15,381
ISRU related cargo	19,435	16,354	31,177	26,879	34,311
Terrestrial hydrogen	5420	4719	0	2556	0
Lander vehicle structure	3186	3077	3597	3838	3924
Lander vehicle propellant	10,985	10,370	10,158	16,461	13,224
Terminal propulsion	1018	1018	1018	1018	1018
Forward aeroshell	9918	9918	9918	9918	9918
Parachutes/mechanisms	700	700	700	700	700
Total descent stage mass	66,043	61,537	71,949	76,751	78,476
NTR propulsion system	23,400	21,854	25,552	27,257	27,870
NTR propellant	45,300	42,234	49,380	52,676	53,860
Total cargo lander mass	**134,743**	**125,625**	**146,881**	**156,684**	**160,206**

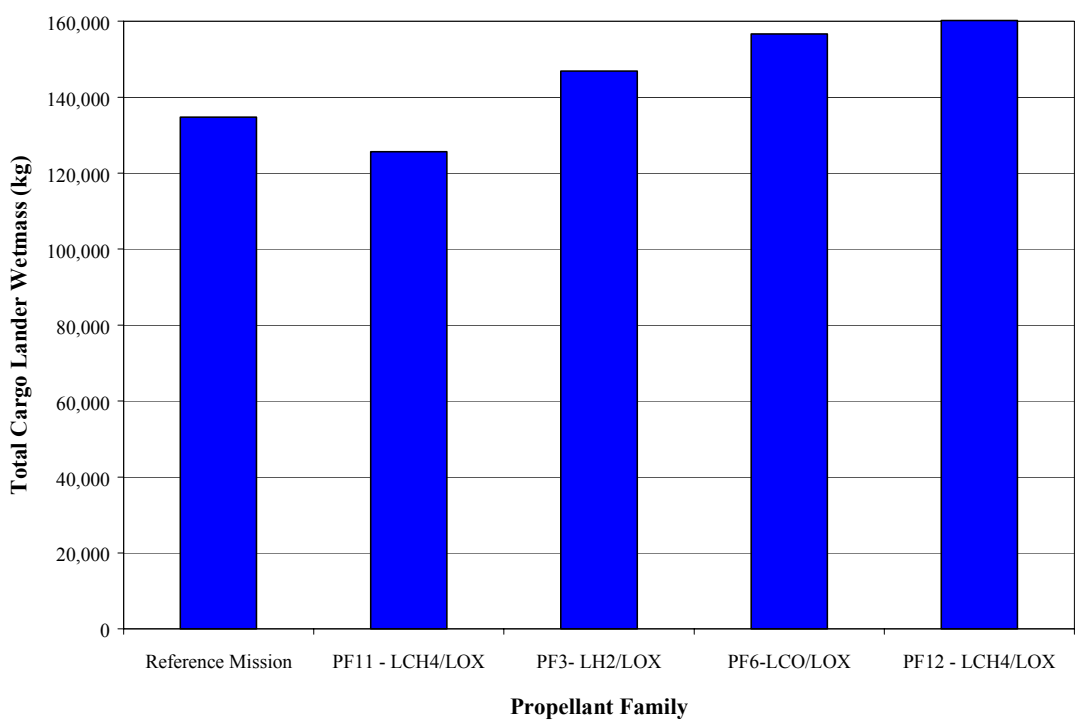

Figure 76. Trans-Mars Injection Cargo Vehicle Wetmass for Each Propellant Family

These results are notably different from the 100-person and 10,000-person colony analysis. In the colony scenarios, propellant families that did not require terrestrial hydrogen were more attractive. A major

difference in the Reference Mission is that the ISRU systems are only used for one cycle. Thus, the savings for not having to bring hydrogen to Mars is only incurred once, rather than on a continuous and larger scale as in the colony scenarios. If the same hardware were used for multiple missions, there would be crossover points where PF11 would fall behind the other propellant combinations (in terms of total mass, which is used as the primary measure of merit). PF6 was only analyzed for the case of using terrestrial hydrogen for the consumable water production (it is not required for propulsion). Based on the comparison between PF11 and PF12, it appears that PF6 would not benefit from a one-time use ISRU hydrogen production system (for life support water production).

The crew lander vehicle and Earth return vehicle also use the same propellants as the ascent stage; however, these propellants are brought from Earth. The motivation for using the same propellant combination is to allow a common propulsion technology to be employed for all three vehicles. In this way, the crew lander and Earth return vehicles would also be affected by the propellant family for PF3 and PF6 (PF12 would be identical to PF11, since the propellants are brought from Earth and ISRU is not involved). These systems would clearly be larger for PF6, further widening the gap with PF11. There would potentially be a mass savings for PF3, but it would have to be significant to compensate for the larger ISRU systems requirements. Additionally, the long-duration parking requirement for the Earth return vehicle in Mars orbit would likely require significant thermal conditioning to handle the LH_2. A further issue with PF3 is that the three vehicles sizes would no longer be similar. The cargo lander would be heavier, and the other two have the potential to be lighter. This affects the approach of using common earth launch and Mars TNR systems for the three vehicles.

The conclusion is that CH_4/LOX, using terrestrial hydrogen, is the propellant combination of choice for this mission.

10.0 ISRU ASSESSEMENT FOR MARS SAMPLE RETURN

Vehicle analysis for a Mars Ascent Vehicle (MAV) that could be used early for Mars sample return missions was an ISRU-based conducted mission under consideration is the MAV insertion of a payload canister of Martian soil and rock samples into a specified orbit. The most recent NASA baseline mission requirements and specifications that have been established are shown in Table 55. The "solid" size and mass listed in Table 55 refers to the current baseline terrestrial propellant system identified by NASA, a solid motor, which is compared against an ISRU SCO/LOX system.

Table 55. Baseline MAV Requirements and Specifications

Mission duration	90 sol
Total payload mass	5 kg (4 kg canister and 1 kg sample of soil)
Payload fairing mass	3 kg
Power availability on the lander	1000-1500 W-hrs/sol
Launch location	45 degrees east latitude
Orbit destination	500 km circular, 45 degree incl.
Delta-V requirements for the MAV	Stage 1: 2500 m/s Stage 2: 1700 m/s Total: 4200 m/s
Delivered I_{SP} for both stages:	286.0 s
Solid motor length constraint	3.3 m
Solid motor diameter constraint	0.5 m
MAV ground support equipment (erection system, thermal canister, and supplemental heaters)	~30-60 kg
All solid MAV mass breakdown	Stage 1: 187.0 kg Stage 2: 75.0 kg Payload: 5 kg Payload fairing: 3 kg Total vehicle mass: 270 kg
Total solid MAV related mass, including ground support equipment	315 kg (assuming an average of approximate range of ground support equipment: 45 kg)

Source: NASA/MSFC Study-2002.

Based upon an existing solid fuel regression rate database for SCO/LOX, a preliminary sizing analysis was conducted for solid CO fuel grains for a Mars Ascent Vehicle (MAV) application. The objective of the analysis was to obtain an initial estimate of the geometric characteristics of grains for end-burning hybrid engines burning SCO and LOX. The analysis relied on ORBITEC regression rate data for SCO burning with GOX in ORBITEC's Mark II cryogenic solid hybrid engine, as well regression rate data for HTPB fuel obtained during an ORBITEC end-burning hybrid test program.

Sizing the fuel grains for a specific application requires the selection of both an average thrust level and

total burn time to obtain the total impulse required to complete the mission. The baseline MAV mission requires an 8 kg payload (5 kg sample and container plus 3 kg payload fairing) to be accelerated to approximately 4200 m/s (this is the delta V requirement). To calculate the propellant mass required, the parameters listed in Table 56 were specified for the analysis. Based on this scenario, the mass schedule shown in Table 57 was calculated for the two-stage vehicle.

Table 56. Major Assumptions for MAV Analysis

Parameter	Stage 1	Stage 2
Velocity Increment (ΔV)	2500 m/s	1700 m/s
Mixture Ratio (MR)	0.56	0.56
Specific Impulse (Isp)	279.7 s	279.7 s
Structural Mass Fraction (SMF)	0.18	0.48
Propellant Mass Fraction (PMF)	0.82	0.52

Table 57. MAV Mass Schedule (in kg)

Parameter	Stage 1	Stage 2
Initial Stage (or Vehicle) Mass, Mi	195	64.2
Structural Mass, Ms	35.1	30.8
Propellant Mass, Mp	160	33.4
Payload Mass, Mpay	72.2	8
SCO Mass, Mf	103	21.4
LOX Mass, Mo	57	12
Total Impulse (kN-s)	438.6	91.6

With the propellant masses defined, the solid CO grain geometry can be designed based on the desired thrust level and burn time.

To size the SCO grain for the end-burning hybrid case, a regression rate correlation developed for HTPB and GOX was employed, but modified by an empirical factor to account for the probable increase in regression rate when SCO is used in place of HTPB. Equation (3) shows the correlation used in the analysis:

$$r = A*(0.40\ G_o^{\ 0.62}) \qquad (3)$$

where r is in mm/s and G_o is in kg/m^2-s. The term in parentheses is the empirically-developed correlation that relates regression rate to oxidizer mass flux for HTPB and GOX in an end-burning hybrid. The factor A accounts for the estimated change in regression rate that would occur in an end-burning hybrid burning SCO and GOX. For the current analysis, A was set equal to 5 since a comparison of regression rates at equal mass fluxes for HTPB and SCO in *conventional* hybrids indicate that SCO regresses on the order of 5 times faster than HTPB over the range of mass fluxes tested. The choice of factor A is the main assumption in the analysis.

The sizing analysis starts by determining the SCO and LOX flow rates into the combustion chamber necessary to produce the desired thrust for the given specific impulse and mixture ratio as described by Eqs. (4) and (5):

$$\dot{m}_f = \frac{T}{g \cdot I_{sp}} \frac{1}{1 + O/F} \qquad (4)$$

and

$$\dot{m}_o = \frac{O}{F}\dot{m}_f \tag{5}$$

The total amount of fuel and oxidizer required for each stage are simply Eqs (4) and (5) multiplied by the thrust times.

The oxidizer mass flux, G_o, required to produce $\dot{m}_f$ can be determined by combining Eq. (3) with

$$\dot{m}_f = \rho A_b r \tag{6}$$

and the definition of G_o as the oxidizer mass flow rate into the combustion port divided by the port cross-sectional area:

$$G_o = \frac{\dot{m}_o}{A_p} \tag{7}$$

However, for the end-burning hybrid configuration, the port area, A_p, is equivalent to the burning surface area, A_b, in Eq. (6). Combining Eqs (3), (6), and (7), with A_b=A_p, yields

$$G_o = \left[4x10^{-4} A \frac{O}{F}\rho\right]^{\frac{1}{1-0.62}} \tag{8}$$

where the fuel density, r, is known (937 kg/m^3) and the factor 4x10^{-4} is equivalent to the 0.4 factor in Eq. (3) for r in m/s, rather than mm/s.

A similar analysis can be conducted for a dual-disk end burning configuration wherein the grain chamber contains two fuel disks: one disk occupying the volume above the swirl oxidizer injector and a second disk below the injector. This configuration allows for a more compact grain chamber design, but requires that the lower disk incorporate a central port to allow combustion gases to escape through the exit nozzle. Assuming that this port contributes negligibly to the overall fuel flow rate, Equation (8) becomes:

$$G_o = \left[2 \bullet 4x10^{-4} A \frac{O}{F}\rho\right]^{\frac{1}{1-0.62}} \tag{9}$$

The fuel regression rate can be found by substituting the known G_o from Eq. (8) or (9) back into Eq. (3). Similarly, the grain geometry can now be determined by solving for A_b in Eq. (5). The grain diameter follows, assuming a circular port. The grain thickness is determined by calculating the volume required to contain the total fuel mass in a right circular cylinder, and the known A_b.

Tables 58 and 59 summarize the results of the analysis for the two stages presented in Table 57. A dual-disk geometry was employed. The burn time was varied from 10 to 60 s, resulting in the corresponding thrust and acceleration levels indicated. For each case, the thrust and burn time produce the required total impulse for each stage. The grain diameter-to-length ratio decreases with increasing burn time (decreasing thrust and acceleration). The 50-s burn time gives an initial acceleration of 3.4 g's for Stage 1 and requires two SCO grains 0.46 m (18 in.) diameter and 0.34 m (13.3 in.) thick. The Stage 2 grains burn for 20 s and have a diameter of 0.33 m and a thickness of 0.138 m. These grain cases also fit within the diameter constraint of 0.5 m.

Another interesting result of the analysis is that since the fuel surface area is the same as the port cross-sectional area for the end-burning hybrid configuration, there is a unique oxidizer mass flux that provides

a desired mixture ratio for the engine, independent of thrust level (see Eq. (8)). Therefore, for SCO/LOX, one must use G_o=1.14 kg/m^2-s to achieve a mixture ratio of 0.56, assuming A=5. This result also assumes that the regression rate depends solely on G_o and not on other parameters.

Table 58. Stage 1 End-Burning Hybrid Grain Results for SCO/LOX MAV (A=5)

Time, s	Thrust, N	a_i, gees	D, m	D/L
10	43860.0	16.75	1.02	15.206
20	21930.0	8.37	0.721	5.376
30	14620.0	5.58	0.589	2.926
40	10965.0	4.19	0.51	1.901
50	**8772.0**	**3.35**	**0.456**	**1.36**
60	7310.0	2.79	0.416	1.035

Table 59. Stage 2 End-Burning Hybrid Grain Results for SCO/LOX MAV (A=5)

Time, s	Thrust, N	a, gees	D, m	D/L
10	9160.0	12.95	0.466	6.949
20	**4580.0**	**6.47**	**0.329**	**2.457**
30	3053.3	4.32	0.269	1.337
40	2290.0	3.24	0.233	0.869
50	1832.0	2.59	0.208	0.622
60	1526.7	2.16	0.19	0.473

The SCO/LOX MAV would be shipped from Earth dry, and the propellants manufactured in-situ on the Martian surface during the 90-sol mission duration. The main components of the ISRU system are a propellant production plant, a cryocooler, and a dedicated ISRU power system. Assuming an 83 sol production period and a 7 sol contingency, Table 60 summarizes the ISRU system characteristics. Of the total power requirement listed in Table 60 for the ground system, 39% is required to run the cryocooler for manufactured propellant liquefaction and propellant tank heat-leak makeup; the major balance of power feeds the propellant production plant. The SCO tank is nested inside of the LOX tank, allowing the LOX to serve as the coolant for freezing and maintaining the SCO grain.

Table 60. SCO/LOX ISRU System Summary

Production period (sols)	83
Propellant production rate (kg/sol)	2.3
CO/O_2 ISRU propellant plant mass (kg)	10.0
Cryocooler cooling efficiency (%)	13.4
Cryocooler mass (kg)	16.4
Total system power consumption (W)	948
ISRU Power system mass (kg)	96.7

The total ISRU system mass is 123.0 kg, which is 70.4 kg lighter than the total propellant mass required by the SCO/LOX MAV. The total combined dry mass of the ISRU SCO/LOX MAV and supporting

ISRU system that would be shipped from Earth is 240.9 kg, including: the 4 kg empty payload canister, a 3 kg payload fairing, 45 kg of ground support equipment, a 123.0 kg ISRU system, and a 65.9 kg dry vehicle. The mass of the ground support equipment was assumed to be identical to that required for the all solid MAV, which is a conservative estimate as the SCO/LOX MAV would not require a thermal canister or heaters. Based on the aforementioned assumptions and analysis presented, implementation of the SCO/LOX MAV would provide a mass savings of ~ 74 kg, or 23.5%, as compared to the all solid MAV.

11.0 SUMMARY DESCRIPTION OF THE BEST ISRU PROPELLANT ARCHITECTURE FOR A 100-PERSON MARS COLONY

As indicated by the study results, and based upon the study assumptions and guidelines, the total ISRU carbon monoxide/oxygen propellant combination was determined to be the optimum solution. This section provides a brief overview summary of the overall system or architecture for that propellant combination and includes the related systems for a 100-person colony. Because we could not distinguish between a solid CO and a liquid CO fuel, we have not selected a specific one in the architecture; both concepts are represented. Additionally, we did not fully investigate the use of ISRU for habitats and infrastructure construction (based on study guidelines), but we recommend that the best architecture maximize ISRU across the board to keep costs down.

11.1 Time Frame, People and Base

The 100-person colony would begin after the early unmanned and manned exploration period which is defined as from now through 2040. Colonization would begin in the year 2040 and start with 20 crew members already there. The population model for the 100-person colony is summarized in Table 61. The population grows linearly from 20 to a total of 100 by 2050. The population remains at 100 people through 2090. All of the inhabitants will stay on the surface of Mars for approximately 6 years. The typical service rotation would include a 4-6 month transit from Earth to Mars, a 70-72 month surface stay, and a 4-6 month transit from Mars to Earth. The second to last two columns list the number of people that will need to be transported to and from Mars during each launch opportunity.

Table 61. ORBITEC Population Model for the 100-Person Colony 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

The elements and layout of the 100-person Mars colony were developed to determine the needs of the colony on a per person basis. The colony design is based on a self-sustaining lunar colony concept previously developed by ORBITEC. The specifications for the pressurized modules of the base are summarized in the Table 62. These specifications represent the minimal requirements that must be satisfied to accommodate 100 persons for extended periods of time. It should be noted that some of the spaces identified could be combined into common areas. For example, some of the plant growth and animal areas could be integrated into public open spaces (parks). This would provide the inhabitants important interaction with plants and animals. The numbers are not based on a specific design, but they are simply being used to determine the overall scale of the base. Figure 77 shows one potential layout of the 100-person Mars colony.

Table 62. Summary of Pressurized Module Requirements of the 100-Person Mars Colony

Use of Space	Surface Area Required (m^2)	Estimated Height (m)	Volume (m^3)
COMMAND & CONTROL CENTER	**500**	**3**	**1,500**
HABITATATION	**16,190**	**--**	**73,010**
Personal Habitats	***4,900***	***3***	***14,700***
Public Habitats	***3,090***	***--***	***21,410***
Business, Shops, Offices	340	4	1,360
Hospital/Clinic	150	3	450
Assembly (churches, halls)	150	5	750
Recreation and Entertainment	500	3	1,500
Public Open Space (park)	1,000	14	14,000
Service Industry	400	3	1,200
Transportation	200	3	1,200
Mechanical Subsystems	50	1	50
Miscellaneous	300	3	900
Storage Areas	***1,500***	***3***	***4,500***
Repair and Maintenance	***1,000***	***10***	***10,000***
CELSS Facilities	***5,700***	***-***	***22,400***
Environmental Control	400	3	1,200
Waste Recycling	800	4	3,200
Plant Growing Area	2,500	4	10,000
Animal Areas	1,000	4	4,000
Food Processing, Storage	500	4	2,000
Agriculture Drying Areas	500	4	2,000
ISRU PROCESSING	**2,500**	**10**	**25,000**
PRODUCT MANUFACTURING	**1,500**	**10**	**15,000**
POWER GENERATION, STORAGE, & DISTRIBUTION	**250**	**4**	**1,000**
SCIENCE AND TECHNOLOGY LABORATORY	**1,500**	**4**	**6,000**
LAUNCH & LANDING AREA	**--**	**--**	**--**
TOTAL	**--**	**--**	**121,510**

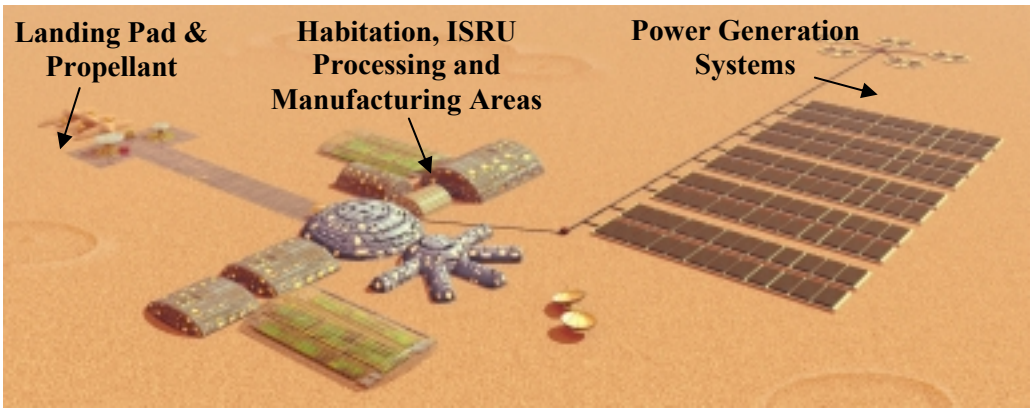

Figure 77. Overall Layout of the 100-Person Mars Colony

Figure 78 shows the detailed layout of the pressurized modules in the 100-person colony. The public habitat areas would occupy the central location of the base along with the central command and control center. The ISRU processing and manufacturing facility is the primary structure to be established after the initial habitat areas are in place. The Closed Ecological Life Support System (CELSS) would provide all the atmospheric requirements for living on Mars. The food acreage sized to support 100 people and will include growing, harvesting, and producing foodstuffs. A second greenhouse is included for complete redundancy in the case of a large-scale crop failure or accident. By proper design, it would be possible to integrate the agriculture and animal areas into attractive park areas that could be used for leisure and recreation. Power generation (nuclear reactors and solar photovoltaic arrays) are located at an optimum distance from the habitat areas and a safe distance from the launch and landing complex. The nuclear reactors must be located far enough away from the rest of the base to ensure safety while the solar arrays must be far enough from any dust generating activities (see Figure 79).

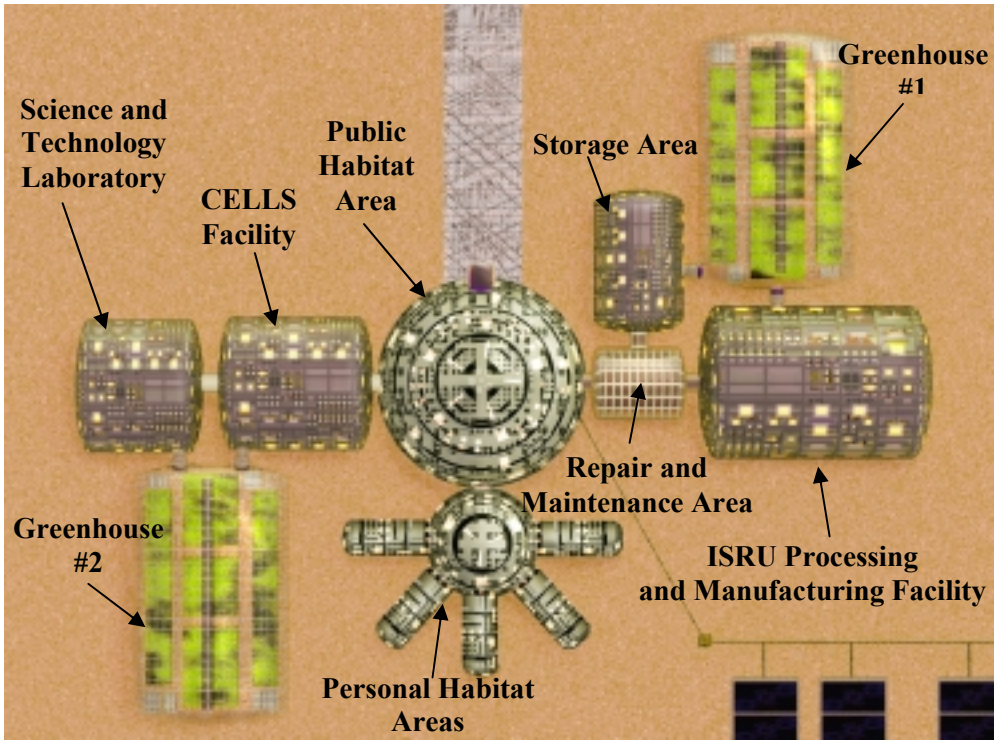

Figure 78. Layout of Pressurized Modules of the 100-Person Colony

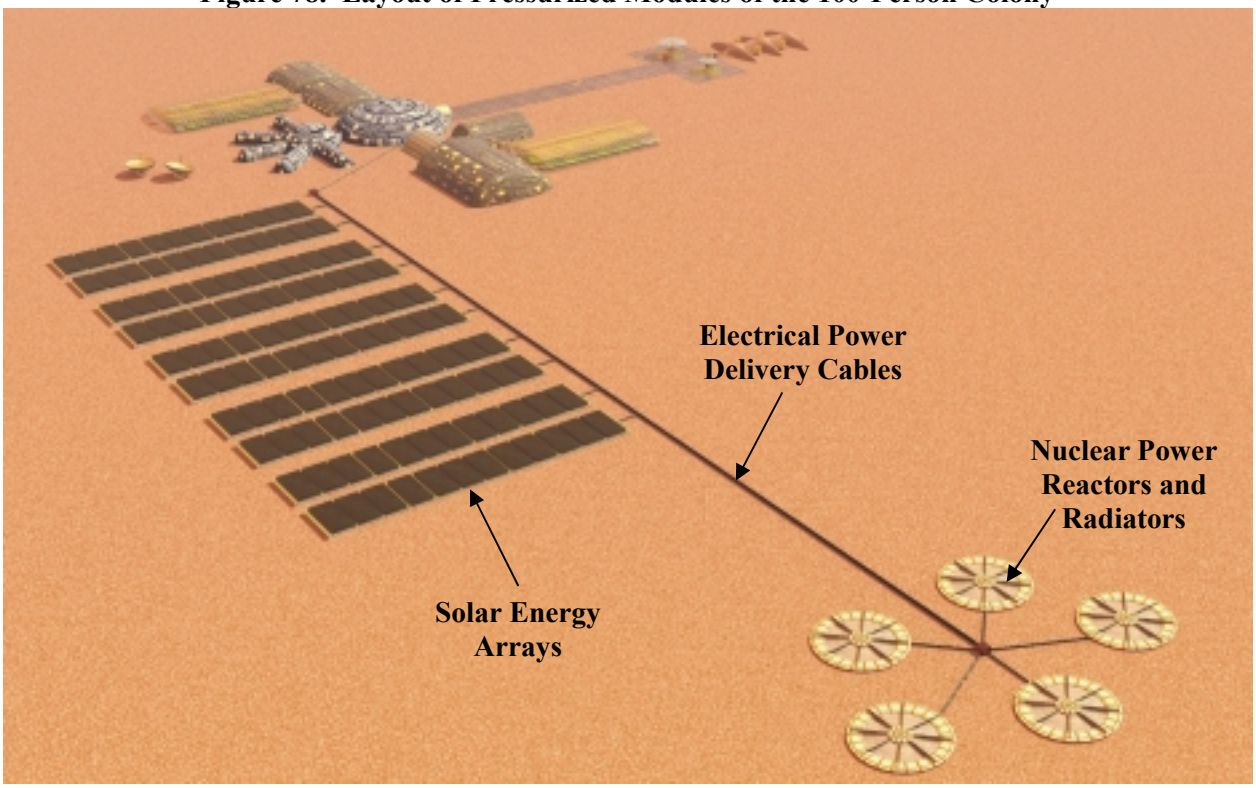

Figure 79. Power Generation Systems in the 100-Person Colony

The launch and landing facility for the base should be located away from the base because of possible blast debris. Figure 80 shows the launch and landing complex for the 100-person colony. Two different flight vehicles can be accommodated at the launch and landing complex. The propellants are generated by ISRU production plants and stored in four spherical tanks. The tanks are separated by mounds of Mars soil for safety. A paved road extends from the launch and landing complex back to the main colony.

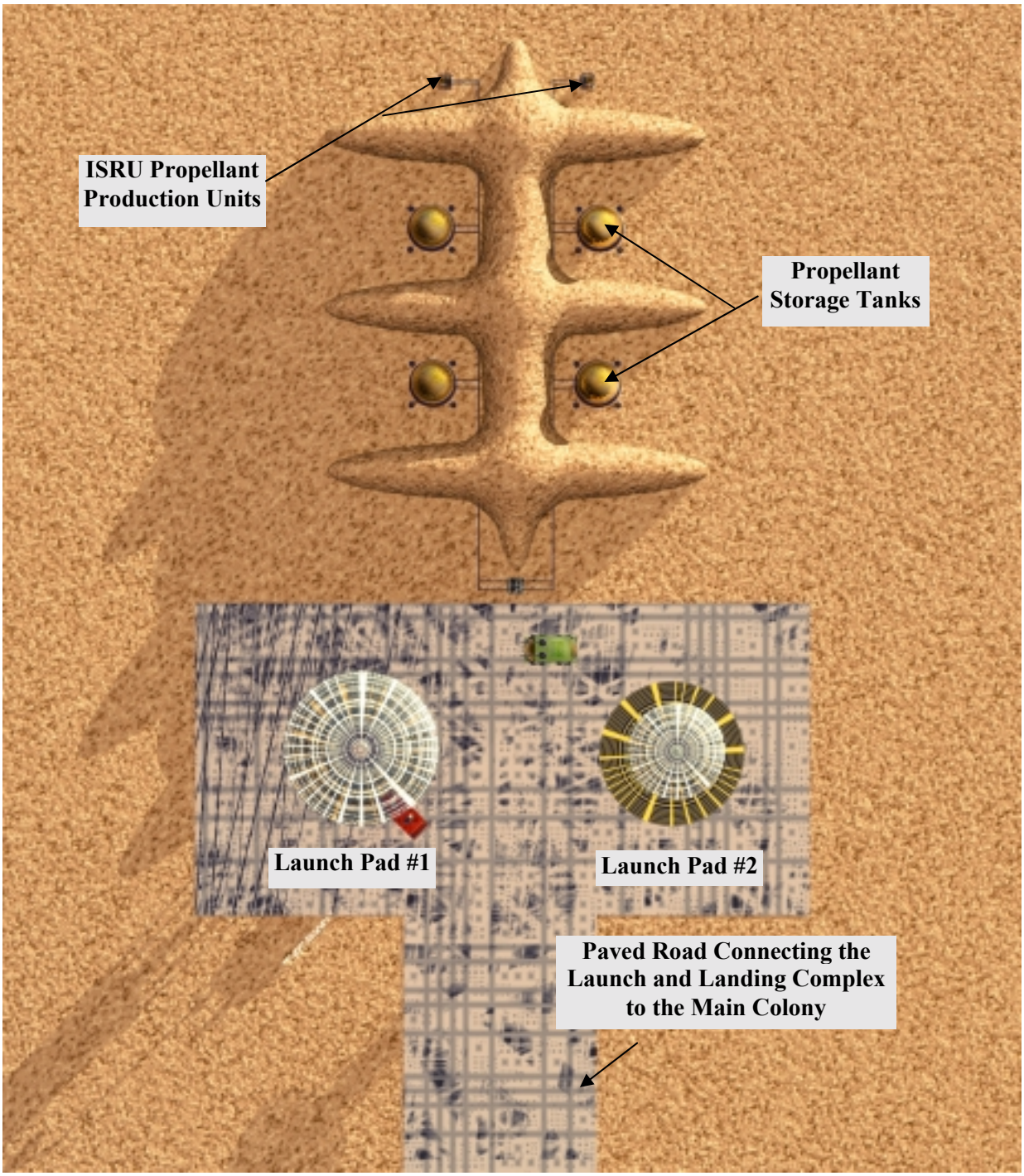

Figure 80. Launch and Landing Complex for the 100-Person Colony

The two major components in the infrastructure model are the habitat mass and the power system mass. According to the colony design and analysis discussed in the previous section, each colonist requires 1,215 m^3 of pressurized volume. The colony is expected to utilize inflatable structures to minimize the mass that must be sent from Earth. Based on previous inflatable module concepts (Nowak, et al, 1992; Sadeh, et al, 1996; Rice, et al, 1998), a mass of 2.8 kg/m^3 is assumed for the structural mass. The crew systems mass is estimated at 1,833 kg/person and the other subsystems mass is estimated at 3,250

kg/person (Kennedy, 1992). The habitat power system requirements are based on a power estimate of 25 kW per person (Larson, Pranke, 2000). The power system mass is based on a modular SP-100 power system design with a 750 kWe output and a mass of 18,500 kg (Mason and Bloomfield, 1989). Multiple power systems are used to meet the power needs of the habitat. Table 63 shows the results of the infrastructure model. Note that the total infrastructure mass stays the same after Colony Cycle 5 where the population reaches its maximum (100 people).

Table 63. Infrastructure Model for 100-Person Colony

Colony Cycle	Years	Mars Surface Population			Total Habitat Mass (kg)	Habitat Power System* (kg)	Total Infrastructure Mass (kg)
		Transient	Perm.	Total			
0	<2040	20	0	20	158,279	18,500	176,779
1	2040-42	36	0	36	284,902	37,000	321,902
2	2042-44	52	0	52	411,525	37,000	448,525
3	2044-46	68	0	68	538,149	55,500	593,649
4	2046-48	84	0	84	664,772	55,500	720,272
5	2048-50	100	0	100	791,395	74,000	865,395
6	2050-53	100	0	100	791,395	74,000	865,395
7	2053-55	100	0	100	791,395	74,000	865,395
8	2055-57	100	0	100	791,395	74,000	865,395
9	2057-59	100	0	100	791,395	74,000	865,395
10	2059-61	100	0	100	791,395	74,000	865,395
11	2061-63	100	0	100	791,395	74,000	865,395
12	2063-66	100	0	100	791,395	74,000	865,395
13	2066-68	100	0	100	791,395	74,000	865,395
14	2068-70	100	0	100	791,395	74,000	865,395
15	2070-72	100	0	100	791,395	74,000	865,395
16	2072-74	100	0	100	791,395	74,000	865,395
17	2074-76	100	0	100	791,395	74,000	865,395
18	2076-79	100	0	100	791,395	74,000	865,395
19	2079-81	100	0	100	791,395	74,000	865,395
20	2081-83	100	0	100	791,395	74,000	865,395
21	2083-85	100	0	100	791,395	74,000	865,395
22	2085-87	100	0	100	791,395	74,000	865,395
23	2087-90	100	0	100	791,395	74,000	865,395

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

11.2 Colony Missions and Activities

To help define the activities of the colonists on Mars, we developed classes of activities or missions and gave them a frequency of occurrence. The mission categories included the following:

- Scientific Exploration & Research (past life, current life, meteorology, atmospheric soundings – rockets, astronomy, geology, etc.)
- Commercial Exploration (water, minerals, metals, biochemistry, etc.)
- Terraforming (beginning experiments, and building with time accordance with a terraforming program plan)

- Infrastructure Construction (habitats, buildings, stores, offices, ports, production facilities, roads, launch and landing ports, etc.)
- Agriculture/Farming (harvesting, animals, breeding, slaughter, food production)
- Manufacturing/Industrial Activities (product manufacturing, chemical processing, other industrial activities)
- Resource Mining (water from soil, oxygen, metals concrete, basalt, etc.)
- Weather/Environmental (station deployment, repair, satellite launch)
- Communications Navigation Services (station deployment, repair, satellite launch)
- Surveying/Mapping (airplane/balloon/satellite)
- Personal Transportation (job, school, shopping, living, vacation/sight-seeing, recreation/sports, etc.)
- 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 (oxygen, water, nitrogen, etc.)
- Waste/Trash Management (human wastes, farming wastes, manufacturing wastes, construction wastes, etc.)
- Health Care/Maintenance
- Virtual Travel Market.

The mission frequency of each of these areas for the 100-person colony is given in Appendix C.

11.3 Earth-to-Mars Transportation System

The Earth-to-Mars transportation system was not specified in the study; however, the cost of this transportation leg was base lined at $5,000/kg. To achieve this cost, we assumed that: (1) the Earth surface to Earth orbit is achieved by low-cost people and cargo vehicles that likely use air breathing combined cycle propulsion; and (2) the Earth orbit to Mars orbit transfer is likely achieved by a large nuclear thermal propulsion system (see Figure 81) that routinely operates in a cyclic pattern between Earth and Mars, similar to what is now proposed by Stan Borowski of NASA/GRC.

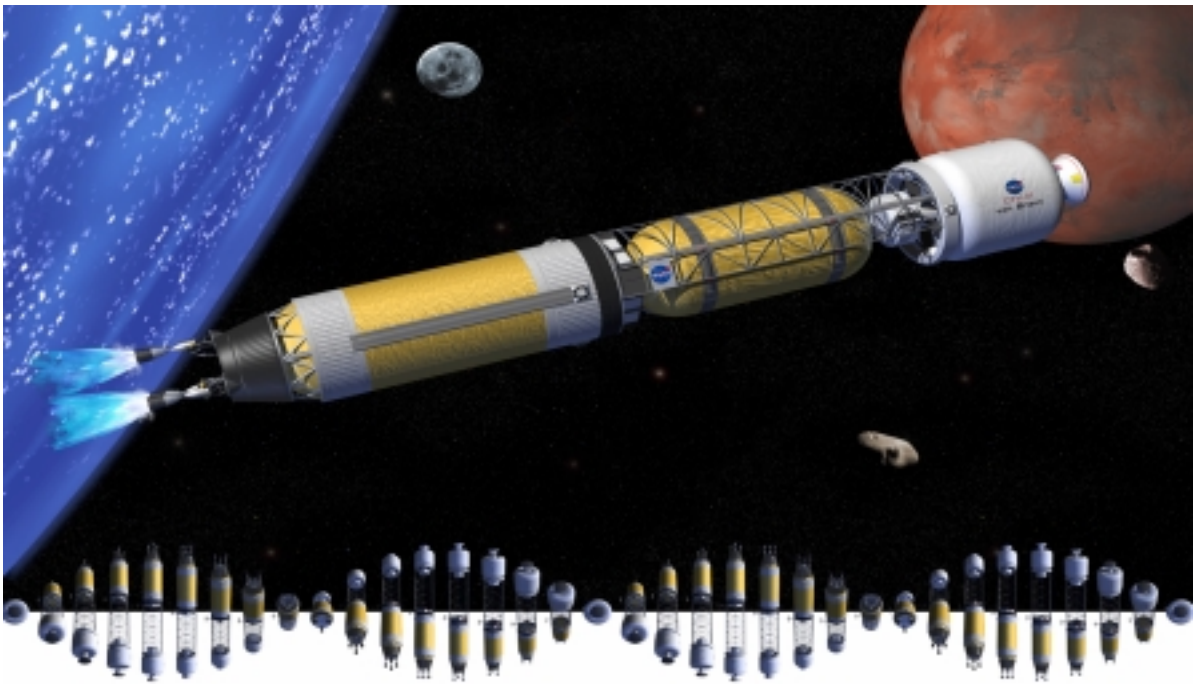

Figure 81. NASA/GRC Nuclear Thermal Rocket Concept for Manned Mars Missions

11.4 Mars Hopper Flight Systems

Mars "Hopper Flight Vehicles" are all rocket-powered vehicles included in this study, with the exception of sounding rockets. They are used to transport people and supplies, for science and exploration missions, and for emergency rescue, from either one place to another on the surface or from orbit-to-surface or surface-to-orbit. The missions were grouped according to the following mission types: (1) manned/unmanned; (2) mission type; and (3) surface-to-orbit, and orbit-to-surface. A total of three vehicle types were identified for the 100-person colony with the characteristics shown in Table 64.

Table 64. Characteristics of the Three Hopper Vehicle Types for the 100-Person Colony

Vehicle	Personnel Capability	Maximum Payload (kg)	Maximum ΔV (m/s)	Mission Type
IRIS	Robotic	300	8378	Base-to-remote area
ARES	2	600	8378	Base-to-remote area
HYPERION	82	12,300	4360	Surface-to-orbit

The missions are described below for IRIS, ARES, and HYPERION for the 100-person colony traffic model.

IRIS. Maximum people: zero – robotic; Maximum range: 10,000 km round trip (20,000 km total). IRIS is a small robotic hopper that flies from an established base to a remote location up to 10,000 km away. Mission operations are completed during a 60-day period, during which time, in-situ resource utilization (ISRU) is applied to process the atmosphere into enough propellant for the return trip home (with the exception of PF1, which brings along all the propellant for the return journey). All carbon and oxygen are directly obtained from the atmosphere. Applications for IRIS include: remote site sample collection, on-site testing, and extended observation at a remote location. Generally, IRIS is designed to address issues such as the search for past/present life, initial resource detection, and planetary science. IRIS is used for a

substantial amount of science during the early colonization years and shifts more towards industrial applications as the colony grows.

ARES. Maximum people: 2; Maximum range: 10,000 km round trip (20,000 km total); ARES is essentially the manned version of Iris. It flies from an established base to a remote location up to 10,000 km away. Mission operations are nominally completed during a 20-day period, during which time, in-situ resource utilization (ISRU) is applied to process the atmosphere into enough propellant for the return trip home (with the exception of PF1, which brings along all the propellant for the return journey). All carbon and oxygen are directly obtained from the atmosphere. Applications for ARES include: remote site sample collection, on-site testing, and extended observation at a remote location. Generally, ARES is designed to address issues such as the search for past/present life, initial resource detection, and planetary science. This vehicle is used for a substantial amount of science during the early colonization years and shifts more towards industrial applications as the colony grows.

HYPERION. Maximum people: 82; Maximum range: shuttle between Mars orbit and Mars surface. HYPERION is dedicated to shuttling personnel and cargo to and from Mars orbit. The number of missions reflects a growing mars population in addition to the dynamics of starting people on their journey home after their tour of duty on the Martian surface. HYPERION docks in Mars orbit where it receives and delivers personnel to a nuclear powered shuttle vehicle operating between Earth and Mars orbit. HYPERION fuels at a main base and brings enough propellant up for the return landing, which relies on aerobraking.

An artistic rendering of the HYPERION shuttle vehicle using LCO/LOX as the propellant is shown in Figure 82. All of the major components (personnel module, combustion chambers/nozzles, and propellant tanks) are drawn to scale; Table 65 lists the key dimensions.

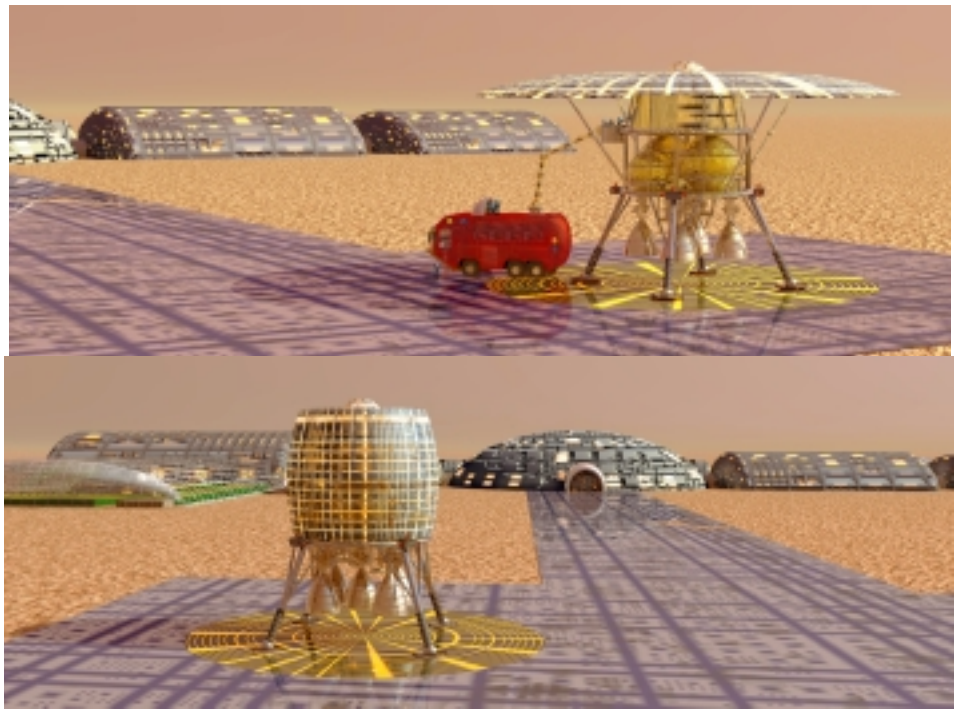

Figure 82. Artistic Rendering of HYPERION for PF6-LCO/LOX on the 100-Person Colony Landing Pad
Top View: Personnel Unloading from Vehicle

Bottom View: Aeroshell in Closed Position

Table 65. ARES Hopper Vehicle Characteristics for SCO and LCO Propellant Families

Propellants	PF6-SCO/LOX	PF6-LCO/LOX
P_c (psia)	300	1000
I_{SP} (sec)	279.7	285.6
Engine Type	hybrid	bi-propellant
Reserve Propellant (%)	3.5	3.5
Thrust to Weight	2	2
Engine Mass	438	766
Engine Thrust to Weight	189	101
Oxidizer Tank Mass	144	184
Fuel Tank/Grain Case Mass	692	346
Structure Mass	4062	3964
Crew cabin Mass	5981	5981
Space suit mass	100	100
Consumables mass	709	709
Cryocooler Mass	1330	1232
Power Systems Mass	1326	1255
ISRU Plant Mass	1652	1579
Avionics Mass	60	60
Electon. Thermal Control Mass	60	60
Aerobrake and Landing Mass	3456	3365
Attitude control Mass	237	231
Payload Mass	500	500
Payload/Wet Mass (%)	0.46	0.48
Dry Mass/Wet Mass (%)	19.0	19.7
Total Propellant Mass	88,569	82,878
Wet Mass	109,316	103,210

A few additional elements are required for the roundtrip vehicle models. These vehicles fly out to a remote location and either bring along all of their propellant for the return trip, or an ISRU propellant processing system. The aerobrake structure also serves as an antenna for microwave power receiving from the orbital power source.

The roundtrip vehicles also carry along cryocoolers for propellant liquefaction, required for both ISRU production and handling boiloff. There is a tradeoff between the mass of the insulation (thickness) and the refrigeration system. The cryogenic tank insulation thickness was parametrically varied while solving for the overall vehicle mass. The insulation thickness which resulted in the minimum total vehicle mass was selected for each propellant family and roundtrip vehicle type. Figure 83 is an artistic rendering of ARES. Figure 84 shows another view of the 100-person landing area with both HYPERION and ARES, and a mobile robotic fueling station on the pad. The propellant storage tanks and ISRU processors are shown in the background.

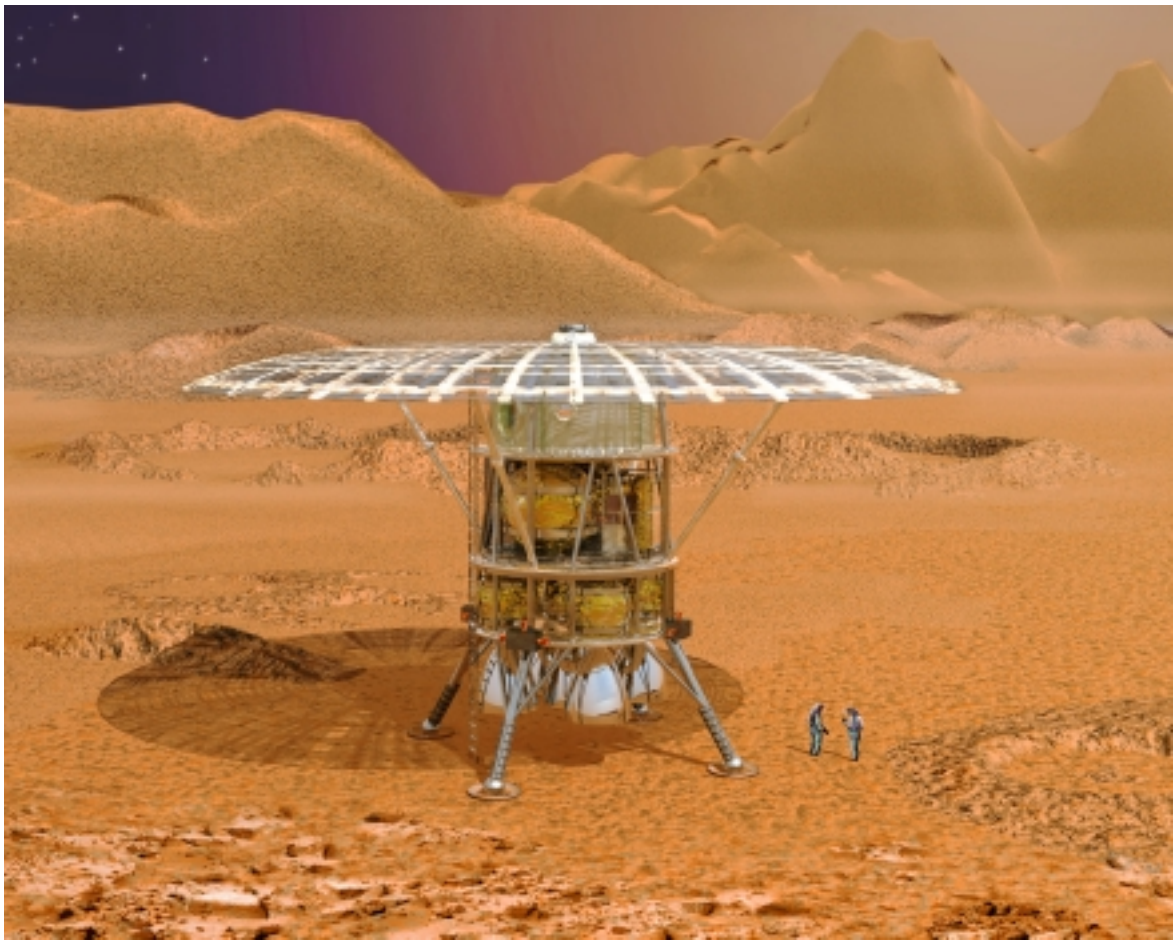

Figure 83. Artistic Rendering of ARES

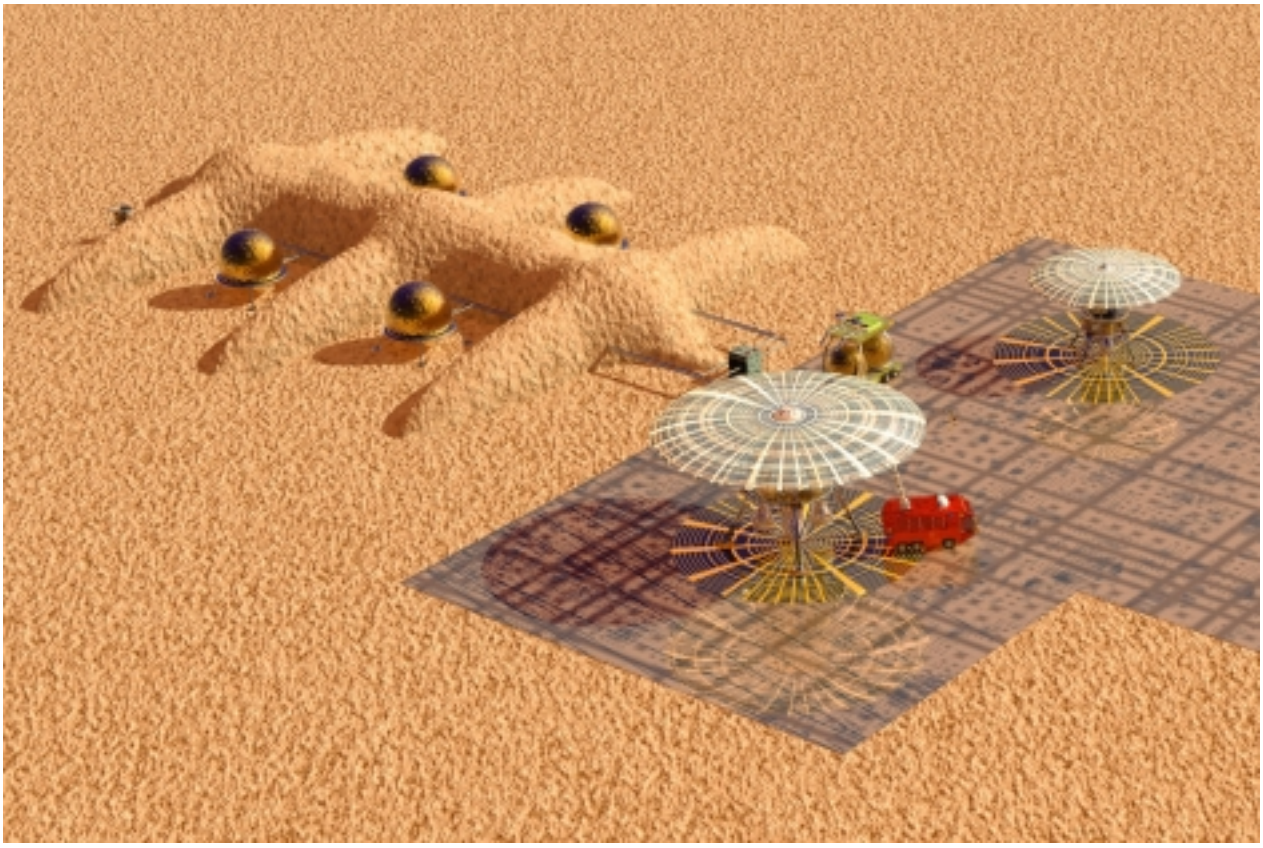

Figure 84. Vehicle Landing Area for 100-Person Colony

11.5 Mars Ground Vehicles

Ground vehicles are similar to terrestrial trucks. They are the most fuel efficient mode of getting around on the red planet, and are therefore the backbone of the Martian transportation system. They are used to transport people and supplies, and for science and exploration missions. The missions dictated by the traffic models for the 100-person colony led to a total of four vehicle types were identified for the 100-person colony with the characteristics shown in Table 66.

Table 66. Ground Vehicle Characteristics

Name	Range (km)	Max Cargo Mass (kg)	Personnel Capability	Function
GAMMA	Indefinite	50	0	Nuclear Powered Autonomous Rover
TYCHE	2000	300	0	Light duty robotic rover
ZEPHYRUS	2000	5000	0	Heavy duty robotic rover
SELENE	1000	525	7	Multi-use manned vehicle

Ground vehicle model output for SELENE is given in Table 67.

Table 67. Ground Vehicle Model Output for SELENE

Propellants	LCO/LOX
Propellant energy Density (J/kg)	4,591,000
Power Supply	fuel cell
Reserve Propellant (%)	10
Maximum Number of People	7
Base Vehicle Mass	4053
Fuel Cell Mass	96
Oxidizer Tank Mass	13
Fuel Tank Mass	23
Exhaust Propellant Tanks Mass	22
Crew Cabin Mass	3328
Space Suit Mass	350
Cryocooler Mass	8
Electric Motor Mass	12
Mass People	525
Other Consumables	124
Cargo Mass	175
Total Propellant Mass	904
Fully Loaded Vehicle Mass	**9633**

11.6 System Costs

The cost for this overall best option is the lowest cost approach that is presented in Section 7.0. The overall absolute cost data should not be used to predict the total cost of this activity, because not all costs were included (salaries of colonists, etc.). The cost data are useable only in comparison to other options and sensitivities. Additional cost consideration would need to be made to develop absolute cost data for the ????? and period of operation.

12.0 STUDY RESULTS AND CONCLUSIONS

All results and conclusions drawn from this study must be taken within the context of the study assumptions as outlined within this report. The results and conclusions given below are categorized by the given work area of the study.

12.1 Mars Mission/Traffic Model Development

- Various classes of activities or missions that would be expected in a small (e.g., 100-person) or large (e.g., 10,000-person) Mars colonization effort were developed.

- A Mars terraforming effort would likely be the major and only reason for a large human colony on Mars.

- To properly develop the requirements for future colonies, the mission categories for future mission model development should include the following: Scientific Exploration & Research, Commercial Exploration, Terraforming, Infrastructure Construction, Agriculture/Farming, Manufacturing/Industrial Activities, Resource Mining, Weather/Environmental Monitoring, 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, Recreation/Sports, Virtual Travel Market.

- While all these above missions and activities were identified in the total system view, only certain ones had a direct effect on the study analysis. It was concluded that the following four mission categories were identified as significant consumers of ISRU propellants, and thus having the potential to impact the study:

  - Scientific Missions (Search for Past/Present Life, Planetary Science, Mars Moon Studies)
  - Commercial (Resource Development)
  - Transportation (Human Transport Between Mars Surface and Orbit, Cargo Transport Between Mars Surface and Orbit, Ground/Surface Transportation, Flight Transportation)
  - Government (Law Enforcement, Search and Rescue, Medical Transport).

- Because of research and development efforts occurring in both colony sizes, the number of missions in the traffic model is not linearly related to the colony population; the number of missions per person is significantly higher for the 100-person colony.

- Several missions with similar transportation requirements (payload, distance, vehicle type, and personnel requirements) can be efficiently completed by the same vehicle.

- The traffic models, or mission frequency data, that were developed were based on the views of many of ORBITEC's visionary staff, where we projected, debated and formed a consensus of what would be considered reasonable values.

- The Moon should be used first as a test operation for a 100-person colony that would eventually be placed on Mars.

12.2 Propellants and Propellant Processing Systems

- The propellant/propulsion systems that were initially considered for flight vehicles to be analyzed in the system tradeoffs are shown below:

  - LH_2/LOX Bi-Propellant Liquid Propulsion
  - LH_2/SOX Cryogenic Solid Hybrid Propulsion
  - SC/LOX Vortex Hybrid Propulsion (later dropped from final analysis)
  - LCO/LOX Bi-Propellant Liquid Propulsion
  - SCO/LOX Cryogenic Solid Hybrid Propulsion
  - SC_2H_2/LOX Cryogenic Solid Hybrid Propulsion (later dropped from final analysis)
  - LC_2H_4/LOX Bi-Propellant Liquid Propulsion
  - SC_2H_4/LOX Cryogenic Solid Hybrid Propulsion
  - LCH_4/LOX Bi-Propellant Liquid Propulsion
  - SCH_4/LOX Cryogenic Solid Hybrid Propulsion.

- During the conduct of the study, we performed experimental rocket test firings that indicated that solid C and C_2H_2 should be dropped because of operability considerations. Toluene was considered as a possible replacement for the low-hydrogen based propellants C and C_2H_2; however, it was considered too late to be included in this study.

- Hydrogen transport to Mars is very expensive compared to existing ISRU technologies, so either non-hydrogen based propellants (CO/LOX) or hydrogen-derived from Martian sources should be utilized.

- Propellant production plants should operate continuously under steady-state conditions with propellants being stored until needed.

- All storable equipment shipped from Earth should be sent one colony cycle early and parked in orbit. This will minimize the propellant production requirements for downloading the equipment to the surface. Downloading this equipment over the entire colony cycle will greatly reduce the amount of propellant production capacity needed.

- The ease of extracting CO and O_2 from the largely CO_2 Martian atmosphere leads to relatively power efficient and small processing systems.

- The water extraction systems used for the total ISRU propellant families requiring hydrogen are relatively massive, and they have to move enormous volumes of the Martian atmosphere through the processor to collect a sufficient amount of water.

- Non-hydrogen based propellants offer the best solution to reduce overall costs associated with a Mars colony, if hydrogen is not easily available on Mars.

12.3 Vehicle Design and Maintenance

- Many of the roundtrip missions defined in the traffic model cannot be accomplished by conventional chemical propellant combinations without the use of power-beaming (the power systems required for ISRU processing are too massive). The missions could be re-defined to eliminate the need for power beaming (for example: increased mission duration, reduced ΔV requirements, allowing multiple hops).

- A fleet of 6 and 4 hopper vehicle types can efficiently complete all missions defined for the 100-person and 10,000-person colony traffic models, respectively.

- A total of 12 and 23 vehicles are required to complete all hopper vehicle missions for the 100-person and 10,000-person colonies, respectively.

- The relative size of the one-way hopper vehicles is primarily determined by the propellant family I_{SP}.

- The relative size of the round-trip hopper vehicles for a given propellant family is driven by a combination of variables, including: the amount of hydrogen that must be brought along for the return trip, I_{SP}, thermal conditioning requirements, and the mass efficiency of ISRU propellant processing plant.

- A fleet of 4 and 3 ground vehicle types can efficiently complete all missions in the 100-person and 10,000-person colony traffic models, respectively.

- Because they are more efficient, ground vehicles are extensively used in the traffic model. A total of 52 and 258 vehicles are required for the 100-person and 10,000-person colonies, respectively.

- In sharp contrast to the hopper vehicles, the relative size and cost of the ground vehicles are not highly sensitive to the mass-based propellant performance (mass-based propellant performance is the I_{SP} for the flight vehicles and delivered J/kg for the ground vehicles).

- Aero-brakes and a Mars orbital power beaming system are critical technologies for affordable Mars exploration and colonization activities.

12.4 Cost Modeling

- Because ISRU reduces the total 100-person colony cost by as much as a factor of 36 and reduces the total 10,000-person colony cost by as much as a factor of 50, ISRU propellant production is absolutely necessary to perform future manned Mars missions/colonization.

- Analysis indicated a reasonable baseline cost for Earth-to-Mars orbit delivery as $5000/kg.

- For a given propellant family, the total cost for the hybrid and bi-propellant hopper vehicles are nearly identical.

- The CO/O_2 systems greatly benefit from not having to carry along return trip hydrogen for the roundtrip missions.

- Propellant Family #6 (PF6) - CO/O_2 achieves the lowest total cost for both the 100-person and 10,000-person colony scenarios.

- The total ground vehicle cost is not very sensitive to the propellant family used for both the 100-person and 10,000-person colonies.

- Implementing ISRU propellant production for the ground vehicles does not provide any significant cost savings.

- Implementing ISRU propellant production for the hopper vehicles has a profound affect on the total hopper vehicle cost, reducing their total cost by a factor of up to 120 and 980 for the 100-person and 10,000-person colonies, respectively.

- Increasing the amount of ISRU implementation decreases the total hopper vehicle cost for every propellant family considered for both the 100-person and 10,000-person colonies.

- The superior propulsive performance (I_{SP}) offered by increasing amounts of hydrogen (in a propellant combination) does not offset the high cost associated with either shipping hydrogen or making it in-situ for the 100-person and 10,000-person colonies.

- General infrastructure costs (those which are not dependant on the transportation system) were found to account for a significant amount of the total colony cost: 40% of the total cost for the 100-person colony (PF6-LCO/LOX), and 88% of the total cost for the 10,000-person colony (PF6-LCO/LOX).

12.5 Overall Sensitivity Analysis

- The primary finding of the sensitivity analysis is that the selection of CO/LOX as the lowest cost propellant combination is amazingly robust to uncertainty in the study.

- There is an Earth-to-Mars orbit delivery cost below which it is less expensive to ship the required hydrogen from Earth rather than producing it via ISRU on Mars. For the 100-person colony, this cost ranges between ~$1300/kg to $1900/kg, depending on the propellant family. For the 10,000-person colony, this cost ranges between ~$600/kg to $800/kg, depending on the propellant family.

- The baseline Earth-to-Mars orbit delivery cost is assumbed to be $5000/kg. If the actual Earth-to-Mars orbit delivery cost were higher than $5000/kg, the use of ISRU and PF6-CO/O both become even more attractive.

- The total costs for both the 100-person and 10,000-person colonies are highly sensitive to the Earth-to-Mars orbit delivery cost.

- If subsurface water were easily available at the bases, ISRU LH_2/LOX (PF3) would become the lowest cost propellant combination for the 10,000-person colony and cost about the same as PF6-LCO/LOX for the 100-person colony.

- The use of multiple propellant families does not provide any significant benefit over using only PF6-CO/O_2.

12.6 Early Manned Missions (2020-2040)

- The lowest total Earth launch mass for the Early Manned Exploration Period is achieved using PF11-LCH_4/LOX, which implements terrestrial hydrogen and ISRU CO and O_2 for propulsion and life support.

- The reduced hydrogen requirement achieved by using CO/LOX (hydrogen is still required for life support in the CO/LOX scenario) is not offset by the lower performance of this propellant combination for the Early Manned Exploration period.

- Utilizing ISRU hydrogen for life support and propulsion does not reduce the overall Earth launch mass for any propellant combination considered; it is more efficient to bring the hydrogen from Earth. This is a result of using the ISRU hydrogen systems only once. This finding does not factor in the relative merit of using the ISRU hydrogen systems for future missions. The availability of subsurface water may also impact this conclusion.

12.7 Mars Sample Return

- The use of a dual-disk end burning SCO/LOX vortex hybrid is an attractive candidate for use as the MAV propulsion system for a Mars Sample Return mission.

- Implementing an SCO/LOX vortex hybrid as the MAV propulsion for a Mars Sample Return mission could reduce the total Earth launch mass by ~74 kg compared to the current baseline all solid propulsion system. The SCO/LOX MAV system is estimated to be ~24% lighter than the all solid version.

13.0 RECOMMENDATIONS

In this section, we provide study recommendations and a list of future technology work that needs to be achieved before this architecture can be carried out.

13.1 Study Recommendations

- Recent discoveries of potentially large amounts of water just below the surface of Mars should be considered in any further analysis.

- Per the recent discovery that water ice may be abundant near the surface, analyze the possible effects of this finding on the study results.

- For cases using water from under the surface of Mars, a design study should be conducted on a mining or drilling systems to determine the mass and energy costs associated with recovery of this water.
- A water extraction system and electrolysis unit should be analyzed for utilization of the sub-surface Martian water deposits to provide a LH_2/LOX propellant source.

- Detailed system designs should be conducted for the CO/O_2 and the other most attractive propellant production systems in their full-scale configuration to improve the accuracy of the total estimated mass and energy requirements.

- Design and build a Martian water ice simulator and conduct experiments to help to develop mining, research, and ISRU processing technologies.

- General infrastructure was found to account for a significant amount of the total colony cost. The general infrastructure costs are independent of the propellant used. It is recommended that an integrated study that compares the cost, reliability and technology readiness level of different types infrastructure be conducted, including: ISRU concrete, inflatables, regolith sintering, terrestrial components, DUNE (low energy autonomous deployment of Martian structures), and combinations thereof.

- Analyze the cost of transporting goods from the surface of Earth-to-Mars orbit in more detail, accounting for the specific requirements of people, hydrogen, inert equipment, etc.

- Further analyze the assumption of using beamed power from Mars orbit, determine its effects on this study, evaluate the ramifications of implementing alternate approaches, and perform a system design study.

- Aero-brake systems design work should be a priority, as this technology is vital to keeping costs down.

13.2 Technology Development Recommendations

The list below, in no particular order, lists the items that were identified in this study that require additional technology development before implementation:

- CO/LOX, CH_4/LOX, and H_2/LOX hybrid and bi-propellant liquid propulsion systems

- CO/LOX, CH_4/LOX, and H_2/LOX propellant processing systems
- Orbital power beaming systems
- Nuclear propulsion and power reactors
- Orbiting nuclear power systems
- Large biodomes
- Aerobraking
- Aerobrakes with microwave power antennas integrated
- Low-g effects on humans, animals and plants
- Radiation effects and shielding
- Animal habitats and green houses
- Study MAV ISRU systems for follow-on missions
- Mars personnel and cargo rovers
- Defining the colony needs for animals, sports, recreation, etc
- Human Psychological issues and human factors
- Martian ice/soil simulator
- Self-cleaning solar energy and green house systems
- Mars mining operations and technologies
- Mars ISRU-based materials production and manufacturing
- Rocket backpacks for explorers/colonists
- Oxygen production from carbon dioxide gas breathing packs
- Mars terraforming technologies and modeling
- Small nuclear powered robotic rover.

APPENDIX A
BIBLIOGRAPHY

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BIBLIOGRAPHY

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APPENDIX B
APPROACH WORKSHOP

APPENDIX B
APPROACH WORKSHOP

This appendix provides a summary of the results of the study approach workshop that was held June 21-22, 2000, in Madison, Wisconsin (see Agenda at the end of Appendix B).

The key aspect of the workshop was to the review of the overall study approach that was proposed for the Phase II study effort. The purpose of the workshop was to gain valuable interaction between certain exploration/ISRU experts and the ORBITEC study team (the agenda is given at the end of this Appendix). The workshop focused on two study tasks: (1) to refine the study approach, ground rules, and possible advanced concepts, and (2) assess the possible activities that would be needed at a Mars base (the Mission Model).

The participants who attended and contributed to the project workshop are listed as: ORBITEC – Dr. Eric Rice, Dr. Doug O'Handley, Mr. Robert Gustafson, Dr. Martin Chiaverini, Mr. Dan Gramer, Mr. Jerry Hanley, Dr. Jim Jordan, Mr. Bill Knuth, Dr. T.D. Lin, Mr. Matt Malecki, Dr. Bob Morrow, Mr. Pete Priest, Mr. Ron Teeter, Mr. Brant White, Dr. Leslie Gertsch, Dr. Richard Gertsch, and Mr. Marty Harms; NASA - Dr. Mike O'Neal (KSC); Universities: Dr. George Miley (U of IL), Dr. Mike Duke (CSM), Dr. Jerry Kulcinski (UW); Others: Niklas Jarvstrat (Literati), Dr. Paul Spudis (LPI), Mr. John Hunt (DOA/FPL), and Dr. Ed McCullough (Boeing).

B.1 Summary

Basically, the overall study approach that was developed in Phase I was blessed at the workshop. However, there were several suggestions that were made to try to reduce the complexity and mount of work that is implied by the ambitious approach. A workshop consensus was provided on the following major items as follows:

- The ORBITEC approach is sound
- It was agreed that a 20-year manned exploration period before colonization was appropriate, as we originally suggested
- The costs in the cost model should reflect the transport cost to go from the surface of the Earth to the surface of Mars
- Two scenarios were recommended over the three we originally suggested, namely 100-persons and 10,000-persons at the end of the 50-year period (dropped the 1000-person middle scenario)
- It was suggested to drop the use of Lunar water option in the study.

In addition to the very interesting debates and discussions, many other insights were gained that were used in the study.

As a result of the consensus of the workshop, we defined the following scenarios, which we decided to analyze with respect to ISRU:

2000-2020	Early Mars Automated Exploration – a Mars sample return mission
2020-2040	Manned Mars Exploration and Discovery – a look at Mars direct missions
2040-2090	Low Sustained 100 person Mars Colony
2040-2090	High Final 10,000 person Mars Colony.

It was believed that there should be substantial lunar base activity that will support technology development for the Manned Mars Missions, therefore we should start the Manned Mars activity in 2020.

It was recommended that we tie the ORBITEC Self-Sufficient Lunar Base Study effort (A NIAC Phase I study, D. O'Handley, 2001) to this Mars effort, and that the lunar base be a precursor to the Mars base.

It should be noted that the project study team reviewed the workshop results and selectively used what it believes to be appropriate for inclusion in the study.

B.2 Workshop Mission Model Development

At the workshop, we sought input from defined groups of the participants regarding missions. To facilitate this, we placed the workshop participants into 4 different groups, with specific focus areas that were developed during the Phase I effort, and modified again during the early part of the Phase II effort, as listed below. During the workshop, each group met separately in an attempt to define specific Mars missions. This activity proved too difficult within the time constraints, and the groups developed various thoughts and recommendations, which are summarized below by group. The subsections that follow provide a summary of the group results.

GROUP 1. ***Exploration/Political*** [Niklas/Hanley/O'Handley/Duke/L. Gertsch/Spudis]

- Scientific Exploration & Research (past life, current life, meteorology, atmospheric soundings-rockets, astronomy, geology, etc.)
- Commercial Exploration (water, minerals, metals, biochemistry, etc.)
- Government Activity/Law Enforcement/Prisons/Jails/Emergency Rescue/Response/Signage
- Health Care/Maintenance/Hospitals
- Earth/Moon/Phobos/Demos Vacations for Martians
- Entertainment/Recreation (virtual, real, golf, fishing, movies, theater, music, pets, sports, recreation, etc.)
- Education/Schools/Fieldtrips
- Commercial Ventures (virtual and real travel for Earthlings, minerals, etc.).

GROUP 2. ***Food/Life Support/Terraforming*** [Morrow/O'Neal/Priest/Harms/Hunt]

- Agriculture/Farming (harvesting, animals, breeding, slaughter, food production)
- Life Support (oxygen, water, nitrogen, etc.)
- Waste/Trash Management/Recycle/Chemical Recovery (human wastes, farming wastes, manufacturing wastes, construction wastes, etc.)
- Mars Terraforming (beginning experiments, and building with time accordance with a terraforming program plan).

GROUP 3. All ***Transportation/Power*** [Teeter/Knuth/Malecki/Gramer/Chiaverini]

- Personal Transportation (job, school, shopping, living, vacation/sight-seeing, recreation/sports, etc.)
- Food/Package/Product/Cargo/Mail Delivery
- Delivery/Goods/Services/Cargo/Plow sand/Ground transport systems
- Launch/Space Transport, Satellite/Earth Cargo Launch
- Main Power/Auxiliary/Emergency Power/Lighting/Energy Storage/Power Distribution
- Support of Ground and Flight Systems (maintenance, plow dust/sand).

GROUP 4. ***Mining/Processing/Automation/Manufacture/Construction*** [Gustafson/R. Gertsch/McCullough/Lin/White/Jordan]

- Resource Mining and Storage (water from soil, oxygen, metals, concrete, basalt, etc.)
- Infrastructure Construction (habitats, buildings, stores, offices, ports, production facilities, roads, launch and landing ports, etc.)
- Manufacturing/Industrial Activities (product manufacturing, chemical processing, other industrial activities)
- Weather/Environmental (station deployment, repair, satellite launch)
- Communications Navigation Services (station deployment, repair, satellite launch)
- Surveying/Mapping (airplane/balloon/satellite).

The group reports that were developed as part of the workshop are given below.

B.2.1. Group 1: Exploration/Political

Several mission types were discussed within the scope of two possible inhabitation scenarios. In general, the missions that were identified and discussed by this group were:

- Scientific expeditions
- Resource surveys/development
- Detailed site characterization
- Human support systems
- Robotic exploration
- Remote system maintenance and repair.

Small Base. The first scenario is a single base of 100 people. In this case, a tour of duty of 4 years would be expected with half the group being replaced every 2 years at each maximum-efficiency Earth-Mars transfer launch window. The notable advantage of this configuration is that the base would never be manned entirely by a new crew. Twelve scientific expeditions would be carried out each year. Each 6-person expedition would last about 30 days and could involve long-distance (global) travel. Fuel for the expedition vehicles would be provided by ISRU fuel production facilities at the main base or onboard the vehicle. Resource exploration and development expeditions would also take place monthly and involve 6 crewmembers. The expeditions would seek to discover useful natural resources in the vicinity (approximately 500 km) of the base.

An unspecified number of expedition (scientific or resource exploration and development) support missions would also be carried out depending on the needs and circumstances of a particular year's planned missions. In addition to these extra-base activities, a variety of on-site activities would occupy the 100-person crew. Existing infrastructure, transportation, and power production facilities would require crew for daily operations, as well as less frequent maintenance and repair, and new technology would need to be installed and tested. Other crew activities would include human support services and the operation of in-situ propellant production facilities and launch and landing facilities for Earth-Mars vehicles, Martian orbital vehicles, and Martian atmospheric vehicles.

Large Base. The second scenario is a large-scale inhabitation of 10,000 people. Half of the 10,000 people would be permanent residents and 10-year tours of duty would be required of the other half. At each maximum efficiency Earth-Mars launch window (every two years), 1,000 of the temporary residents would be exchanged for new recruits. Detailed scientific investigations would be carried out at 3 satellite bases and detailed site surveys for the purpose of locating new large-scale bases would be carried out at 3 additional sites.

Resource development would be carried out in the vicinity of the base as well as at remote sites. Water to replace life support system losses would be mined in the vicinity of the main base. Scientific opinion is currently divided as to whether near-surface water reservoirs exist in the Martian crust and the resolution of this question is critical to moving forward in a discussion of how in-situ Martian water resources could be utilized. Other manufacturing materials would also be mined at remote sites up to 500 km from the main base. The locations of these sites and thus the means of transportation back to the main base are dependent on the natural abundance of the desired materials in the region surrounding the main base.

In addition to the infrastructure operations discussed in the small-scale case above, the large base would also require crew and facilities for infrastructure (power production, habitats, propellants, agriculture, and manufacturing) expansion to accommodate population increases due to immigration and births. For a population of 10,000, it is estimated that there would be approximately 200 births per year and an equal number of immigrants (i.e., temporary residents that wish to remain).

Launch and landing facilities would also have to be significantly larger than in the small-scale case and would need to be able to expand to accommodate the increasing demands of a growing population.

B.2.2. Group 2: Food/Life Support/Terraforming

Small Base. Group members discussed the prospective methods of food production and life support for a Martian base. The base considered was a single-site, nuclear powered base capable of supporting 100 permanent residents. The purpose of the base would be to conduct on-site scientific experiments and off-site exploratory and scientific missions. Terraforming techniques would also be investigated within the controlled environment of the base and surrounding area.

The group concluded that agricultural activity would be carried out in an adjacent food-production complex. The complex would be housed in a 2000-m^3 inflatable structure and would include a food storage facility and an automated system for planting, maintaining, and harvesting the agricultural produce. Livestock would not be raised.

The life support system of such a base would recycle originally transported material and use ISRU techniques to replace system losses of O_2, N_2, and CO_2. Life support gases and carbon-based compounds for manufacturing would be produced by processing the atmosphere and soil. Waste material would be recycled or stored.

Large Base. Also considered was a large-scale base cluster capable of accommodating 10,000 permanent residents. The total population would be divided between 11 locations: one main base with 9,500 residents and 10 satellite bases with 50 people each. Five of the satellite bases would be within rover distance and the remaining five would be within hopper distance. This base distribution would allow for centralized agricultural production, recycling, and primary energy production, while allowing for scientific studies of broad areas of the Martian surface.

Agricultural production would be limited to a 200,000-m^3 central food production and storage complex located at the main base and operated by automated planters and harvesters. An estimated 5 kg/person/day (250 kg/base/day, 7500 kg/base/month) of agricultural produce would be transported to the satellite bases. Satellite bases would have local storage facilities for non-perishables and receive fresh produce via regular deliveries.

Life support systems would also be centered at the main base. Waste material would be recycled to minimize ISRU requirements. Satellite bases would be re-supplied by the main base, although the exact

nature of the re-supply and the extent to which on-site ISRU techniques would be utilized is highly dependent on the power source and location of the satellite bases. Waste material recycling and storage would be carried out primarily at the main base. Several different processing techniques could be used to minimize the space consumed by non-recyclables, including incineration, microbial decomposition, and mechanical compaction.

Three methods were considered for effecting large-scale terraforming of the Martian environment:

1) *Chemical production*: 100 million tons of CFCs per year would be produced. ISRU techniques and large-scale processing plants would produce the chemicals and dispersment vehicles would be used to release the gases to the atmosphere.
2) *Increase albedo*: 100 – 1,000 million tons of dust per year would be introduced to the atmosphere to increase the portion of solar energy absorbed by the planet. Dust would be mined and dispersed by spreading/spraying vehicles.
3) *Increase solar flux*: Orbiting mirrors would increase the total flux of solar energy into the Martian environment. ISRU techniques would be employed for space-based mirror manufacturing.

The group concluded that within the 50-year period of the study, only the beginning of ecopoeisis would take place.

B.2.3. Group 3: Transportation/Power

Group 3 discussed the various mission categories, which included:

- Personal Transportation (job, school, shopping, living, vacation/sight-seeing, recreation/sports, etc.)
- Food/Package/Product/Cargo/Mail Delivery
- Delivery/Goods/Services/Cargo
- Launch/Space Transport/Satellite/Earth Cargo Launch
- Main Power/Auxiliary/Emergency Power/Lighting/Energy Storage/Power Distribution
- Support of Ground and Flight Systems (maintenance, plow dust/sand).

However, it was concluded that transportation and power requirements were so interdependent on other aspects of MARS base scenario and infrastructure development assumptions that system sizing and flight frequency estimates could not be made until more was known about the requirements of the other group categories. Instead, based on known information, a number of general conclusions were developed. They are:

1. The ability to put in place a robust nuclear power capability would greatly reduce ISRU propellant needs for transportation vehicles. Electrically-powered rail, maglev, and road-based transportation systems might then supply most ground-based transportation requirements.
2. Personal transport becomes mostly public transport (electrically powered). A population of 10,000 could dwell in a series of "Metrodome" like structures connected by public transportation.
3. Minimum energy Earth-Mars transit opportunities are two years apart (26 months). This frequency may not be adequate to support a Mars population of 10,000. Finding a solution to this problem is difficult, unless a major propulsion breakthrough is accomplished.
4. The largest overall ISRU propellant need will be for Mars-Earth transit of vehicles, people and cargo.
5. The "Hopper" will be the largest Mars surface ISRU consumer. This need can be reduced if an efficient aerodynamic vehicle can be designed.
6. Efficient use of resources may dictate the design of large, multi-purpose Science/Exploration

Rovers rather than having separate rovers for each purpose.

7. Regardless of scenario, Mars base and population buildup will result in a very large Earth to Mars net mass flow. However, a large ISRU propellant capability will be needed for return to Earth of empty, or near empty transport vehicles.

B.2.4. Group 4: Mining/Processing/Automation/Manufacture/Construction

Group 4 evaluated the mining, processing, automation, manufacture and construction missions. In the small base scenario, the mining and manufacturing activity will likely be restricted to life support materials and perhaps some construction materials. This activity would be expanded in the large base scenario to also include propellants, fibers and metals. The group assumed that the base(s) will have one or more large nuclear reactors that would produce electricity. Most of the mining, manufacturing and construction equipment would be powered by electricity. The electricity would be provided by fuel cells. Although the fuel cells may use ISRU components (H_2/O_2 or CO/O_2), there will be little requirement for ISRU fuels and oxidizers. Specific conclusions are listed below each mission.

- ***Resource Mining and Storage (water from soil, oxygen, metals, concrete, basalt, etc.)***
  - Significant amount of mining equipment will be required from Earth, at least initially
  - If a nuclear reactor is present, most or all of the mining equipment will be driven by electricity instead of ISRU fuels/oxidizers
  - Electricity could be stored in fuel cells or batteries which may require ISRU components

- ***Infrastructure Construction (habitats, buildings, stores, offices, ports, production facilities, roads, launch and landing ports)***
  - Significant amount of construction equipment will be required from Earth, at least initially
  - If a nuclear reactor is present, most or all of the construction equipment will be driven by electricity instead of ISRU fuels/oxidizers
  - Electricity could be stored in fuel cells or batteries which may require ISRU components
  - Concrete will be widely used only if significant amounts of water are available on Mars

- ***Manufacturing/Industrial Activities (product manufacturing, chemical processing, other industrial activities)***
  - Most manufacturing and industrial equipment will be located near the bases and be powered by electricity (directly from the nuclear reactor power grid)
  - ISRU fuels and propellants will not be required for this activity

- ***Weather/Environmental (weather station deployment, repair, satellite launch)***
  - Any weather/environmental satellites will be built and launched from Earth and placed into Mars orbit
  - Weather stations would be deployed with a ground vehicle powered by electricity
  - Electricity could be stored in fuel cells or batteries which may require ISRU components

- ***Communications Navigation Services (station deployment, repair, satellite launch)***
  - Most of this mission will be met with satellites in Mars orbit
  - Communications/navigation satellites will be built and launched from Earth
  - ISRU fuels and propellants will not be required for this activity

- ***Surveying/Mapping (aerocraft, balloon, satellite)***
  - Most of this mission will be met with satellites in Mars orbit

- Surveying/mapping satellites will be built and launched from Earth
- Aerocraft may be used to provide high-resolution mapping/surveying from low altitudes
- Aerocraft would utilize ISRU fuels/oxidizers.
-

B.3 Workshop Technical Presentations

Various technical presentations were also provided by the participants at the Workshop as listed below. Hard copies of these presentations were made available to the participants and the project.

- Bob Gustafson (ORBITEC) - Extraction and Use of Mars Water
- Richard Gertsch (ORBITEC/MTU) - Factors in Planetary Mining/Exraction Operations
- T. D. Lin (ORBITEC) - Use of Mars Concrete
- George Miley (UI) - Mars LENR-Based Power Applications
- Marty Harms (ORBITEC) - Mars Terraforming.

MARS MEETING AGENDA (6/21/00)

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

Orbital Technologies Corporation (ORBITEC), Space Center, 1212 Fourier Drive, Madison, Wisconsin 53717
Phone: 608-827-5000, Fax: 608-827-5050
June 21-22, 2000

Wednesday, June 21, 2000

8:30 Donuts, Fruit, Coffee and Juice
9:00 Welcome to ORBITEC - Eric Rice, ORBITEC President and CEO
9:15 Overview/Purpose of NIAC/ORBITEC Mars Study Approach Workshop - Eric Rice (PI)
9:30 Participant Introductions - All
9:45 Basis of the Advanced Concept - Eric Rice
10:00 Break/Informal Communications
10:30 Phase I Project Results - Eric Rice

- Related Experimental Work - Marty Chiaverini/Dan Gramer
- Overall Study Approach - Eric Rice
- System Requirements/Ground Rules - Eric Rice
- Propellant Family Scenarios - Eric Rice
- Mission and Traffic/Use Model - Ron Teeter
- Vehicle/System Families Scenarios - Robert Gustafson
- Cost Models/Cost-Benefit Analysis - Ron Teeter

11:30 Phase II Study Plan Overview - Eric Rice
12:00 Onsite Lunch
1:00 Discussion of Study Approach, Architecture Elements and Basic Ground Rules
2:00 Propellant Processing Scenarios - Eric Rice
2:15 Define Mission Models - Ron Teeter
2:30 Group Sessions for Mission Model Definition - All
3:30 Break/Informal Communications
3:45 Group Sessions for Mission Model Definition (continued) - All
5:00 Adjourn
5:15 Organized Group Wednesday Evening Dinner at Damons

Thursday, June 22, 2000

7:30 Donuts, Fruit, Coffee, Juice
8:00 Group Sessions for Mission Model Definition (continued) - All
9:00 Mission Model Group Results - by Group Leaders
9:40 Define Vehicle/System Family Scenarios - Bob Gustafson
10:00 Break/Informal Communications
10:30 Technical Discussions/Presentations (~10 minutes each)

- Bob Gustafson (ORBITEC) - Extraction and Use of Mars Water
- Richard Gertsch (ORBITEC/MTU) - Factors in Planetary Mining/Exraction Operations
- T. D. Lin (ORBITEC) - Use of Mars Concrete
- George Miley (UI) - Mars LENR-Based Power Applications (via ~11:00 telecon-217-333-3772)
- Marty Harms (ORBITEC) - Mars Terraforming

11:10 Wrap-up Discussions
11:30 Adjourn

11:30 Offsite Lunch on Own (suggest Houlihan's, Damon's, Fitzgerald's, Pleasant View Golf, Friday's, Subway, Denny's, Hardee's, Culver's, McDonald's, etc.) Maps to eating places will be provided).

APPENDIX C
MISSION DEFINITION AND TRAFFIC MODELS

Mission Category: Scientific Missions

Mission/Submission Scope?	Line Item Specifics	Mission Frequency				# of Crew or Robotic	Mission Duration	Distance from Base (km)	Travel Time	Payload (kg)	Mission Reference Number	System Type Required
		Low		High								
		Year 1	Year 50	Year 1	Year 50							
Past/Present life	Far-ranging ballistic hopper missions to remote sites for sample collection, or on-site testing	12	12	12	28	2	5 days	5000	minutes	100	1	flight
		3	3	3	7	2	10 days	10000	minutes	100	2	flight
		13	15	13	30	rob	10 days	5000	minutes	100	3	flight
		7	8	7	15	rob	20 days	10000	minutes	100	4	flight
	Short-range scientific rover missions	150	25	150	120	2	3 days	<500	hours	100	5	ground
		37	6	37	30	rob	6 days	<500	hours	100	6	ground
	Long-range robotic missions for extended observation	12	13	12	13	rob	2 mo	10000	minutes	100	7	flight
		12	6	12	6	rob	1 mo	1000	days	100	8	ground
	nuclear powered rover	***4***	***4***	***4***	***4***	rob	infinite	arbitrary	n/a	50	9	ground
Planetary Science (geology, mineralogy, water ice, CO_2 ice, liquid water, atmospheric science, soil science)	Far-ranging ballistic hopper missions to remote sites for sample collection, or on-site testing	12	12	12	28	2	5 days	5000	minutes	300	10	flight
		3	3	3	7	2	10 days	10000	minutes	300	11	flight
		13	15	13	30	rob	10 days	5000	minutes	300	12	flight
		7	8	7	15	rob	20 days	10000	minutes	300	13	flight
	Short-range scientific rover missions	45	5	45	24	2	3 days	<500	hours	300	14	ground
		7	1	7	6	rob	6 days	<500	hours	300	15	ground
	Long-range robotic missions for extended observation	12	13	12	13	rob	2 mo	10000	minutes	300	16	flight
		12	6	12	6	rob	1 mo	1000	days	300	17	ground
	nuclear powered rover	***4***	***4***	***4***	***4***	rob	infinite	arbitrary	n/a	50	18	ground
	atmospheric probe	7	7	7	10	rob	1 day	10000	minutes	10	19	flight
	atmospheric probe	9	9	9	10	rob	minutes	n/a	minutes	2	20	sounding rocket
	atmospheric probe	13	13	13	31	rob	indefinite	<500	indefinite	2	21	balloon
	atmospheric/surface observation probe	53	53	53	106	rob	hours	n/a	hours	4	22	aerocraft
	weather baloon	200	200	200	400	rob	hours	n/a	hours	2	23	balloon
Mars/Mars moon studies	characterization	4	4	4	7	rob	1 week	orbit	hours	500	24	flight
	characterization	2	2	2	4	3	1 week	orbit	hours	1000	25	flight

Note: Bold italicized entries in the frequency column indicate a quantity, not a frequency (for missions of indefinite duration)

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	**Year 50**	**Year 1**	**Year 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

Note: Bold italicized entries in the frequency column indicate a quantity, not a frequency (for missions of indefinite duration)

Mission Category:	Transportation											
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	**Year 50**	**Year 1**	**Year 50**							
Human Mars-Earth Transport	Mars Ascent/Descent vehicle	2	2	2	44	2	<1 day	orbit	minutes	80 people	36	flight
						robotic	<1 day	orbit	minutes	80 people	37	flight
Cargo Mars-Earth Transport	Mars Ascent/Descent vehicle					2	<1 day	orbit	minutes	18650	38	flight
						robotic	<1 day	orbit	minutes	18650	39	flight
Martian Surface Transportation (Ground)	Intrabase human transport (small)	0	0	0	500	2	days	500	days	2 people	40	ground
	Intrabase human transport (medium)	0	0	0	1000	2	days	500	days	5 people	41	ground
	Intrabase human transport (large)	0	0	0	700	2	days	1000	days	20 people	42	ground
	Intrabase cargo transport (small)	0	0	0		rob	days	500	days	100	43	ground
	Intrabase cargo transport (medium)	0	0	0		rob	days	500	days	1000	44	ground
	Intrabase cargo transport (large)	0	0	0		rob	days	500	days	5000	45	ground
Martian Ballistic Transportation (Flight)	Hopper mission to remote base	0	0	0	50	2	1 day	5000	minutes	20 people	46	flight
	Hopper mission to remote base	0	0	0	50	2	1 day	5000	minutes	4000	47	flight

Mission Category:	Government											
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	Year 50	Year 1	Year 50							
Government missions	transporting criminals to main base	0	0	0	10	3	1 day	<5000	minutes	2 people	48	flight
	government transport	0	0	0	50	3	1 day	<5000	minutes	2 people	49	flight
	ballistic rescue mission	2	2	2	20	3	1 day	<5000	minutes	2 people + 100	50	flight
	rover rescue mission	3	4	3	25	3	1 day	<500	hours	2 people + 100	51	ground
Health Care	emergency medical transport	1	1	1	20	3	1 week	<5000	minutes	1 person + 50	52	flight

100-Person Colony Mission Model for Flight Vehicles

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	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	115
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	23
3	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	8	140
4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	75
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	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	115
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	23
12	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	8	140
13	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	75
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	3	3	3	3	3	3	3	3	3	3	3	3	3	69
20	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	92
21	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	138
22	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	529
23	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	87	2001
24	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	46
25	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	23
26	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	115
27	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	23
28	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	8	140
29	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	75
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	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	23
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*																								0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	23
52	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	23

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.

100-Person Colony Traffic Model for Flight Vehicles

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	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	8	140
4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	75
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	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	8	140
13	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	75
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	3	3	3	3	3	3	3	3	3	3	3	3	3	69
28	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	8	140
29	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	75
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**	**41**	**41**	**41**	**41**	**44**	**44**	**44**	**44**	**44**	**44**	**46**	**46**	**49**	**49**	**52**	**52**	**52**	**52**	**52**	**55**	**1056**

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	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	115
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	23
10	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	115
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	23
26	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	115
27	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	23
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
*50**	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	23
52*	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	23
TOTAL	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**460**

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	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	23
39!	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
TOTAL	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**	**?**

Vehicle Type	Colony Cycle (one cycle is ~26 Earth months)																							Number of Mission*Days
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
V3	2283	2283	2283	2283	2283	2283	2283	2463	2463	2463	2463	2463	2463	2583	2583	2763	2763	2943	2943	2943	2943	2943	3123	**59,289**
V4	368	368	368	368	368	368	368	368	368	368	368	368	368	368	368	368	368	368	368	368	368	368	368	**8,464**
V5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**

10,000-Person Colony Mission Model for Flight Vehicles

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).**

10,000-Person Colony Traffic Model for Flight Vehicles

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

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

10,000-Person Colony Traffic Model for Flight Vehicles

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	1	1	1	1	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	240
TOTAL	2	1	1	1	1	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	240

Vehicle Type	Colony Cycle (one cycle is ~26 Earth months)																							Number of Mission*Days
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
V1	7	10	13	24	27	30	40	43	47	57	60	70	73	77	87	90	93	103	107	110	120	123	126	1,537
V2	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	5	5	5	85
V3	2460	2460	2460	2640	2640	2640	3000	3000	3000	3180	3180	3360	3540	3660	3660	3840	4020	4020	4200	4200	4200	4380	4560	78,300
V4	361	381	421	422	422	483	483	543	604	604	604	665	665	665	786	786	786	847	847	848	908	969	1009	15,109
V5	0.25	0.25	0.25	0.25	0.25	2	2	1.75	2.75	2.5	2.75	2.5	3.25	3.25	3.25	3.25	4	4	4	4	4.75	4.75	4.75	60.8
V6	0.5	0.25	0.25	0.25	0.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	60.0

Vehicle Type	Colony Cycle (one cycle is ~26 Earth months)																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
V1	0.009	0.013	0.017	0.031	0.035	0.038	0.051	0.055	0.06	0.073	0.077	0.09	0.094	0.099	0.112	0.115	0.119	0.132	0.137	0.141	0.154	0.158	0.162
V2	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.006	0.006	0.006
V3	3.154	3.154	3.154	3.385	3.385	3.385	3.846	3.846	3.846	4.077	4.077	4.308	4.538	4.692	4.692	4.923	5.154	5.154	5.385	5.385	5.385	5.615	5.846
V4	0.463	0.488	0.54	0.541	0.541	0.619	0.619	0.696	0.774	0.774	0.774	0.853	0.853	0.853	1.008	1.008	1.008	1.086	1.086	1.087	1.164	1.242	1.294
V5	3E-04	3E-04	3E-04	3E-04	3E-04	0.003	0.003	0.002	0.004	0.003	0.004	0.003	0.004	0.004	0.004	0.004	0.005	0.005	0.005	0.005	0.006	0.006	0.006
V6	6E-04	3E-04	3E-04	3E-04	3E-04	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004

cumulative number of missions

Vehicle Type	Colony Cycle (one cycle is ~26 Earth months)																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
V1	1	5	12	24	39	57	79	104	133	166	202	242	285	332	383	437	494	555	620	688	760	835	913
V2	3	6	9	12	15	18	21	24	27	30	34	38	42	46	50	54	58	62	66	70	75	80	85
V3	41	82	123	167	211	255	305	355	405	458	511	567	626	687	748	812	879	946	1016	1086	1156	1229	1305
V4	19	39	61	84	107	134	161	191	225	259	293	331	369	407	452	497	542	591	640	690	743	800	859
V5	1	2	3	4	5	13	21	28	39	49	60	70	83	96	109	122	138	154	170	186	205	224	243
V6	2	3	4	5	6	19	32	45	58	71	84	97	110	123	136	149	162	175	188	201	214	227	240

100-Person Colony Mission Model for Ground Vehicles

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	
5	65	63	60	58	55	53	50	48	45	43	40	38	35	33	31	28	26	23	21	18	16	14	12	875
6	16	15	15	14	14	13	12	12	12	11	10	10	9	8	7	7	6	5	5	4	4	3	3	215
8	5	5	5	5	5	5	5	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	2	90
*9**	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	n/a
14	20	19	18	17	16	15	15	14	13	13	12	11	10	9	9	8	7	6	5	4	4	3	2	250
15	3	3	3	3	3	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	40
17	5	5	5	5	5	5	5	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	2	90
*18**	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	n/a
30	65	63	60	58	55	53	50	48	45	43	40	38	35	33	31	28	26	23	21	18	16	14	12	875
31	16	15	15	14	14	13	12	12	12	11	10	10	9	8	7	7	6	5	5	4	4	3	3	215
33	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	2	2	2	2	2	75
*34**	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	n/a
35	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	75
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	35

Mission Reference Number in italics indicates round trip.

100-Person Colony Traffic Model for Ground Vehicles

Ground Vehicle #1 (G1)

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	
6	16	15	15	14	14	13	12	12	12	11	10	10	9	8	7	7	6	5	5	4	4	3	3	**215**
8	5	5	5	5	5	5	5	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	2	**90**
15	3	3	3	3	3	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	**40**
17	5	5	5	5	5	5	5	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	2	**90**
31	16	15	15	14	14	13	12	12	12	11	10	10	9	8	7	7	6	5	5	4	4	3	3	**215**
33	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	2	2	2	2	2	**75**
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
TOTAL	**49**	**47**	**47**	**45**	**45**	**42**	**40**	**38**	**38**	**36**	**34**	**33**	**30**	**28**	**26**	**24**	**22**	**20**	**19**	**17**	**17**	**15**	**13**	**725**

100-Person Colony Traffic Model for Ground Vehicles

Ground Vehicle #2 (G2)

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	
35	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	**75**
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
TOTAL	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**4**	**4**	**4**	**4**	**4**	**4**	**75**

Ground Vehicle #3 (G3)

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	
5	65	63	60	58	55	53	50	48	45	43	40	38	35	33	31	28	26	23	21	18	16	14	12	**875**
14	20	19	18	17	16	15	15	14	13	13	12	11	10	9	9	8	7	6	5	4	4	3	2	**250**
30	65	63	60	58	55	53	50	48	45	43	40	38	35	33	31	28	26	23	21	18	16	14	12	**875**
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
51	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	**35**
TOTAL	**150**	**145**	**138**	**133**	**126**	**121**	**115**	**110**	**103**	**99**	**92**	**87**	**80**	**75**	**71**	**64**	**59**	**52**	**47**	**40**	**36**	**31**	**26**	**2000**

Ground Vehicle #4 (G4)

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	
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
TOTAL	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Ground Vehicle #5 (G5)

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	
*9**	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	**n/a**
*18**	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	**n/a**
*34**	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	**n/a**
TOTAL	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**

Number of Mission-Days Required per Colony Cycle

Vehicle Type	Colony Cycle (one cycle is ~26 Earth months)																							Number of Mission*Days
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
G1	630	618	618	606	606	588	576	516	516	504	492	462	444	432	420	360	348	336	306	294	294	282	222	**10470**
G2	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	240	240	240	240	240	240	**4500**
G3	451	436	415	400	379	364	346	331	310	298	277	263	242	227	215	194	179	158	143	122	110	95	80	**6035**
G4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
G5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**

100-Person Colony Traffic Model for Ground Vehicles

Total Distance (km) Traveled per Colony Cycle

Vehicle Type	Colony Cycle (one cycle is ~26 Earth months)																							# of km Traveled
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
G1	63000	61000	61000	59000	59000	56000	54000	50000	50000	48000	46000	44000	41000	39000	37000	33000	31000	29000	27000	25000	25000	23000	19000	**980000**
G2	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	8000	8000	8000	8000	8000	8000	**150000**
G3	2E+05	1E+05	1E+05	1E+05	1E+05	1E+05	1E+05	1E+05	1E+05	1E+05	93000	89000	82000	77000	73000	66000	61000	54000	49000	42000	38000	33000	28000	**2035000**
G4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
G5	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	**4736160**

10,000-Person Colony Mission Model for Ground Vehicles

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	
5	65	65	64	63	63	62	62	61	61	60	59	59	58	58	57	56	56	55	54	54	53	53	52	1350
6	16	16	16	16	16	16	15	15	15	15	15	15	14	14	14	14	14	14	13	13	13	13	13	335
8	5	5	5	5	5	5	5	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	2	90
*9**	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	n/a
14	20	20	19	19	18	18	17	17	16	16	15	15	15	14	14	13	13	12	12	11	11	10	10	345
15	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	65
17	5	5	5	5	5	5	5	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	2	90
*18**	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	n/a
30	65	65	64	63	63	62	62	61	61	60	59	59	58	58	57	56	56	55	54	54	53	53	52	1350
31	16	16	16	16	16	16	15	15	15	15	15	15	14	14	14	14	14	14	13	13	13	13	13	335
33	5	5	5	4	4	4	4	4	4	4	3	3	3	3	3	3	2	2	2	2	2	2	2	75
*34**	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	n/a
35	3	3	3	3	4	4	4	5	5	5	6	6	6	6	7	7	7	8	8	8	9	9	9	135
40	0	10	20	29	39	49	59	69	79	89	99	109	119	129	139	149	158	168	178	188	197	207	217	2500
41	0	20	40	58	78	98	118	138	158	178	198	218	238	258	278	298	316	336	356	376	394	414	434	5000
42	0	14	28	42	56	68	84	97	111	125	139	153	166	180	194	208	221	234	248	262	276	290	304	3500
43	0	50	100	145	195	245	295	345	395	445	495	545	595	645	695	745	790	840	890	940	985	1035	1085	12500
44	0	100	200	290	390	490	590	690	790	890	990	1090	1190	1290	1390	1490	1580	1680	1780	1880	1970	2070	2170	25000
45	0	70	140	210	280	340	420	485	555	625	695	765	830	900	970	1040	1105	1170	1240	1310	1380	1450	1520	17500
51	1	2	2	2	3	3	4	4	5	5	6	6	7	7	7	8	8	9	9	10	10	11	11	140

Mission Reference Number in italics indicates round trip.

10,000-Person Colony Traffic Model for Ground Vehicles

Ground Vehicle #1 (G1)

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	
6	16	16	16	16	16	16	15	15	15	15	15	15	14	14	14	14	14	14	13	13	13	13	13	**335**
8	5	5	5	5	5	5	5	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	2	**90**
15	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	**65**
17	5	5	5	5	5	5	5	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	2	**90**
31	16	16	16	16	16	16	15	15	15	15	15	15	14	14	14	14	14	14	13	13	13	13	13	**335**
33	5	5	5	4	4	4	4	4	4	4	3	3	3	3	3	3	2	2	2	2	2	2	2	**75**
43	0	50	100	145	195	245	295	345	395	445	495	545	595	645	695	745	790	840	890	940	985	1035	1085	**12500**
TOTAL	**50**	**100**	**150**	**194**	**244**	**294**	**342**	**390**	**440**	**490**	**539**	**589**	**637**	**687**	**737**	**785**	**829**	**879**	**927**	**976**	**1021**	**1071**	**1119**	**13490**

10,000-Person Colony Traffic Model for Ground Vehicles

Ground Vehicle #2 (G2)

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	
35	3	3	3	3	4	4	4	5	5	5	6	6	6	6	7	7	7	8	8	8	9	9	9	**135**
44	0	100	200	290	390	490	590	690	790	890	990	1090	1190	1290	1390	1490	1580	1680	1780	1880	1970	2070	2170	**25000**
45	0	70	140	210	280	340	420	485	555	625	695	765	830	900	970	1040	1105	1170	1240	1310	1380	1450	1520	**17500**
TOTAL	**3**	**173**	**343**	**503**	**674**	**834**	**1014**	**1180**	**1350**	**1520**	**1691**	**1861**	**2026**	**2196**	**2367**	**2537**	**2692**	**2858**	**3028**	**3198**	**3359**	**3529**	**3699**	**42635**

Ground Vehicle #3 (G3)

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	
5	65	65	64	63	63	62	62	61	61	60	59	59	58	58	57	56	56	55	54	54	53	53	52	**1350**
14	20	20	19	19	18	18	17	17	16	16	15	15	15	14	14	13	13	12	12	11	11	10	10	**345**
30	65	65	64	63	63	62	62	61	61	60	59	59	58	58	57	56	56	55	54	54	53	53	52	**1350**
40	0	10	20	29	39	49	59	69	79	89	99	109	119	129	139	149	158	168	178	188	197	207	217	**2500**
41	0	20	40	58	78	98	118	138	158	178	198	218	238	258	278	298	316	336	356	376	394	414	434	**5000**
51	1	2	2	2	3	3	4	4	5	5	6	6	7	7	7	8	8	9	9	10	10	11	11	**140**
TOTAL	**150**	**150**	**147**	**145**	**144**	**142**	**141**	**139**	**138**	**136**	**133**	**133**	**131**	**130**	**128**	**125**	**125**	**122**	**120**	**119**	**117**	**116**	**114**	**3045**

Ground Vehicle #4 (G4)

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	
42	0	14	28	42	56	68	84	97	111	125	139	153	166	180	194	208	221	234	248	262	276	290	304	**3500**
TOTAL	**0**	**14**	**28**	**42**	**56**	**68**	**84**	**97**	**111**	**125**	**139**	**153**	**166**	**180**	**194**	**208**	**221**	**234**	**248**	**262**	**276**	**290**	**304**	**3500**

Ground Vehicle #5 (G5)

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	
*9**	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	**n/a**
*18**	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	**n/a**
*34**	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	**n/a**
TOTAL	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**

Number of Mission-Days Required per Colony Cycle

Vehicle Type	Colony Cycle (one cycle is ~26 Earth months)																							Number of Mission*Day
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
G1	660	710	760	775	825	875	913	903	953	1003	1023	1073	1111	1161	1211	1201	1216	1266	1304	1348	1393	1443	1433	**24560**
G2	180	350	520	680	910	1070	1250	1475	1645	1815	2045	2215	2380	2550	2780	2950	3105	3330	3500	3670	3890	4060	4230	**50600**
G3	451	482	503	524	552	576	604	628	656	680	702	732	757	784	808	830	857	879	903	931	952	980	1004	**16775**
G4	0	14	28	42	56	68	84	97	111	125	139	153	166	180	194	208	221	234	248	262	276	290	304	**3500**
G5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**

10,000-Person Colony Traffic Model for Ground Vehicles

Total Distance (km) Traveled per Colony Cycle

Vehicle Type	Colony Cycle (one cycle is ~26 Earth months)																							# of km Traveled
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
G1	65000	90000	1E+05	1E+05	2E+05	2E+05	2E+05	2E+05	3E+05	3E+05	3E+05	3E+05	4E+05	4E+05	4E+05	4E+05	4E+05	5E+05	5E+05	5E+05	5E+05	6E+05	6E+05	**7495000**
G2	6000	91000	2E+05	3E+05	3E+05	4E+05	5E+05	6E+05	7E+05	8E+05	9E+05	9E+05	1E+06	1E+06	1E+06	1E+06	1E+06	1E+06	2E+06	2E+06	2E+06	2E+06	2E+06	**21520000**
G3	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	3E+05	3E+05	3E+05	3E+05	3E+05	3E+05	3E+05	4E+05	4E+05	4E+05	4E+05	4E+05	4E+05	4E+05	5E+05	**6935000**
G4	0	14000	28000	42000	56000	68000	84000	97000	1E+05	1E+05	1E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	3E+05	3E+05	3E+05	3E+05	**3500000**
G5	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	**4940460**

APPENDIX D
VEHICLE DESIGN GROUND RULES DOCUMENT

APPENDIX D. VEHICLE DESIGN GROUND RULES DOCUMENT

This appendix contains the design ground rules for the major Mars transportation system vehicles. The main objective of the ground rules is to define an internally consistent study for the different propellant combinations, and for flight systems, engine types (hybrid and liquid).

The fleet design process balances the total number of vehicles required against efficient usage. For example, it would be uneconomical to use a vehicle with a 10,000 kg payload capability for several missions that transport only a 10 kg payload. Alternatively, development and maintenance costs are driven up along with the total number of vehicle types. These considerations along with iterative analysis results from the vehicle design models drove the fleet definition process.

Weather balloons, sounding rockets, and unmanned airplanes introduce new vehicle designs into the study, yet have little effect on the final results (due to very low payloads, and hence low propellant requirements). Therefore, these vehicles are a part of the overall transportation system, but their designs are considerably less detailed than the other vehicles. The design approach for these three elements of the transportation system are discussed in the main body of the report, and the guidelines for the hopper, intra-planetary, ascent/decent, and ground vehicles designs are included here.

D.1 Sub-Orbital (Hopper) Space Flight Vehicles

General Operation

- One-way vehicles: flies from an established base to another established base where it refuels for the next hop.
- Roundtrip vehicles: flies from an established base to a remote area, and then back to an established base. It caries along all return trip propellant, or ISRU equipment for manufacturing return trip propellant.

Miscellaneous Systems

- All vehicles use aerobraking, aerobrake mass is equal to 14% of initial landing wetmass, correlation given by Larson (Larson et al).
- Structure (trusses, links, bolts, etc.): 5% of total wet mass "based on historical precedent" taken from Guernsey, (Guernsey et al, 1998).
- Power systems: 80 kg (internal estimate, does not include thermal systems for cryogenic propellants or ISRU processing)
- Thermal control: 60 kg (internal estimate, does not include requirements for cryogenic propellants or ISRU processing)
- Avionics: 60 kg (internal estimate)
- Attitude control: 1% of vehicle drymass (internal estimate)

Propellant Performance

- Optimum mixture ratio is assumed to be that which delivers the highest I_{SP}
- Propellant I_{SP} and C^* calculated using NASA/Glen Chemical Equilibrium Analysis Program

Propellant Tanks

- **All tanks constructed from material with a density equal to and strength two times of the aluminum-lithium alloy currently used for LOX and LH_2 tanks on the Shuttle STS.**

Properties taken from UW Student Vehicle Design Group Final Report (Gillis et al, 2000): AlLi 2090-T81 yield strength: 575 MPa, density: 2590 kg/m^3 at 150 K

- Tank wall thickness is established by using the thin-wall pressure vessel equations along with a safety factor of 1.5 where tank pressure times 1.5 = yield strength. Safety factor taken from Larson (Larson et al).
- Minimum allowable tank wall thickness is 0.762 mm
- Mass for tank connections and fittings is assumed to be 20% of base tank mass
- **Nominal tank pressure: 14.7 psia**
- Tank pressurization is supplied by turbomachinery
- 3.5% of the propellant is considered to be unusable/reserves
- 5% tank ullage allotted

Tank Insulation and Cooling

- All boiloff is recovered (either by base infrastructure or by onboard refrigeration system for roundtrip vehicles)
- Thermal control:
  - Roundtrip vehicles (long duration missions): thermal system designed to minimize overall system mass (combined refrigeration system and insulation mass)
  - One-way vehicles: insulation thickness sized to achieve a daily boiloff rate of 2.5%; no active cooling on vehicles
- Tanks insulated with material that has the same thermal conductivity and density as aerogel, k = 0.005 W/m-K in Martian atmosphere, density of aerogel = 16.02 kg/m^3 (Hickey, 1997). Internal estimate adds 20% heat leak and an additional 30% of the insulation mass for insulation structures.
- Radiation insulation (aluminized mylar) properties: emmissivity: 0.84, absorptivity of outer mli layer to sun irradiation: 0.17 (Incropera and Dewitt, 1996)
- Thermal analysis: assume average Mars temperature to be 190 K, with radiation and combined convection considered. Average solar irradiation from MSP 2003 Lander Proposal Information Package is 496 W/m^2; average free and forced convection coefficients are calculated; average wind velocity = 3 m/sec; average pressure = 0.6 kPa. Physical/thermal fluid properties of Mars atmosphere are supplied by the Engineering Equation Solver Program (F-Chart Software).

Crew Cabin/Life Support

- The crew cabin has a short sleeves environment
- One spacesuit for each person on board at 50 kg each
- Crew cabin volume: 3 m^3/person for one-way trips, and 10 m^3/person for roundtrip missions
- Crew cabin mass calculated using a correlation given by Larson (Larson et al), based on mission duration and total number of people onboard
- Crew member and personal luggage: 100 kg per person
- Consumables: 17.72 kg/day for each person

Thrust

- Overall thrust-to-weight at launch (Mars surface) is 2

Combustion Chamber and Nozzle (does not include grain case for hybrids)

- Nozzle and chamber mass are assumed to be directly proportional to their surface area and chamber pressure

- A baseline mass per surface area and pressure relationship was derived from existing flight systems

Propellant Delivery System

- Turbomachinery mass based on correlation given by Koelle (1961), and is correlated against propellant flow rate, pressure, and propellant density. Correlation was internally updated using data for modern systems.
- Propellant delivery lines (plumbing, valves, etc.) are 36% of the turbomachinery mass; an internal empirical correlation developed from data on existing systems

ISRU, Cryocooler, and Power (roundtrip vehicles only)

- Parametric ISRU processor mass and power requirements correlations developed (discussed in main body of report) and applied, as appropriate, for each propellant family
- Hydrogen is only assumed to be available at a base; any ISRU operations that take place away from a base require hydrogen be brought along for processing, if needed
- Cryocooler mass correlation based on 1200W Creare flight system (data provided by Mark Zagarola of Creare Corporation) and internal scaling laws
- Cryocooler power requirements based on correlation supplied by Mark Zagarola of Creare Corporation (accounts for cold side temperature requirement for each propellant)
- All power for roundtrip vehicles in a remote location is beamed down from a constellation of orbiting satellites, receiver mass is 1kg/kw based on a publication by Brown, (Brown, et al 1992).

Hybrids Engine Propulsion Systems

- I_{SP} efficiency of 95%
- Initial port volume is 10% total grain case volume
- All liquid tanks surround and encase the hybrid grain
- All grains have a spherical geometry
- Liquid tanks are spherical
- Chamber pressure: varied from 200-300 psia depending on propellant combination
- Area ratio: 200

Bi-Propellant Propulsion Systems

- I_{SP} efficiency of 95%
- Chamber pressure: 1000 psia
- Area ratio: 200

D.2 Earth To Mars Transit

Nuclear powered spaceships using hydrogen as the working fluid will transport people and cargo to Mars orbit. All life support and hydrogen required for the ship are derived from Earth. These systems are only conceptual in nature; a mass-based cost for delivery of people and materials to/from Mars was implemented. The guidelines for the estimate of this cost are discussed within the final report.

D.3 Mars Ascent/Descent Vehicles

This class of vehicles is for transporting people and cargo to and from Mars orbit.

General Operation

- People and cargo are transferred from a nuclear-powered vehicle in Mars orbit to a chemical propellant-based lander
- Rendezvous in a 500 km circular orbit
- All vehicles carry enough propellant to fly from the surface to an orbital docking station, and land back on the surface. The only exception to this approach is for PF1 (all terrestrial propellants) which refuels in orbit for the landing.

In all other respects, the design ground rules are the same as for one-way Sub-Orbital (hopper) Space Flight Vehicles.

D.4 Ground Vehicles

General Operation

- **Packed roads cleared of major obstacles connect all bases**
- **Missions that do not include intra-base travel require off-road type vehicles**
  - All vehicles carry enough propellant for the entire mission

Power and Propellants

- **Rolling resistance calculated by multiplying the normal force by the road coefficient of friction**
- **Rough, off-road coefficient of friction: 0.1, Packed regolith intra-base road coefficient of friction: 0.025**
  - Drive system: fuel cells power an electric motor
  - Fuel cell mass: 2.5 kg/kW for all propellant combinations. This value was selected after reviewing several publications on fuel cells (Herbert, 1998; Clapp, 1992; Hoffmann http://www.hfcletter.com/letter/apr97-methanol.html; and conversations with Todd Marsh, of DTI Energy, Inc)
  - Fuel cell efficiency**:** 70% of theoretical maxim chemical energy for the reaction. This value was selected after reviewing several publications on fuel cells (Herbert, 1998; Clapp, 1992; Hoffmann, http://www.hfcletter.com/letter/apr97-methanol.html; and conversations with Todd Marsh, of DTI Energy, Inc)
  - Theoretical maximum chemical energy for the reaction taken from Zubrin (1992)
  - Electric motor mass: 0.3 g/W (provided by UNIQ Corporation)
  - Electric motor efficiency: 95% (Huang et al, 1990)
  - Maximum delivered power of vehicle is 1.15 times that required for maximum cruising speed
  - Spent propellant is stored and later recycled at a base

Base Vehicle

  - The base vehicle mass includes the chassis, wheels, suspension, and several other small components, and is solely based on the fully loaded gross vehicle wetmass (Altendorf et al, 1978).

Propellant Tanks

- **All tanks constructed from material with a density equal to and strength two times of the aluminum-lithium alloy currently used for LOX and LH2 tanks on the Shuttle.**

Properties taken from UW Student Vehicle Design Group, 2000 (Gillis, et. al): AlLi 2090-T81 yield strength: 575 MPa, density: 2590 kg/m3 at 150 K

- **Tank wall thickness is established by using the thin-wall pressure vessel equations along with a safety factor of 1.5 where pressure times 1.5 = yield strength. Safety factor taken from Larson (Larson et al)**
- Minimum allowable tank wall thickness is 1.54 mm
- Mass for tank connections and fittings is assumed to be 20% of base tank mass
- **Nominal tank pressure: 14.7 psia**
- 10% of the propellant is considered to be unusable/reserves
- 5% tank ullage allotted

Tank Insulation and Cooling

- Onboard cryocooler powered by fuel cell used to re-liquefy boiloff
- Cryocooler mass correlation based on 1200W Creare flight system (data provided by Mark Zagarola of Creare Corporation) and internal scaling laws
- Cryocooler power requirements based on correlation supplied by Mark Zagarola of Creare Corporation (accounts for cold side temperature requirement for each propellant)
- Thermal control: system designed to minimize overall system mass (combined refrigeration system and insulation mass)
- Tanks insulated with material that has the same thermal conductivity and density as aerogel, k = 0.005 W/m-K in Martian atmosphere, density of aerogel = 16.02 kg/m^3, (Hickey, 1997). Internal estimate adds 20% heat leak and an additional 30% of the insulation mass for insulation structures.
- Radiation insulation (aluminized mylar) properties: emmissivity: 0.84, absorptivity of outer mli layer to sun irradiation: 0.17 (Incropera and Dewitt, 1996)
- Thermal analysis: assume average Mars temperature to be 190 K, with radiation and combined convection considered. Average solar irradiation from MSP 2003 Lander Proposal Information Package is 496 W/m^2; average free and forced convection coefficients are calculated; average wind velocity = 3 m/sec; average pressure = 0.6 kPa. Physical/thermal fluid properties of Mars atmosphere are supplied by the Engineering Equation Solver Program (F-Chart Software).

Crew Cabin/Life Support

- The crew cabin has a short sleeves environment
- One spacesuit for each person on board at 50 kg each
- Crew cabin volume: 3 m^3/person for one-way trips, and 10 m^3/person for roundtrip missions
- Crew cabin mass calculated using a correlation given by Larson (Larson et al), based on mission duration and total number of people onboard
- Crew member and personal luggage: 100 kg per person
- Consumables: 17.72 kg/day for each person

APPENDIX E
VEHICLE DESIGN GROUND RULES DOCUMENT

APPENDIX E VEHICLE DESIGN GROUND RULES DOCUMENT

Propellant Family: PF1-LH_2/LOX						
Vehicle Type	**HERMES**	**EOS**	**IRIS**	**ARES**	**HYPERION**	**ZEUS**
P_c (psia)	1000	1000	1000	1000	1000	1000
I_{SP} (sec)	453.0	453.0	453.0	453.0	453.0	453.0
Engine Type	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant
Reserve Propellant (%)	3.5	3.5	3.5	3.5	3.5	3.5
Thrust to Weight	2	2	2	2	2	2
Engine Mass[1]	148	7.4	4486	12496	516	1889
Oxidizer Tank Mass	91	15.4	1214	2345	201	470
Fuel Tank/Grain Case Mass	695	36.3	2704	5191	1046	1815
ISRU Hydrogen Tank	0	0	0	0	0	0
Hydrogen Mass for ISRU	0	0	0	0	0	0
Structure Mass	564	59.2	35967	98981	2591	34298
Crew Cabin Mass	3107	0	0	5981	7732	0
Space Suit Mass	1100	0	0	100	4100	0
Consumables Mass	0	0	0	709	0	0
Cryocooler Mass	0	37.0	1626	3004	0	0
Power Systems Mass[2]	80	80	80	80	80	80
ISRU Plant Mass	0	0	0	0	0	0
Avionics Mass	60	60	60	60	60	60
Electon. Thermal Control Mass	60	60	60	60	60	60
Aerobrake and Landing Mass	1453	66.2	40181	111914	4306	72931
Attitude control Mass	101	4.6	1091	3039	310	1192
Payload Mass	2200	10	300	500	8200	0 (at liftoff)
Total Propellant Mass	14039	748	631575	1.759E6	53547	216177
Wet Mass	**23698**	**1184**	**719344**	**2.003E6**	**82749**	**328972**

[1]Does not include grain case mass for hybrids
[2]Does not include ISRU power system mass, which is included in "ISRU Plant Mass"
All masses in kg

Propellant Family: PF2 and PF3-LH_2/LOX						
Vehicle Type	**HERMES**	**EOS**	**IRIS**	**ARES**	**HYPERION**	**ZEUS**
P_c (psia)	1000	1000	1000	1000	1000	1000
I_{SP} (sec)	453.0	453.0	453.0	453.0	453.0	453.0
Engine Type	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant
Reserve Propellant (%)	3.5	3.5	3.5	3.5	3.5	3.5
Thrust to Weight	2	2	2	2	2	2
Engine Mass[1]	148	7.4	51	494	516	2427
Oxidizer Tank Mass	91	15.4	55	237	201	546
Fuel Tank/Grain Case Mass	695	36.3	126	534	1046	2107
ISRU Hydrogen Tank	0	0	121	517	0	0
Hydrogen Mass for ISRU	0	0	787	7692	0	0
Structure Mass	564	59.2	405	2760	2591	38606
Crew Cabin Mass	3107	0	0	5981	7732	0
Space Suit Mass	1100	0	0	100	4100	0
Consumables Mass	0	0	0	709	0	0
Cryocooler Mass	0	37.0	177	1019	0	0
Power Systems Mass[2]	80	80	80	80	80	80
ISRU Plant Mass	0	0	276	3658	0	0
Avionics Mass	60	60	60	60	60	60
Electon. Thermal Control Mass	60	60	60	60	60	60
Aerobrake and Landing Mass	1453	66.2	452	4420	4306	73903
Attitude control Mass	101	4.6	32	308	310	1531
Payload Mass	2200	10	300	500	8200	0 (at liftoff)
Total Propellant Mass	14039	748	5116	49999	53547	270698
Wet Mass	**23698**	**1184**	**8098**	**79128**	**82749**	**390018**

[1]Does not include grain case mass for hybrids
[2]Does not include ISRU power system mass, which is included in "ISRU Plant Mass"
All masses in kg

Propellant Family: PF2 and PF3-LH_2/SOX						
Vehicle Type	**HERMES**	**EOS**	**IRIS**	**ARES**	**HYPERION**	**ZEUS**
P_c (psia)	400	400	400	400	400	400
I_{SP} (sec)	447.6	447.6	447.6	447.6	447.6	447.6
Engine Type	hybrid	hybrid	hybrid	hybrid	hybrid	hybrid
Reserve Propellant (%)	3.5	3.5	3.5	3.5	3.5	3.5
Thrust to Weight	2	2	2	2	2	2
Engine Mass[1]	92	4.0	31	343	328	1571
Oxidizer Tank Mass	549	14.7	125	575	886	1900
Fuel Tank/Grain Case Mass	117	5.4	42	465	379	1952
ISRU Hydrogen Tank	0	0	104	477	0	0
Hydrogen Mass for ISRU	0	0	765	8488	0	0
Structure Mass	508	48.5	378	2999	2484	39029
Crew Cabin Mass	3107	0	0	5981	7732	0
Space Suit Mass	1100	0	0	100	4100	0
Consumables Mass	0	0	0	709	0	0
Cryocooler Mass	0	22.3	129	1031	0	0
Power Systems Mass2	80	80	80	80	80	80
ISRU Plant Mass	0	0	305	4530	0	0
Avionics Mass	60	60	60	60	60	60
Electon. Thermal Control Mass	60	60	60	60	60	60
Aerobrake and Landing Mass	1414	55.3	431	4790	4261	74091
Attitude control Mass	99	3.9	30	334	307	1547
Payload Mass	2200	10	300	500	8200	0 (at liftoff)
Total Propellant Mass	13896	637	4969	55173	54015	278194
Wet Mass	**23282**	**1001**	**7808**	**88695**	**82892**	**398484**

[1]Does not include grain case mass for hybrids
[2]Does not include ISRU power system mass, which is included in "ISRU Plant Mass"
All masses in kg

Propellant Family: PF6-LCO/LOX						
Vehicle Type	**HERMES**	**EOS**	**IRIS**	**ARES**	**HYPERION**	**ZEUS**
P_c (psia)	1000	1000	1000	1000	1000	1000
I_{SP} (sec)	285.6	285.6	285.6	285.6	285.6	285.6
Engine Type	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant
Reserve Propellant (%)	3.5	3.5	3.5	3.5	3.5	3.5
Thrust to Weight	2	2	2	2	2	2
Engine Mass[1]	341	19.5	63	766	1502	7994
Oxidizer Tank Mass	95	23	38	184	238	685
Fuel Tank/Grain Case Mass	182	41.8	72	346	452	1289
ISRU Hydrogen Tank	0	0	0	0	0	0
Hydrogen Mass for ISRU	0	0	0	0	0	0
Structure Mass	1677	131.2	426	3964	8577	73033
Crew Cabin Mass	3107	0	0	5981	7732	0
Space Suit Mass	1100	0	0	100	4100	0
Consumables Mass	0	0	0	709	0	0
Cryocooler Mass	0	0	108	1232	0	0
Power Systems Mass[2]	80	80	80	80	80	80
ISRU Plant Mass	0	0	173	2754	0	0
Avionics Mass	60	60	60	60	60	60
Electon. Thermal Control Mass	60	60	60	60	60	60
Aerobrake and Landing Mass	1738	85.5	278	3365	5676	83920
Attitude control Mass	120	5.9	19	231	427	2456
Payload Mass	2200	10	300	500	8200	0 (at liftoff)
Total Propellant Mass	35217	2106	6835	82878	165369	909720
Wet Mass	**45977**	**2623**	**8512**	**103210**	**202473**	**1079297**

[1]Does not include grain case mass for hybrids
[2]Does not include ISRU power system mass, which is included in "ISRU Plant Mass"
All masses in kg

Propellant Family: PF6-SCO/LOX						
Vehicle Type	**HERMES**	**EOS**	**IRIS**	**ARES**	**HYPERION**	**ZEUS**
P_c (psia)	300	300	300	300	300	300
I_{SP} (sec)	279.7	279.7	279.7	279.7	279.7	279.7
Engine Type	hybrid	hybrid	hybrid	hybrid	hybrid	hybrid
Reserve Propellant (%)	3.5	3.5	3.5	3.5	3.5	3.5
Thrust to Weight	2	2	2	2	2	2
Engine Mass[1]	192	10.8	32	438	869	4714
Oxidizer Tank Mass	201	52.9	27	144	539	1347
Fuel Tank/Grain Case Mass	290	17.1	51	692	1380	6503
ISRU Hydrogen Tank	0	0	0	0	0	0
Hydrogen Mass for ISRU	0	0	0	0	0	0
Structure Mass	1690	129.6	385	4062	8879	77963
Crew Cabin Mass	3107	0	0	5981	7732	0
Space Suit Mass	1100	0	0	100	4100	0
Consumables Mass	0	0	0	709	0	0
Cryocooler Mass	0	0	89	1330	0	0
Power Systems Mass2	80	80	80	80	80	80
ISRU Plant Mass	0	0	165	2898	0	0
Avionics Mass	60	60	60	60	60	60
Electon. Thermal Control Mass	60	60	60	60	60	60
Aerobrake and Landing Mass	1764	85.2	253	3456	5858	85500
Attitude control Mass	121	5.8	17	237	442	2598
Payload Mass	2200	10	300	500	8200	0 (at liftoff)
Total Propellant Mass	37108	2183	6484	88569	178595	999140
Wet Mass	**47973**	**2694**	**8003**	**109316**	**216794**	**1.178E6**

[1]Does not include grain case mass for hybrids
[2]Does not include ISRU power system mass, which is included in "ISRU Plant Mass"
All masses in kg

Propellant Family: PF9 and PF10-LC_2H_4/LOX						
Vehicle Type	**HERMES**	**EOS**	**IRIS**	**ARES**	**HYPERION**	**ZEUS**
P_c (psia)	1000	1000	1000	1000	1000	1000
I_{SP} (sec)	375.6	375.6	375.6	375.6	375.6	375.6
Engine Type	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant
Reserve Propellant (%)	3.5	3.5	3.5	3.5	3.5	3.5
Thrust to Weight	2	2	2	2	2	2
Engine Mass[1]	181	8.4	51	632	698	3508
Oxidizer Tank Mass	97	21.6	53	256	229	641
Fuel Tank/Grain Case Mass	65	10.1	36	176	162	488
ISRU Hydrogen Tank	0	0	50	237	0	0
Hydrogen Mass for ISRU	0	0	204	2532	0	0
Structure Mass	747	63.3	385	3593	3746	45733
Crew Cabin Mass	3107	0	0	5981	7732	0
Space Suit Mass	1100	0	0	100	4100	0
Consumables Mass	0	0	0	709	0	0
Cryocooler Mass	0	0	111	1196	0	0
Power Systems Mass[2]	80	80	80	80	80	80
ISRU Plant Mass	0	0	518	7563	0	0
Avionics Mass	60	60	60	60	60	60
Electon. Thermal Control Mass	60	60	60	60	60	60
Aerobrake and Landing Mass	1416	58.5	356	4428	4454	76036
Attitude control Mass	98	4.1	25	307	324	1727
Payload Mass	2200	10	300	500	8200	0 (at liftoff)
Total Propellant Mass	18154	890	5413	67331	76012	404430
Wet Mass	**27365**	**1266**	**7702**	**95741**	**105857**	**532763**

[1]Does not include grain case mass for hybrids
[2]Does not include ISRU power system mass, which is included in "ISRU Plant Mass"
All masses in kg

Propellant Family: PF9 and PF10-SC_2H_4/LOX						
Vehicle Type	**HERMES**	**EOS**	**IRIS**	**ARES**	**HYPERION**	**ZEUS**
P_c (psia)	500	500	500	500	500	500
I_{SP} (sec)	371.5	371.5	371.5	371.5	371.5	371.5
Engine Type	hybrid	hybrid	hybrid	hybrid	hybrid	hybrid
Reserve Propellant (%)	3.5	3.5	3.5	3.5	3.5	3.5
Thrust to Weight	2	2	2	2	2	2
Engine Mass[1]	132	6.0	37	487	513	2611
Oxidizer Tank Mass	107	23.3	57	293	252	714
Fuel Tank/Grain Case Mass	129	6.2	38	504	452	2436
ISRU Hydrogen Tank	0	0	40	197	0	0
Hydrogen Mass for ISRU	0	0	205	2724	0	0
Structure Mass	727	60.9	374	3773	3712	46619
Crew Cabin Mass	3107	0	0	5981	7732	0
Space Suit Mass	1100	0	0	100	4100	0
Consumables Mass	0	0	0	709	0	0
Cryocooler Mass	0	0	106	1375	0	0
Power Systems Mass[2]	80	80	80	80	80	80
ISRU Plant Mass	0	0	524	8140	0	0
Avionics Mass	60	60	60	60	60	60
Electon. Thermal Control Mass	60	60	60	60	60	60
Aerobrake and Landing Mass	1420	57.3	352	4676	4475	76459
Attitude control Mass	98	4.0	24	324	326	1762
Payload Mass	2200	10	300	500	8200	0 (at liftoff)
Total Propellant Mass	18524	888	5435	72424	77911	419715
Wet Mass	**27744**	**1256**	**7692**	**102407**	**107873**	**550516**

[1]Does not include grain case mass for hybrids
[2]Does not include ISRU power system mass, which is included in "ISRU Plant Mass"
All masses in kg

Propellant Family: PF11 and PF12-LCH_4/LOX						
Vehicle Type	**HERMES**	**EOS**	**IRIS**	**ARES**	**HYPERION**	**ZEUS**
P_c (psia)	1000	1000	1000	1000	1000	1000
I_{SP} (sec)	373.6	373.6	373.6	373.6	373.6	373.6
Engine Type	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant
Reserve Propellant (%)	3.5	3.5	3.5	3.5	3.5	3.5
Thrust to Weight	2	2	2	2	2	2
Engine Mass[1]	182	8.7	39	441	706	3544
Oxidizer Tank Mass	102	21.5	46	213	240	674
Fuel Tank/Grain Case Mass	83	17.8	36	168	196	551
ISRU Hydrogen Tank	0	0	53	240	0	0
Hydrogen Mass for ISRU	0	0	224	2511	0	0
Structure Mass	763	65.9	299	2152	3810	46047
Crew Cabin Mass	3107	0	0	5981	7732	0
Space Suit Mass	1100	0	0	100	4100	0
Consumables Mass	0	0	0	709	0	0
Cryocooler Mass	0	0	110	993	0	0
Power Systems Mass[2]	80	80	80	80	80	80
ISRU Plant Mass	0	0	165	2253	0	0
Avionics Mass	60	60	60	60	60	60
Electon. Thermal Control Mass	60	60	60	60	60	60
Aerobrake and Landing Mass	1425	60.6	275	3077	4477	76147
Attitude control Mass	99	4.2	19	214	326	1737
Payload Mass	2200	10	300	500	8200	0 (at liftoff)
Total Propellant Mass	18425	929	4215	47213	77143	410153
Wet Mass	**27686**	**1318**	**5981**	**66965**	**107130**	**539053**

[1]Does not include grain case mass for hybrids
[2]Does not include ISRU power system mass, which is included in "ISRU Plant Mass"
All masses in kg

Propellant Family: PF11 and PF12-SCH_4/LOX						
Vehicle Type	**HERMES**	**EOS**	**IRIS**	**ARES**	**HYPERION**	**ZEUS**
P_c (psia)	500	500	500	500	500	500
I_{SP} (sec)	370.5	370.5	370.5	370.5	370.5	370.5
Engine Type	hybrid	hybrid	hybrid	hybrid	hybrid	hybrid
Reserve Propellant (%)	3.5	3.5	3.5	3.5	3.5	3.5
Thrust to Weight	2	2	2	2	2	2
Engine Mass[1]	135	6.1	28	334	526	2658
Oxidizer Tank Mass	116	24.2	51	241	272	733
Fuel Tank/Grain Case Mass	152	7.3	33	398	533	2849
ISRU Hydrogen Tank	0	0	42	194	0	0
Hydrogen Mass for ISRU	0	0	222	2660	0	0
Structure Mass	732	61.3	279	2140	3736	45799
Crew Cabin Mass	3107	0	0	5981	7732	0
Space Suit Mass	1100	0	0	100	4100	0
Consumables Mass	0	0	0	709	0	0
Cryocooler Mass	0	0	91	1010	0	0
Power Systems Mass2	80	80	80	80	80	80
ISRU Plant Mass	0	0	158	2337	0	0
Avionics Mass	60	60	60	60	60	60
Electon. Thermal Control Mass	60	60	60	60	60	60
Aerobrake and Landing Mass	1428	57.9	263	3146	4500	76413
Attitude control Mass	99	4.0	18	218	328	1759
Payload Mass	2200	10	300	500	8200	0 (at liftoff)
Total Propellant Mass	18704	900	4091	48934	78716	420801
Wet Mass	**27973**	**1271**	**5776**	**69102**	**108843**	**551212**

[1]Does not include grain case mass for hybrids
[2]Does not include ISRU power system mass, which is included in "ISRU Plant Mass"
All masses in kg

APPENDIX F
PROPELLANT REQUIREMENTS
FOR HOPPER VEHICLE MISSIONS

APPENDIX F. PROPELLANT REQUIREMENTS FOR HOPPER VEHICLE MISSIONS

This appendix lists the propellant requirements to complete each Hopper Vehicle mission for the 100 and 10,000-person colony traffic models. Hopper Vehicles" collectively refers to all rocket-powered vehicles included in this study, with the exception of sounding rockets. The propellant requirements listed here are for a "one-way" trip, defined as flying from a base or remote location to a base or remote location. This includes missions which fly into orbit around Mars and back to the surface (considered a one-way trip). Several missions (Mission numbers 1, 2, 3, 4, 7, 10, 11, 12, 13, 16, 26, 27, 28, 29, 32, 50) fly out to a remote location from a base, achieve the mission objectives, and then fly back to a base. The total propellant required to complete these missions (both hops) is twice the "one-way" amount listed here.

F.1 Propellant Requirements for 100-Person Colony Missions

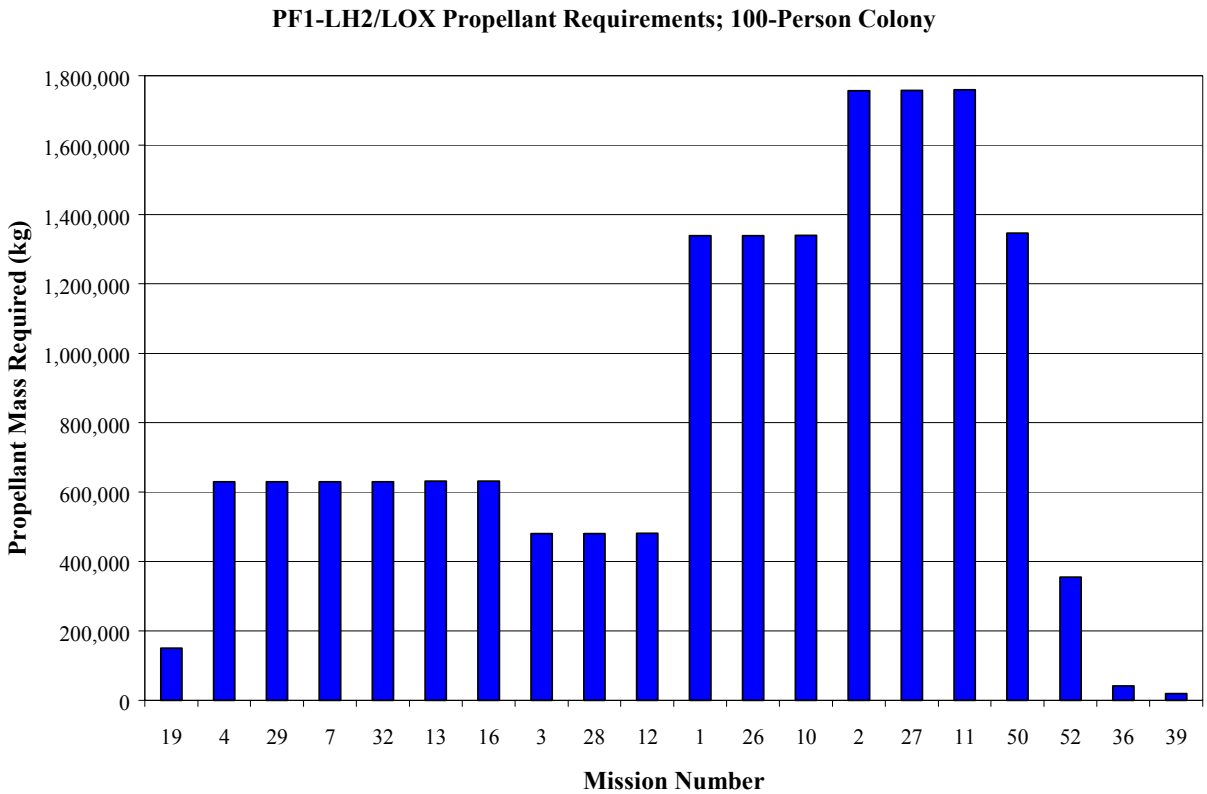

Figure D-1. Single Mission Propellant Requirements for PF1-LH2/LOX; 100-Person Colony

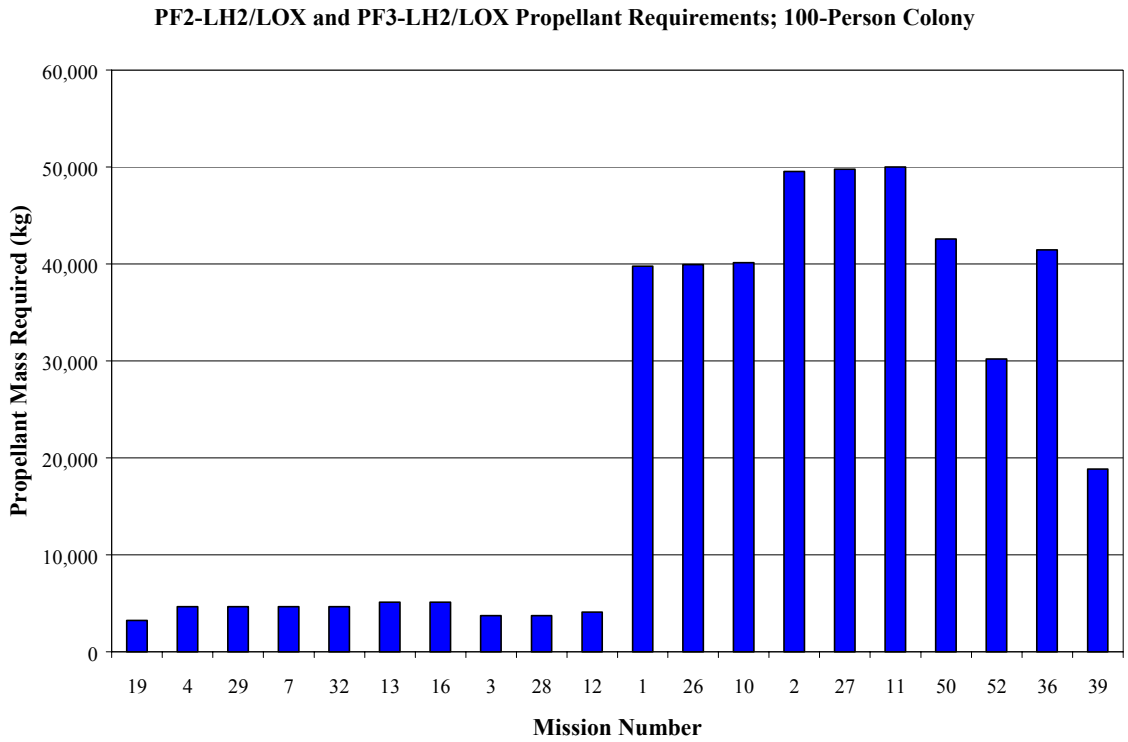

Figure D-2. Single Mission Propellant Requirements for PF2-LH2/LOX and PF3-LH2/LOX; 100-Person Colony

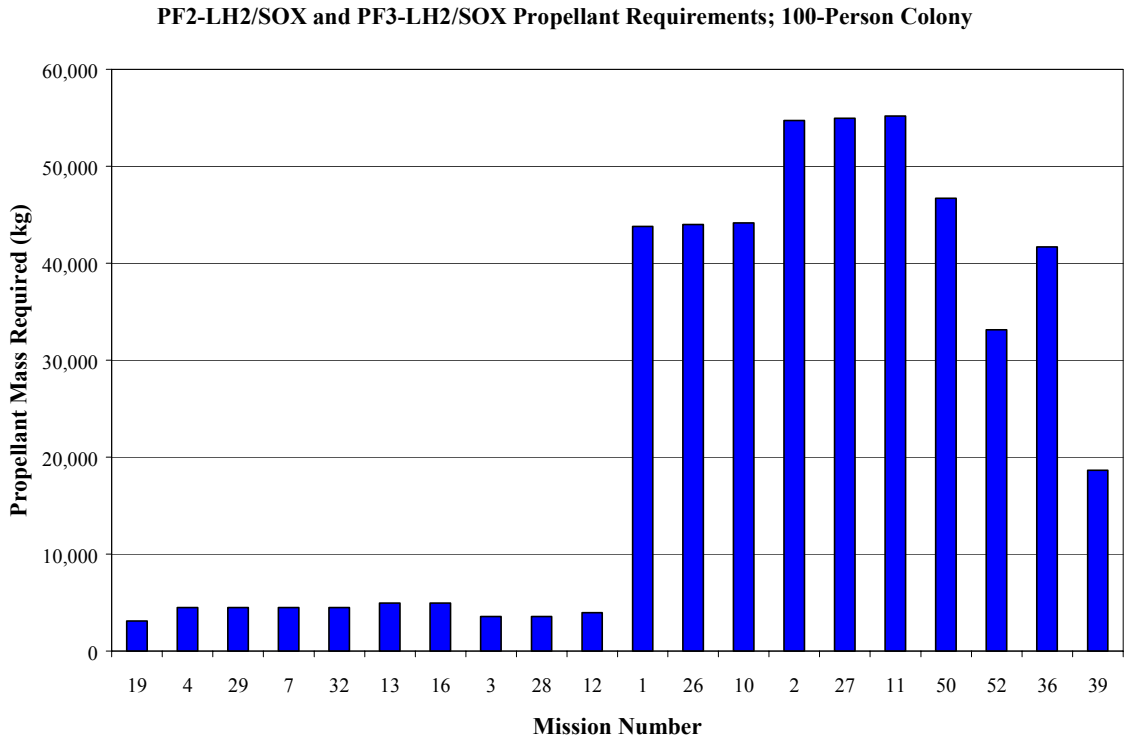

Figure D-3. Single Mission Propellant Requirements for PF2-LH2/SOX and PF3-LH2/SOX; 100-Person Colony

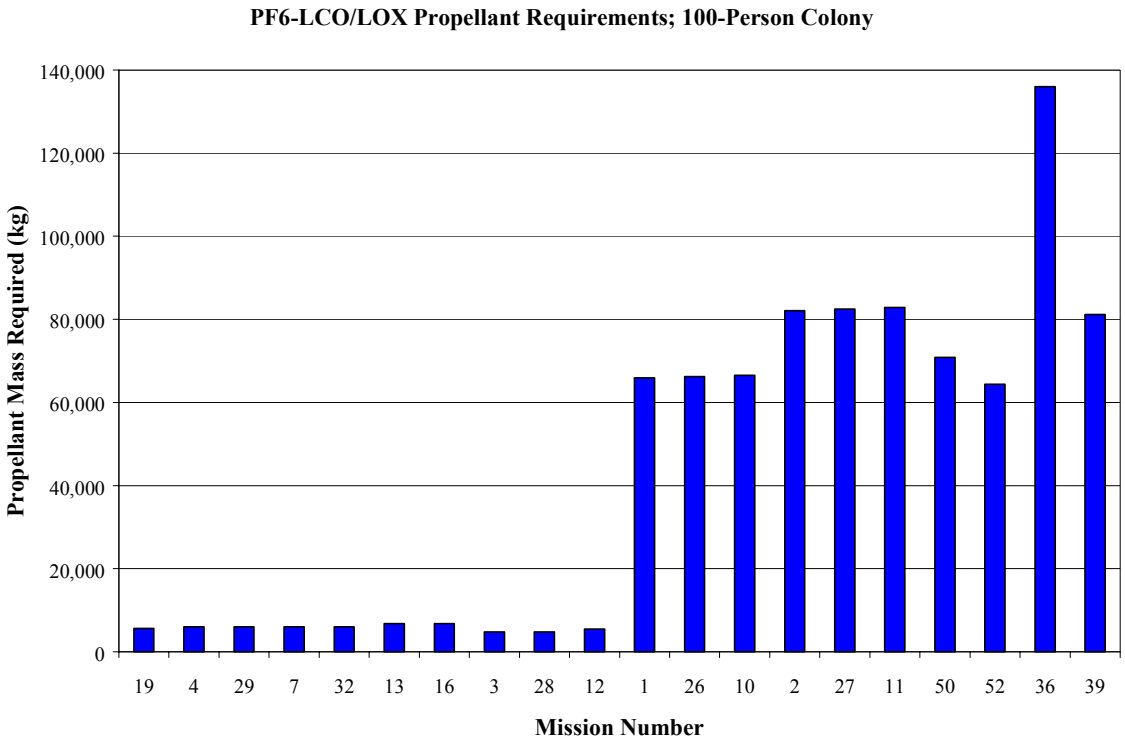

Figure D-4. Single Mission Propellant Requirements for PF6-LCO/LOX; 100-Person Colony

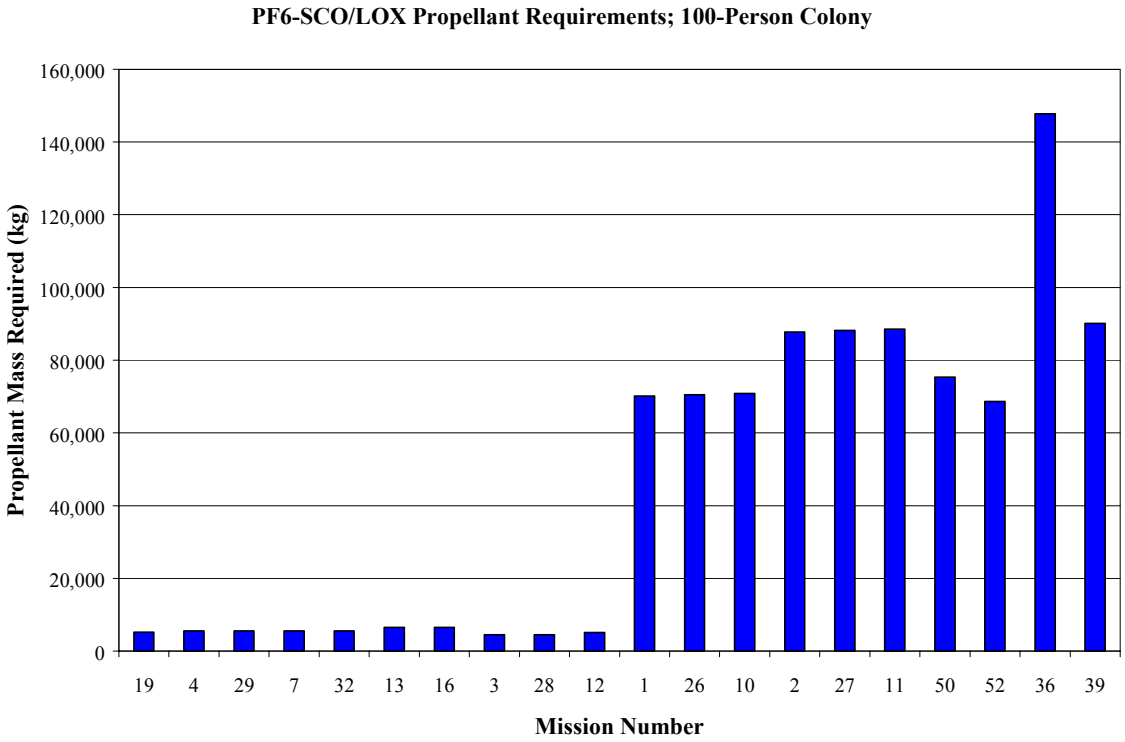

Figure D-5. Single Mission Propellant Requirements for PF-6 SCO/LOX; 100-Person Colony

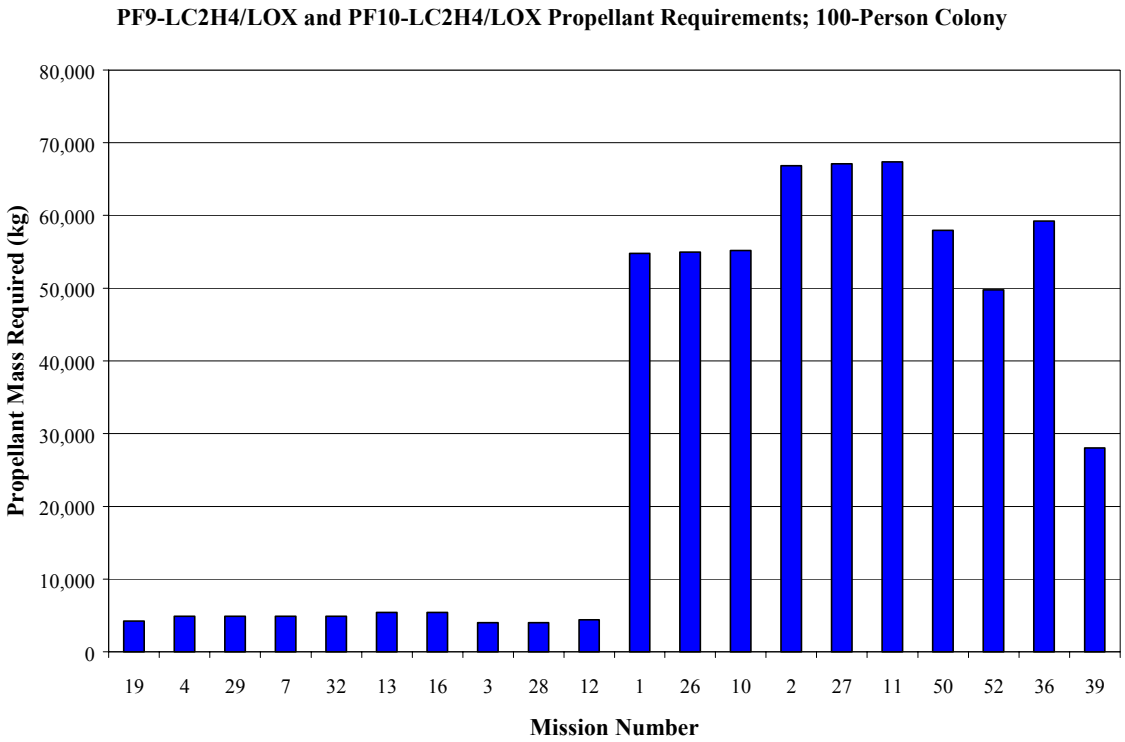

Figure D-6. Single Mission Propellant Requirements for PF-9 LC2H4/LOX and PF10-LC2H4/LOX; 100-Person Colony

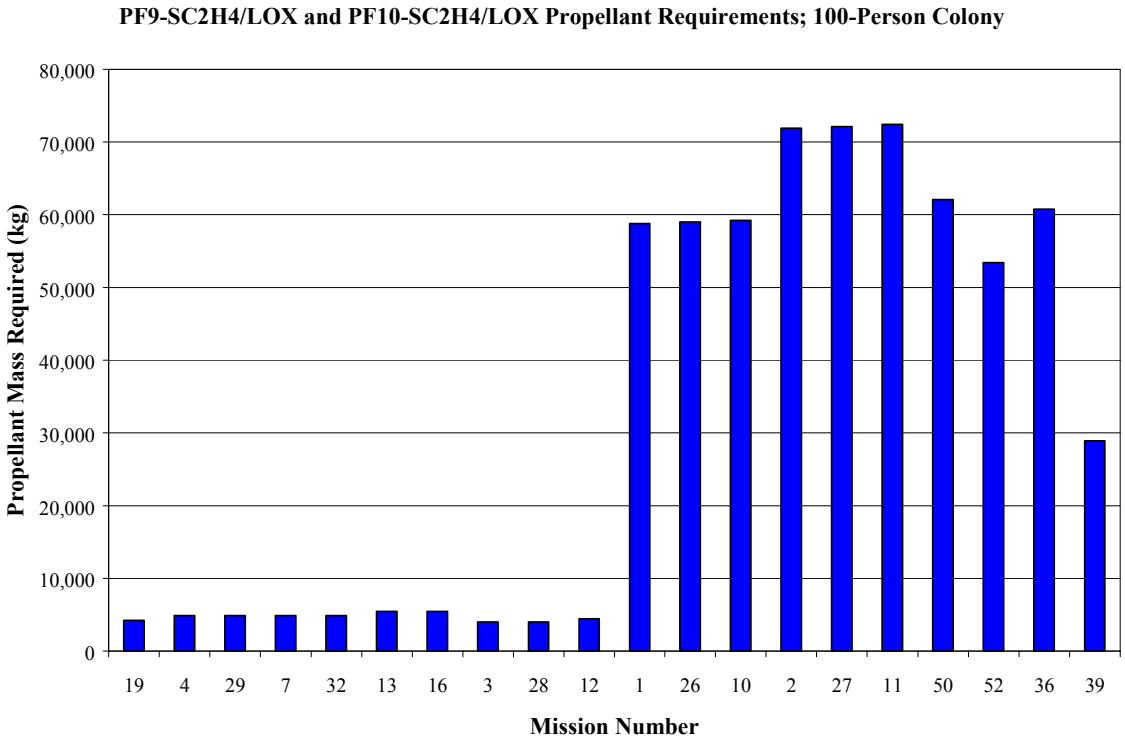

Figure D-7. Single Mission Propellant Requirements for PF-9 SC2H4/LOX and PF10-SC2H4/LOX; 100-Person Colony

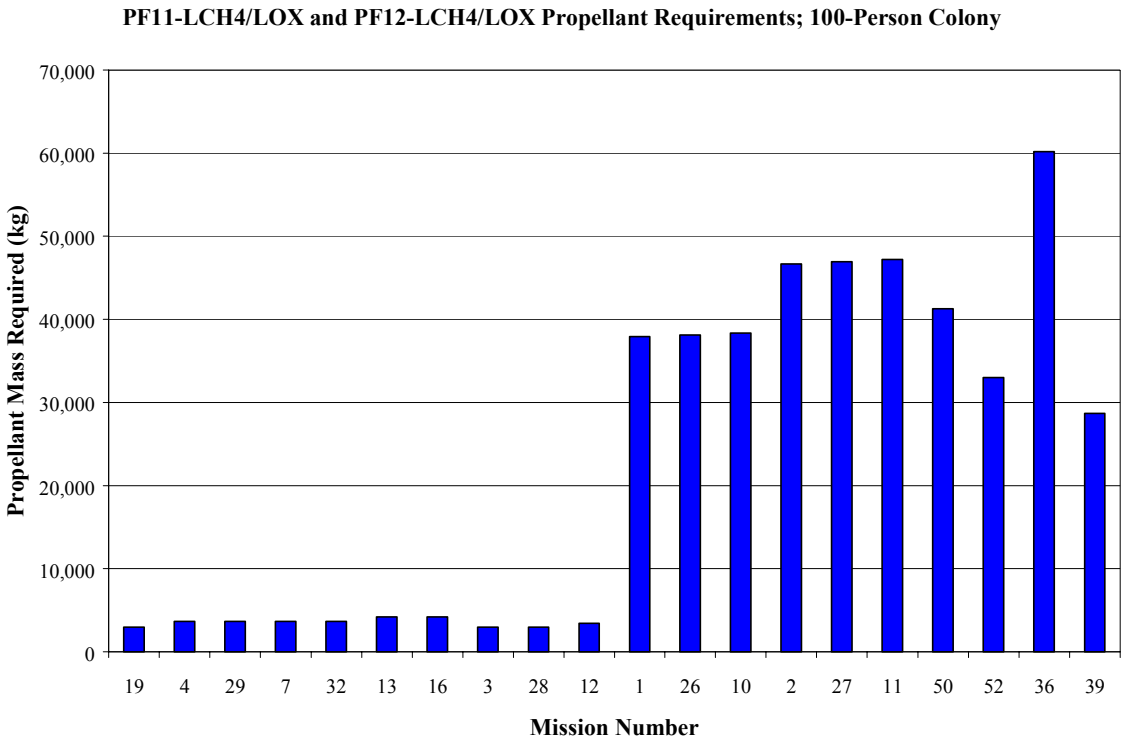

Figure D-8. Single Mission Propellant Requirements for PF-11 LCH4/LOX and PF12-LCH4/LOX; 100-Person Colony

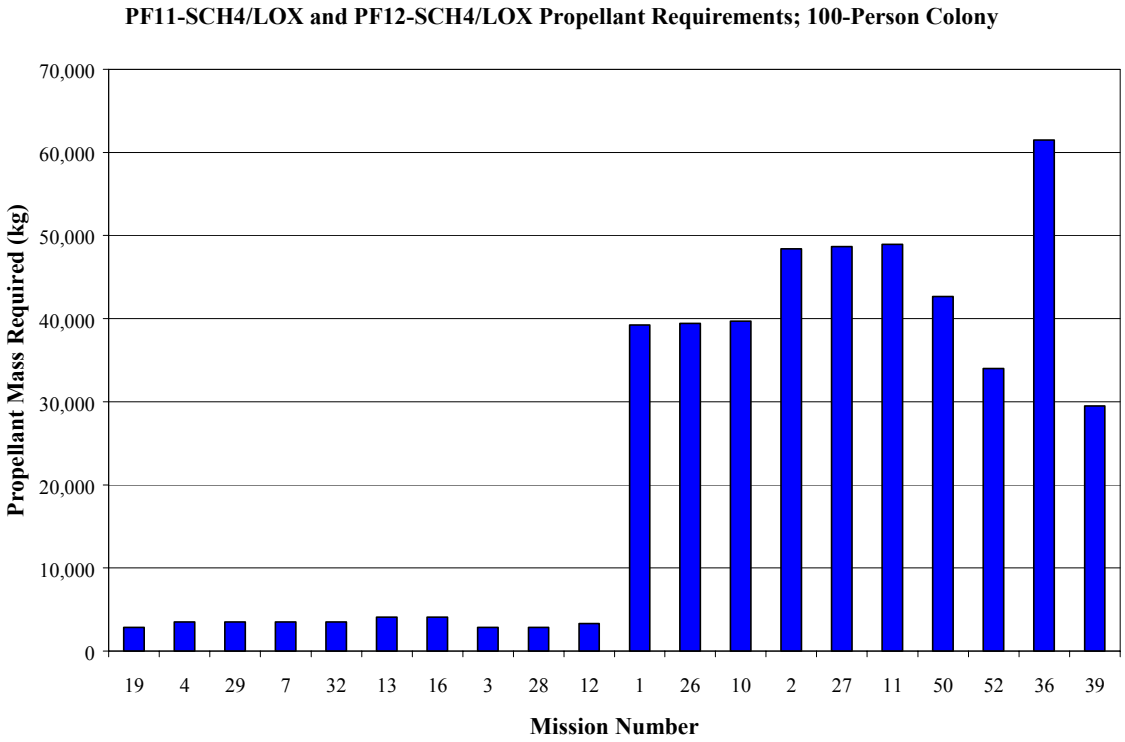

Figure D-9. Single Mission Propellant Requirements for PF-11 SCH4/LOX and PF12-SCH4/LOX; 100-Person Colony

F.2 Propellant Requirements for 10,000-Person Colony Missions

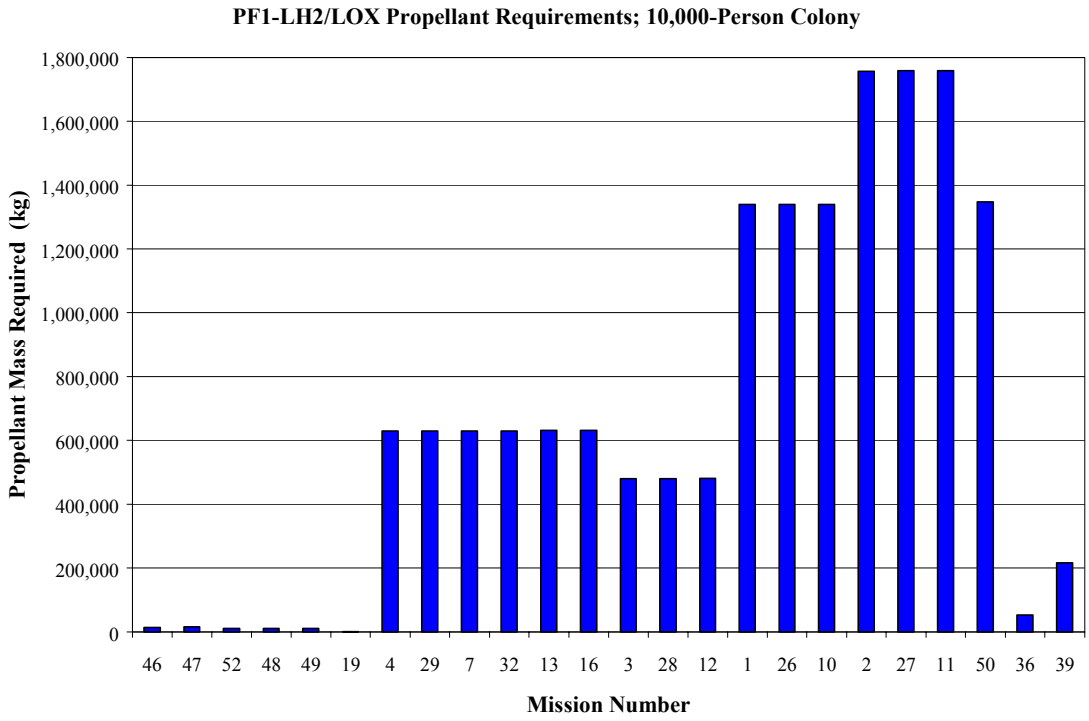

Figure D-10. Single Mission Propellant Requirements for PF1-LH2/LOX; 10,000-Person Colony

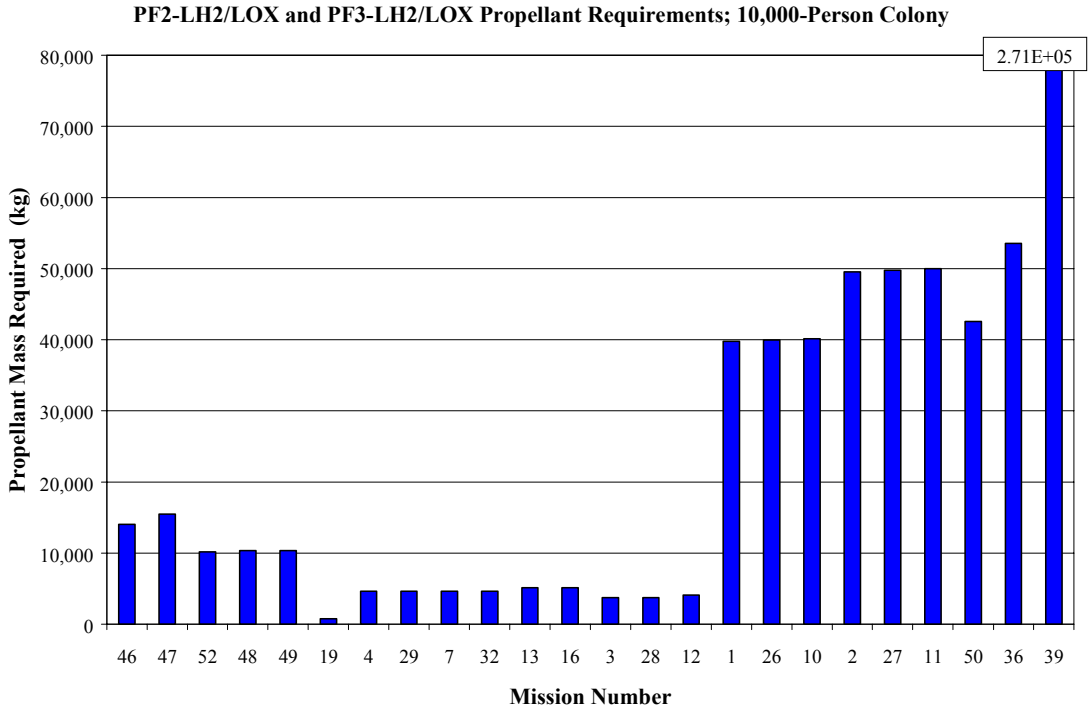

Figure D-11. Single Mission Propellant Requirements for PF2-LH2/LOX and PF3-LH2/LOX; 10,000-Person Colony

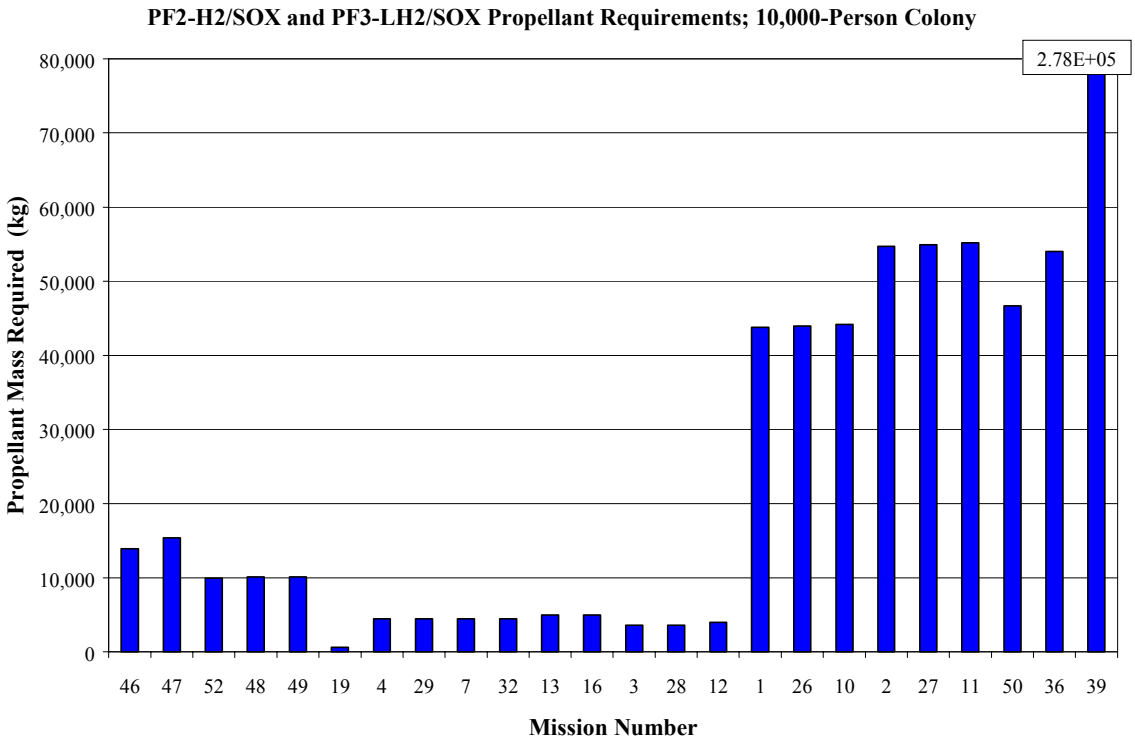

Figure D-12. Single Mission Propellant Requirements for PF2-LH2/SOX and PF3-LH2/SOX; 10,000-Person Colony

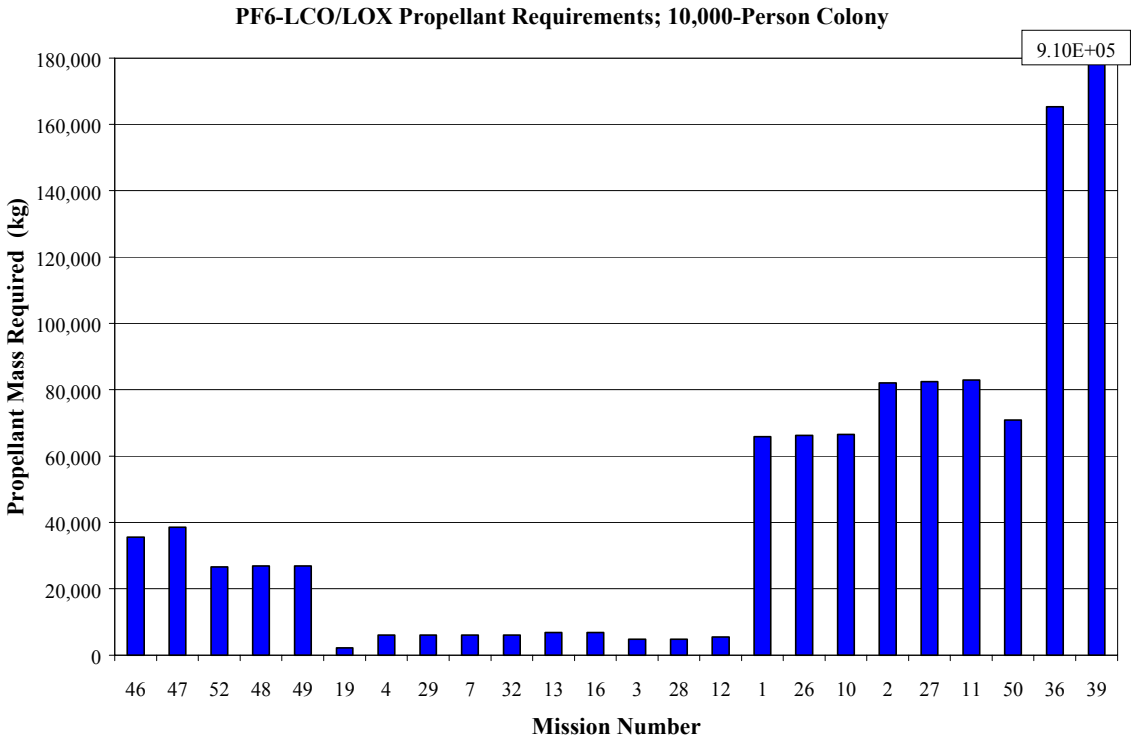

Figure D-13. Single Mission Propellant Requirements for PF6-LCO/LOX; 10,000-Person Colony

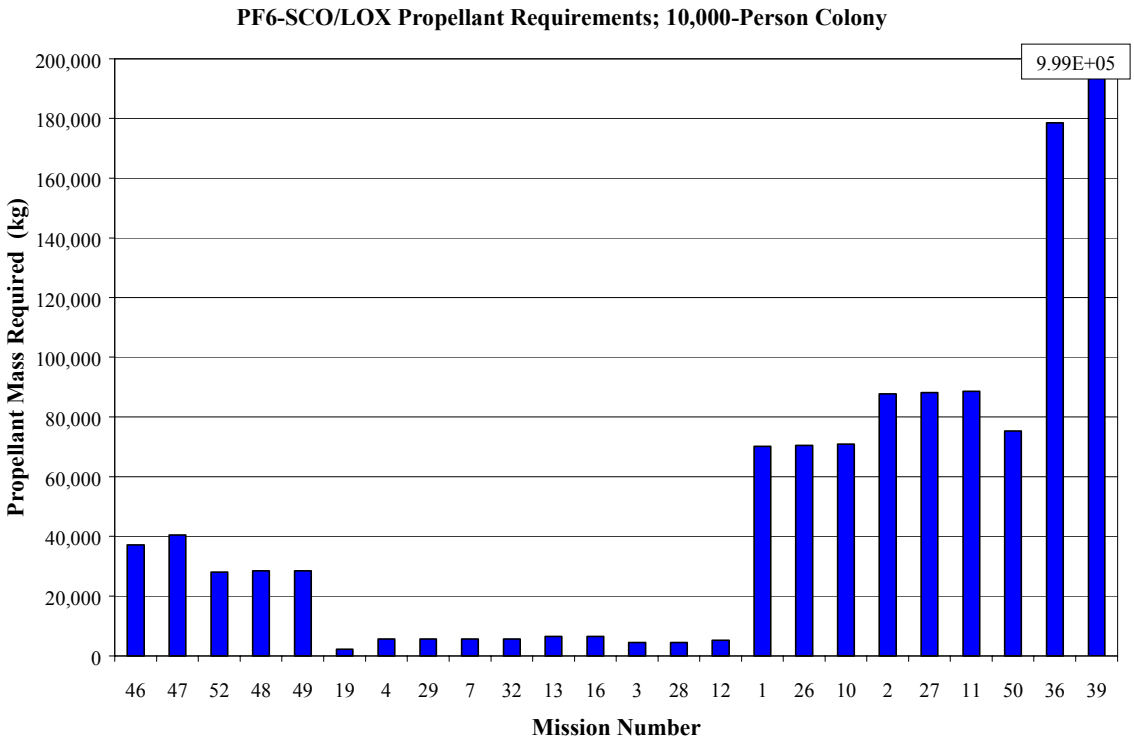

Figure D-14. Single Mission Propellant Requirements for PF-6 SCO/LOX; 10,000-Person Colony

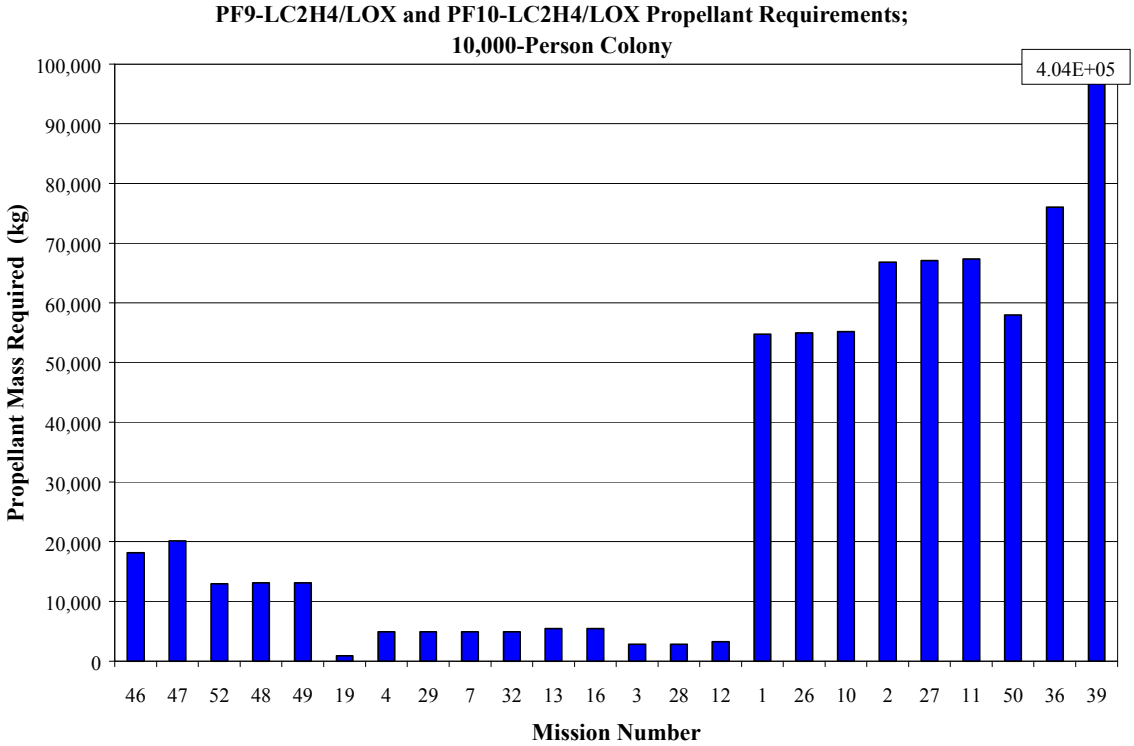

Figure D-15. Single Mission Propellant Requirements for PF-9 LC2H4/LOX and PF10-LC2H4/LOX; 10,000-Person Colony

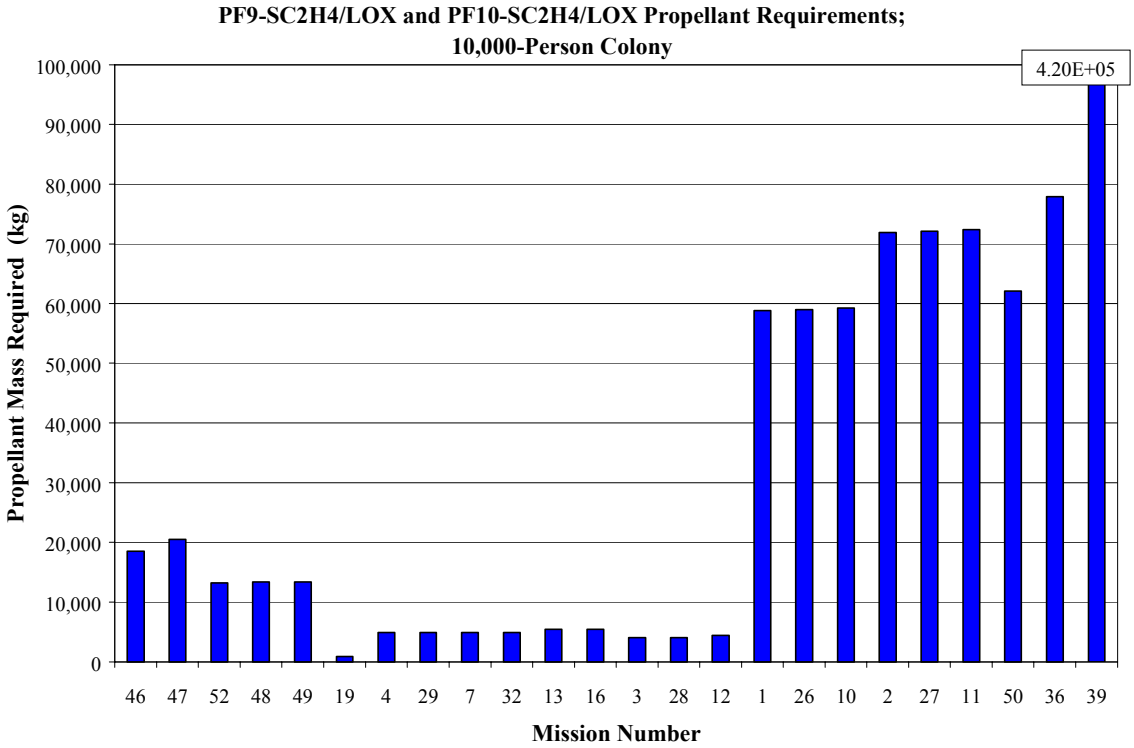

Figure D-16. Single Mission Propellant Requirements for PF-9 SC2H4/LOX and PF10-SC2H4/LOX; 10,000-Person Colony

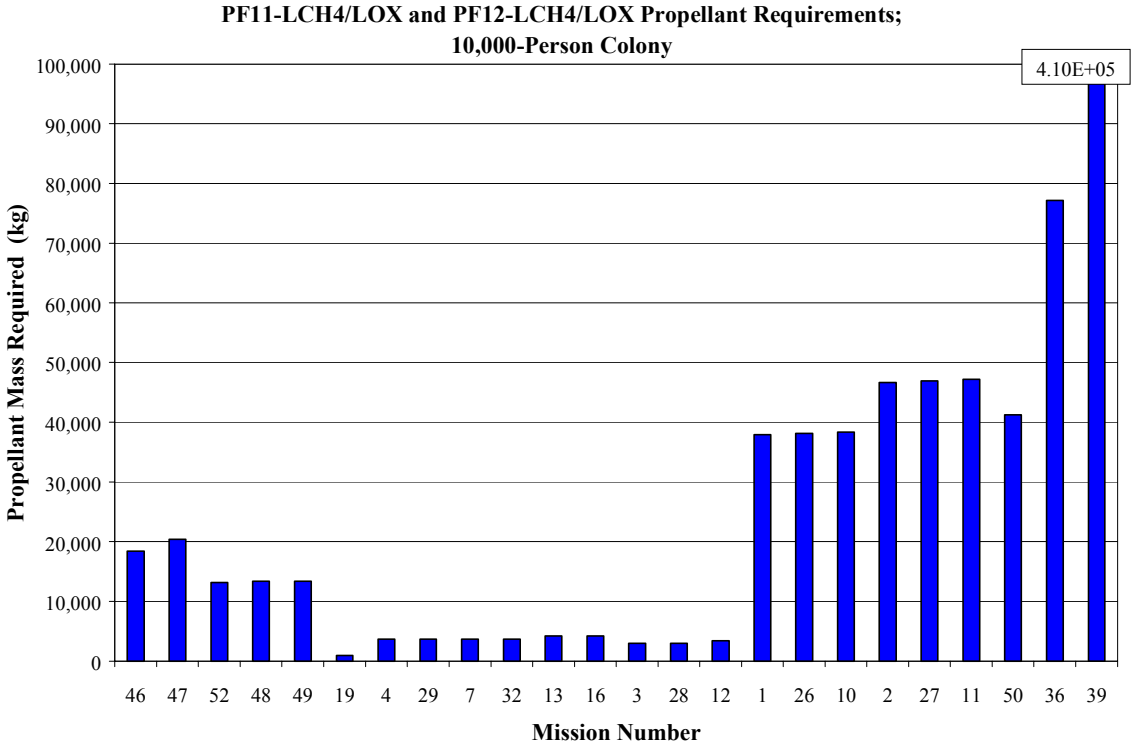

Figure D-17. Single Mission Propellant Requirements for PF-11 LCH4/LOX and PF12-LCH4/LOX; 10,000-Person Colony

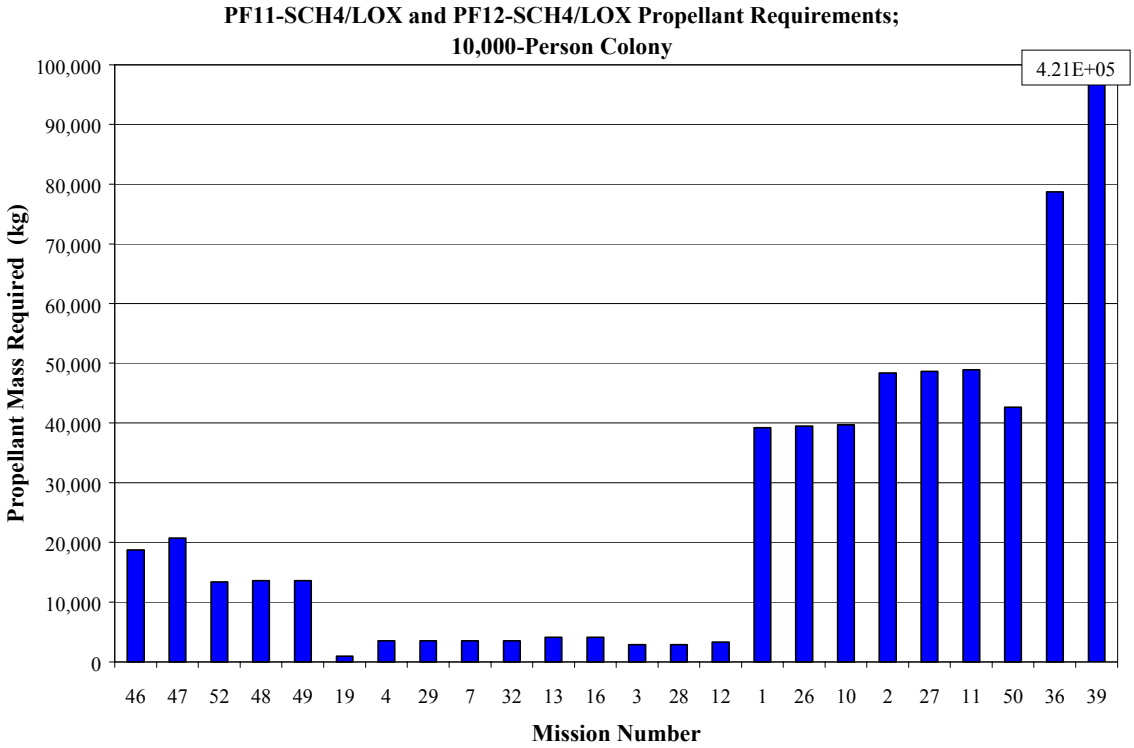

Figure D-18. Single Mission Propellant Requirements for PF-11 SCH4/LOX and PF12-SCH4/LOX; 10,000-Person Colony

APPENDIX G
PROPELLANT PRODUCTION SYSTEM MASS REQUIREMENTS

APPENDIX G. PROPELLANT PRODUCTION SYSTEM MASS REQUIREMENTS

This appendix lists the propellant production mass requirements and per-cycle shipment schedule for the 100 and 10,000-person colony traffic models. Processor Mass includes all propellant production plant, compressor, cryo-cooler, and storage tank masses. Power Mass gives the total mass of nuclear reactors required to provide all the necessary energy for propellant production and liquefaction. In cases using in-situ hydrogen, the WAVAR system mass and power requirements are included in both the processor and power mass totals. Terrestrial hydrogen requirements are given in the Total Hydrogen Mass Required column when applicable. Ground vehicle analysis include the mass of the rovers.

G.1 Propellant Requirements for 100-Person Colony Missions

G.1.1 Flight Vehicle Propellant Family Masses

Table G-1. PF 1 - LOX/LH_2 Propellant Shipping Requirements

Cycle	Total Required Hydrogen (kg/cy)	Total Required Oxygen (kg/cy)	Total Required Propellants (kg/cy)
1	5.67E+07	3.12E+08	3.69E+08
2	5.62E+07	3.09E+08	3.66E+08
3	5.62E+07	3.09E+08	3.66E+08
4	5.62E+07	3.09E+08	3.66E+08
5	5.62E+07	3.09E+08	3.66E+08
6	5.62E+07	3.09E+08	3.65E+08
7	5.62E+07	3.09E+08	3.65E+08
8	5.78E+07	3.18E+08	3.76E+08
9	5.78E+07	3.18E+08	3.76E+08
10	5.78E+07	3.18E+08	3.76E+08
11	5.78E+07	3.18E+08	3.76E+08
12	5.78E+07	3.18E+08	3.76E+08
13	5.78E+07	3.18E+08	3.76E+08
14	5.93E+07	3.26E+08	3.85E+08
15	5.92E+07	3.26E+08	3.85E+08
16	6.08E+07	3.35E+08	3.96E+08
17	6.08E+07	3.35E+08	3.96E+08
18	6.30E+07	3.46E+08	4.09E+08
19	6.30E+07	3.46E+08	4.09E+08
20	6.30E+07	3.46E+08	4.09E+08
21	6.30E+07	3.46E+08	4.09E+08
22	6.30E+07	3.47E+08	4.10E+08
23	6.47E+07	3.56E+08	4.20E+08
TOTAL:	**1.36E+09**	**7.48E+09**	**8.84E+09**

Table G-2. PF 1 - SOX/LH_2 Propellant Shipping Requirements

Cycle	Total Required Hydrogen (kg/cy)	Total Required Oxygen (kg/cy)	Total Required Propellants (kg/cy)
1	4.07E+05	2.24E+06	2.64E+06
2	2.96E+05	1.63E+06	1.92E+06
3	3.33E+05	1.83E+06	2.16E+06
4	2.96E+05	1.63E+06	1.92E+06
5	3.33E+05	1.83E+06	2.16E+06
6	1.09E+05	5.97E+05	7.06E+05
7	1.09E+05	5.97E+05	7.06E+05
8	1.09E+05	5.97E+05	7.06E+05
9	1.09E+05	5.97E+05	7.06E+05
10	1.09E+05	5.97E+05	7.06E+05
11	1.09E+05	5.97E+05	7.06E+05
12	1.09E+05	5.97E+05	7.06E+05
13	1.09E+05	5.97E+05	7.06E+05
14	1.09E+05	5.97E+05	7.06E+05
15	1.09E+05	5.97E+05	7.06E+05
16	1.09E+05	5.97E+05	7.06E+05
17	1.09E+05	5.97E+05	7.06E+05
18	1.09E+05	5.97E+05	7.06E+05
19	1.09E+05	5.97E+05	7.06E+05
20	1.09E+05	5.97E+05	7.06E+05
21	1.09E+05	5.97E+05	7.06E+05
22	1.09E+05	5.97E+05	7.06E+05
23	1.09E+05	5.97E+05	7.06E+05
TOTAL:	**3.62E+06**	**1.99E+07**	**2.35E+07**

Table G-3. PF 2 - LOX/LH_2 with Terrestrial Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	10410	107322	424
2	35	4683	389
3	36	4719	392
4	35	4683	389
5	36	4719	392
6	32	4434	369
7	32	4434	369
8	33	4477	373
9	33	4477	373
10	33	4477	373
11	33	4477	373
12	33	4477	373
13	33	4477	373
14	33	4513	376
15	33	4513	376
16	33	4555	379
17	33	4555	379
18	34	4644	386
19	34	4644	386
20	34	4644	386
21	34	4644	386
22	34	4644	386
23	34	4686	390
TOTAL:	11149	207896	8792
		GRAND TOTAL (kg):	9011322

Table G-4. PF 2 - SOX/LH_2 with Terrestrial Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	10413	114474	452
2	38	4993	415
3	38	5028	418
4	38	4993	415
5	38	5028	418
6	34	4747	395
7	34	4747	395
8	35	4788	398
9	35	4788	398
10	35	4788	398
11	35	4788	398
12	35	4788	398
13	35	4788	398
14	35	4822	401
15	35	4822	401
16	36	4899	408
17	36	4899	408
18	36	4950	412
19	36	4950	412
20	36	4950	412
21	36	4950	412
22	36	4950	412
23	36	4991	415
TOTAL:	11199	221920	9393
		GRAND TOTAL (kg):	9626460

Table G-5. PF 3 - LOX/LH_2 with ISRU Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	871258	536595	0
2	55	15844	0
3	55	15975	0
4	55	15844	0
5	55	15975	0
6	51	15057	0
7	51	15057	0
8	51	15193	0
9	51	15226	0
10	51	15226	0
11	51	15226	0
12	51	15226	0
13	51	15226	0
14	52	15369	0
15	52	15369	0
16	52	15539	0
17	52	15539	0
18	53	15750	0
19	53	15750	0
20	53	15750	0
21	53	15750	0
22	53	15750	0
23	54	15919	0
TOTAL:	872413	878158	0
		GRAND TOTAL (kg):	1750571

Table G-6. PF 3 - SOX/LH_2 with ISRU Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	927774	576969	0
2	58	17083	0
3	59	17214	0
4	58	17083	0
5	59	17214	0
6	54	16294	0
7	54	16294	0
8	55	16425	0
9	55	16458	0
10	55	16458	0
11	55	16458	0
12	55	16458	0
13	55	16458	0
14	55	16598	0
15	55	16598	0
16	56	16762	0
17	56	16762	0
18	57	16968	0
19	57	16968	0
20	57	16968	0
21	57	16968	0
22	57	16968	0
23	57	17132	0
TOTAL:	929010	945559	0
		GRAND TOTAL (kg):	1874569

Table G-7. PF 6 - LOX/CO

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	8453	23150	0
2	214	879	0
3	222	911	0
4	214	879	0
5	222	911	0
6	168	688	0
7	168	688	0
8	169	694	0
9	169	694	0
10	169	694	0
11	169	694	0
12	169	694	0
13	169	694	0
14	170	699	0
15	170	699	0
16	172	705	0
17	172	705	0
18	173	712	0
19	173	712	0
20	173	712	0
21	173	712	0
22	173	712	0
23	175	718	0
TOTAL:	12400	39350	0
		GRAND TOTAL (kg):	51774

Table G-8. PF 9 - LOX/LC$_2$H$_4$ with Terrestrial Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	14666	67268	125
2	876	2836	115
3	890	2872	116
4	876	2836	115
5	890	2872	116
6	790	2615	108
7	790	2615	108
8	797	2637	109
9	797	2637	109
10	797	2637	109
11	797	2637	109
12	797	2637	109
13	797	2637	109
14	802	2655	110
15	802	2655	110
16	808	2677	111
17	808	2677	111
18	816	2703	112
19	816	2703	112
20	816	2703	112
21	816	2703	112
22	816	2703	112
23	822	2725	113
TOTAL:	32679	126642	2571
		GRAND TOTAL (kg):	2729894

Table G-9. PF 9 - LOX/SC$_2$H$_4$ with Terrestrial Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	14734	71947	133
2	940	3046	122
3	2047	3084	124
4	940	3046	122
5	2047	3084	124
6	837	2779	115
7	837	2779	115
8	843	2801	116
9	843	2801	116
10	843	2801	116
11	843	2801	116
12	843	2801	116
13	843	2801	116
14	848	2819	117
15	848	2819	117
16	855	2841	117
17	855	2841	117
18	863	2868	119
19	863	2868	119
20	863	2868	119
21	863	2868	119
22	863	2868	119
23	869	2890	120
TOTAL:	36031	135121	2730
		GRAND TOTAL (kg):	2901197

Table G-10. PF 10 - LOX/LC$_2$H$_4$ with ISRU Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	231713	185788	0
2	814	6840	0
3	828	6917	0
4	814	6840	0
5	828	6917	0
6	727	6377	0
7	727	6377	0
8	734	6413	0
9	734	6435	0
10	734	6435	0
11	734	6435	0
12	734	6435	0
13	734	6435	0
14	739	6482	0
15	739	6482	0
16	745	6540	0
17	745	6540	0
18	753	6611	0
19	753	6611	0
20	753	6611	0
21	753	6611	0
22	753	6611	0
23	760	6668	0
TOTAL:	248349	330410	0
		GRAND TOTAL (kg):	578759

Table G-11. PF 10 - LOX/SC$_2$H$_4$ with ISRU Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	246569	197711	0
2	861	7261	0
3	876	7341	0
4	861	7261	0
5	876	7341	0
6	772	6782	0
7	772	6782	0
8	779	6818	0
9	779	6840	0
10	779	6840	0
11	779	6840	0
12	779	6840	0
13	779	6840	0
14	784	6888	0
15	784	6888	0
16	790	6946	0
17	790	6946	0
18	798	7017	0
19	798	7017	0
20	798	7017	0
21	798	7017	0
22	798	7017	0
23	805	7075	0
TOTAL:	264205	337236	0
		GRAND TOTAL (kg):	601441

Table G-12. PF 11 - LOX/LCH$_4$ with Terrestrial Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	13839	39632	133
2	164	1695	121
3	168	1719	122
4	164	1695	121
5	168	1719	122
6	143	1551	111
7	143	1551	111
8	144	1565	112
9	144	1565	112
10	144	1565	112
11	144	1565	112
12	144	1565	112
13	144	1565	112
14	145	1576	113
15	145	1576	113
16	146	1590	114
17	146	1590	114
18	148	1607	116
19	148	1607	116
20	148	1607	116
21	148	1607	116
22	148	1607	116
23	149	1621	117
TOTAL:	17122	74942	2666
		GRAND TOTAL (kg):	2757587

Table G-13. PF 11 - LOX/SCH$_4$ with Terrestrial Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	14945	42319	141
2	175	1812	128
3	179	1837	129
4	175	1812	128
5	179	1837	129
6	150	1633	117
7	150	1633	117
8	151	1647	118
9	151	1647	118
10	151	1647	118
11	151	1647	118
12	151	1647	118
13	151	1647	118
14	152	1658	118
15	152	1658	118
16	153	1672	119
17	153	1672	119
18	154	1688	121
19	154	1688	121
20	154	1688	121
21	154	1688	121
22	154	1688	121
23	155	1702	122
TOTAL:	18393	79567	2795
		GRAND TOTAL (kg):	2893149

Table G-14. PF 12 - LOX/LCH$_4$ with ISRU Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	254864	167377	0
2	152	5825	0
3	156	5907	0
4	152	5825	0
5	156	5907	0
6	130	5330	0
7	130	5330	0
8	131	5368	0
9	131	5382	0
10	131	5382	0
11	131	5382	0
12	131	5382	0
13	131	5382	0
14	132	5425	0
15	132	5425	0
16	134	5477	0
17	134	5477	0
18	135	5541	0
19	135	5541	0
20	135	5541	0
21	135	5541	0
22	135	5541	0
23	136	5593	0
TOTAL:	257874	288884	0
		GRAND TOTAL (kg):	546759

Table G-15. PF 12 - LOX/SCH$_4$ with ISRU Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	269935	177516	0
2	163	6193	0
3	163	6193	0
4	163	6193	0
5	163	6193	0
6	136	5584	0
7	136	5584	0
8	137	5622	0
9	137	5635	0
10	137	5635	0
11	137	5635	0
12	137	5635	0
13	137	5635	0
14	138	5678	0
15	138	5678	0
16	140	5729	0
17	140	5729	0
18	141	5793	0
19	141	5793	0
20	141	5793	0
21	141	5793	0
22	141	5793	0
23	142	5844	0
TOTAL:	273089	304873	0
		GRAND TOTAL (kg):	577962

G.1.2 – Ground Vehicle Propellant Family Masses

Table G-16. G1 – LOX/LH_2 from Earth

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Oxygen Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Mass (kg/cy)
1	6000	18500	1814	227	20808
2	0	0	356	45	7641
3	0	0	460	57	8321
4	0	0	356	45	8091
5	0	0	356	45	7641
6	0	0	460	57	8321
7	0	0	0	0	450
8	0	0	356	45	8091
9	0	0	460	57	8321
10	0	0	0	0	450
11	0	0	356	45	8091
12	0	0	103	13	1130
13	0	0	356	45	7641
14	0	0	0	0	450
15	0	0	356	45	8091
16	0	0	0	0	450
17	0	0	460	57	8321
18	0	0	0	0	900
19	0	0	0	0	450
20	0	0	356	45	7641
21	0	0	0	0	450
22	0	0	0	0	900
23	0	0	103	13	1130
TOTAL:	6000	18500	6710	839	123781
				GRAND TOTAL:	155830

Table G-17. G2 – LOX/LH_2 with Terrestrial Hydrogen

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Mass (kg/cy)
1	6000	18500	227	20808
2	0	0	45	7641
3	0	0	57	8321
4	0	0	45	8091
5	0	0	45	7641
6	0	0	57	8321
7	0	0	0	450
8	0	0	45	8091
9	0	0	57	8321
10	0	0	0	450
11	0	0	45	8091
12	0	0	13	1130
13	0	0	45	7641
14	0	0	0	450
15	0	0	45	8091
16	0	0	0	450
17	0	0	57	8321
18	0	0	0	900
19	0	0	0	450
20	0	0	45	7641
21	0	0	0	450
22	0	0	0	900
23	0	0	13	1130
TOTAL:	6000	18500	839	123781
			GRAND TOTAL:	149120

Table G-18. G3 – LOX/LH_2 with ISRU Hydrogen

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Mass (kg/cy)
1	17528	18500	0	20808
2	0	0	0	7641
3	0	0	0	8321
4	0	0	0	8091
5	0	0	0	7641
6	0	0	0	8321
7	0	0	0	450
8	0	0	0	8091
9	0	0	0	8321
10	0	0	0	450
11	0	0	0	8091
12	0	0	0	1130
13	0	0	0	7641
14	0	0	0	450
15	0	0	0	8091
16	0	0	0	450
17	0	0	0	8321
18	0	0	0	900
19	0	0	0	450
20	0	0	0	7641
21	0	0	0	450
22	0	0	0	900
23	0	0	0	1130
TOTAL:	17528	18500	0	123781
			GRAND TOTAL:	159810

Table G-19. G4 – LOX/CO

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Mass (kg/cy)
1	6000	18500	0	22775
2	0	0	0	8004
3	0	0	0	8789
4	0	0	0	8454
5	0	0	0	8004
6	0	0	0	8789
7	0	0	0	450
8	0	0	0	8454
9	0	0	0	8789
10	0	0	0	450
11	0	0	0	8454
12	0	0	0	1235
13	0	0	0	8004
14	0	0	0	450
15	0	0	0	8454
16	0	0	0	450
17	0	0	0	8789
18	0	0	0	900
19	0	0	0	450
20	0	0	0	8004
21	0	0	0	450
22	0	0	0	900
23	0	0	0	1235
TOTAL:	6000	18500	0	130735
			GRAND TOTAL:	155235

Table G-20. G5 – LOX/CH_4 with Terrestrial Hydrogen

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Mass (kg/cy)
1	6000	18500	139	21187
2	0	0	27	7732
3	0	0	35	8412
4	0	0	27	8182
5	0	0	27	7732
6	0	0	35	8412
7	0	0	0	450
8	0	0	27	8182
9	0	0	35	8412
10	0	0	0	450
11	0	0	27	8182
12	0	0	7	1130
13	0	0	27	7732
14	0	0	0	450
15	0	0	27	8182
16	0	0	0	450
17	0	0	35	8412
18	0	0	0	900
19	0	0	0	450
20	0	0	27	7732
21	0	0	0	450
22	0	0	0	900
23	0	0	7	1130
TOTAL:	6000	18500	512	125253
			GRAND TOTAL:	150265

Table G-21. G6 – LOX/CH_4 with ISRU Hydrogen

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Mass (kg/cy)
1	15607	18500	0	21187
2	0	0	0	7732
3	0	0	0	8412
4	0	0	0	8182
5	0	0	0	7732
6	0	0	0	8412
7	0	0	0	450
8	0	0	0	8182
9	0	0	0	8412
10	0	0	0	450
11	0	0	0	8182
12	0	0	0	1130
13	0	0	0	7732
14	0	0	0	450
15	0	0	0	8182
16	0	0	0	450
17	0	0	0	8412
18	0	0	0	900
19	0	0	0	450
20	0	0	0	7732
21	0	0	0	450
22	0	0	0	900
23	0	0	0	1130
TOTAL:	15607	18500	0	125253
			GRAND TOTAL:	159360

Table G-22. G7 – LOX/C_2H_5OH with Terrestrial Hydrogen

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Mass (kg/cy)
1	6000	18500	97	21947
2	0	0	19	7875
3	0	0	24	8592
4	0	0	19	8325
5	0	0	19	7875
6	0	0	24	8592
7	0	0	0	450
8	0	0	19	8325
9	0	0	24	8592
10	0	0	0	450
11	0	0	19	8325
12	0	0	5	1167
13	0	0	19	7875
14	0	0	0	450
15	0	0	19	8325
16	0	0	0	450
17	0	0	24	8592
18	0	0	0	900
19	0	0	0	450
20	0	0	19	7875
21	0	0	0	450
22	0	0	0	900
23	0	0	5	1167
TOTAL:	6000	18500	352	127948
			GRAND TOTAL:	152799

Table G-23. G8 – LOX/C_2H_5OH with ISRU Hydrogen

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Mass (kg/cy)
1	10804	18500	0	21947
2	0	0	0	7875
3	0	0	0	8592
4	0	0	0	8325
5	0	0	0	7875
6	0	0	0	8592
7	0	0	0	450
8	0	0	0	8325
9	0	0	0	8592
10	0	0	0	450
11	0	0	0	8325
12	0	0	0	1167
13	0	0	0	7875
14	0	0	0	450
15	0	0	0	8325
16	0	0	0	450
17	0	0	0	8592
18	0	0	0	900
19	0	0	0	450
20	0	0	0	7875
21	0	0	0	450
22	0	0	0	900
23	0	0	0	1167
TOTAL:	10804	18500	0	127948
			GRAND TOTAL:	157251

G.2 Propellant Requirements for 10,000-Person Colony Missions

G.2.1 Flight Vehicle Propellant Family Masses

Table G-24. PF 1 - LOX/LH_2 Propellant Shipping Requirements

Cycle	Total Required Hydrogen (kg/cy)	Total Required Oxygen (kg/cy)	Total Propellant Mass (kg/cy)
1	2.43E+07	1.34E+08	1.58E+08
2	2.47E+07	1.36E+08	1.61E+08
3	2.60E+07	1.43E+08	1.69E+08
4	2.74E+07	1.51E+08	1.78E+08
5	2.74E+07	1.51E+08	1.78E+08
6	3.07E+07	1.69E+08	2.00E+08
7	3.23E+07	1.78E+08	2.10E+08
8	3.49E+07	1.92E+08	2.27E+08
9	3.75E+07	2.06E+08	2.44E+08
10	3.82E+07	2.10E+08	2.48E+08
11	3.82E+07	2.10E+08	2.48E+08
12	4.17E+07	2.29E+08	2.71E+08
13	4.25E+07	2.34E+08	2.76E+08
14	4.31E+07	2.37E+08	2.80E+08
15	4.82E+07	2.65E+08	3.13E+08
16	4.90E+07	2.69E+08	3.18E+08
17	4.99E+07	2.74E+08	3.24E+08
18	5.25E+07	2.88E+08	3.41E+08
19	5.32E+07	2.92E+08	3.46E+08
20	5.38E+07	2.96E+08	3.50E+08
21	5.58E+07	3.07E+08	3.63E+08
22	5.97E+07	3.28E+08	3.88E+08
23	6.19E+07	3.41E+08	4.02E+08
TOTAL:	**9.53E+08**	**5.24E+09**	**6.19E+09**

Table G-25. PF 1 - SOX/LH_2 Propellant Shipping Requirements

Cycle	Total Required Hydrogen (kg/cy)	Total Required Oxygen (kg/cy)	Total Propellant Mass (kg/cy)
1	1.80E+05	9.92E+05	1.17E+06
2	8.43E+04	4.64E+05	5.48E+05
3	9.04E+04	4.97E+05	5.87E+05
4	1.34E+05	7.35E+05	8.68E+05
5	1.40E+05	7.68E+05	9.08E+05
6	8.85E+05	4.87E+06	5.75E+06
7	8.93E+05	4.91E+06	5.80E+06
8	8.90E+05	4.90E+06	5.79E+06
9	9.65E+05	5.31E+06	6.27E+06
10	9.65E+05	5.31E+06	6.27E+06
11	9.79E+05	5.39E+06	6.36E+06
12	9.78E+05	5.38E+06	6.36E+06
13	1.01E+06	5.55E+06	6.56E+06
14	1.02E+06	5.59E+06	6.61E+06
15	1.06E+06	5.82E+06	6.88E+06
16	1.06E+06	5.86E+06	6.92E+06
17	1.10E+06	6.03E+06	7.12E+06
18	1.10E+06	6.07E+06	7.17E+06
19	1.11E+06	6.11E+06	7.22E+06
20	1.15E+06	6.33E+06	7.48E+06
21	1.18E+06	6.51E+06	7.69E+06
22	1.19E+06	6.54E+06	7.73E+06
23	1.20E+06	6.58E+06	7.77E+06
TOTAL:	**1.94E+07**	**1.07E+08**	**1.26E+08**

Table G-26. PF 2 - LOX/LH_2 with Terrestrial Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	8234	114863	475
2	38	0	411
3	41	0	441
4	44	0	467
5	45	0	473
6	146	169856	1170
7	147	3802	1186
8	163	30915	1313
9	179	32158	1445
10	161	0	1323
11	169	0	1380
12	173	0	1433
13	178	5142	1468
14	179	2614	1479
15	219	75938	1790
16	189	0	1592
17	194	0	1627
18	218	4394	1810
19	200	0	1696
20	202	0	1715
21	241	44631	1993
22	222	0	1895
23	225	0	1930
TOTAL:	11807	484314	30513
		GRAND TOTAL (kg):	31009242

Table G-27. PF 2 - SOX/LH_2 with Terrestrial Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	10428	131964	546
2	40	0	437
3	43	0	470
4	46	0	497
5	47	0	503
6	151	165135	1221
7	153	3713	1237
8	175	43093	1414
9	173	2172	1424
10	167	0	1384
11	188	25204	1527
12	179	0	1500
13	184	1424	1534
14	186	2566	1544
15	240	100675	1957
16	196	0	1667
17	201	0	1703
18	238	4950	1979
19	208	0	1776
20	210	0	1797
21	263	46344	2169
22	230	0	1987
23	233	0	2024
TOTAL:	14180	527239	32296
		GRAND TOTAL (kg):	32837481

Table G-28. PF 3 - LOX/LH_2 with ISRU Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	952865	557175	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	705978	407160	0
7	24904	14571	0
8	135645	79480	0
9	143842	84343	0
10	0	0	0
11	0	0	0
12	113264	67306	0
13	0	0	0
14	5528	3464	0
15	428779	248875	0
16	0	0	0
17	0	0	0
18	0	0	0
19	0	0	0
20	0	0	0
21	189251	113162	0
22	0	1000	0
23	32559	21938	0
TOTAL:	2732614	1598474	0
		GRAND TOTAL (kg):	4331088

Table G-29. PF 3 - SOX/LH_2 with ISRU Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	1001892	591952	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	800650	467042	0
7	0	0	0
8	101216	60887	0
9	219977	129315	0
10	0	0	0
11	0	0	0
12	52244	32788	0
13	0	0	0
14	3419	2240	0
15	655194	382734	0
16	0	0	0
17	0	0	0
18	0	0	0
19	0	0	0
20	0	0	0
21	0	0	0
22	47276	35228	0
23	0	495	0
TOTAL:	2881869	1702682	0
		GRAND TOTAL (kg):	4584551

Table G-30. PF 6 - LOX/CO

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	8613	35173	0
2	270	0	0
3	293	0	0
4	316	0	0
5	325	0	0
6	9702	89346	0
7	1532	1269	0
8	1550	1438	0
9	1651	8322	0
10	1649	0	0
11	1675	1931	0
12	1699	1969	0
13	1757	4812	0
14	1771	1106	0
15	1833	5065	0
16	1844	912	0
17	1903	4841	0
18	1941	3120	0
19	1954	1124	0
20	1971	1350	0
21	2050	6479	0
22	2091	3414	0
23	2115	1980	0
TOTAL:	50504	173652	0
		GRAND TOTAL (kg):	224179

Table G-31. PF 9 - LOX/LC_2H_4 with Terrestrial Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	25525	88627	159
2	945	0	119
3	2119	0	129
4	1100	0	137
5	1126	0	139
6	34784	143239	375
7	4258	2527	380
8	5440	6393	394
9	17821	49247	470
10	4647	0	425
11	4713	0	429
12	5920	0	447
13	4974	0	458
14	6105	0	461
15	9156	37588	541
16	5292	0	498
17	5442	0	510
18	6680	0	529
19	5625	0	532
20	5681	0	538
21	19086	37819	607
22	6077	0	584
23	8763	5840	626
TOTAL:	191280	371281	9488
		GRAND TOTAL (kg):	10050466

Table G-32. PF 9 - LOX/SC_2H_4 with Terrestrial Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	25609	94138	169
2	1008	0	128
3	1095	0	139
4	1173	0	147
5	2292	0	149
6	36280	160497	410
7	4450	0	399
8	5640	0	415
9	18057	49988	494
10	4862	0	447
11	4928	0	452
12	6144	0	471
13	5204	0	482
14	6335	0	486
15	10732	50945	586
16	5541	0	525
17	5694	0	537
18	6942	0	558
19	5889	0	561
20	7040	0	568
21	19599	39805	655
22	6579	0	632
23	7766	0	644
TOTAL:	198860	395373	10053
		GRAND TOTAL (kg):	10647659

Table G-33. PF 10 - LOX/LC$_2$H$_4$ with ISRU Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	277072	210168	0
2	945	0	0
3	2119	0	0
4	1100	0	0
5	1126	0	0
6	378956	309534	0
7	4052	0	0
8	9267	2476	0
9	130402	106020	0
10	4441	0	0
11	4507	0	0
12	5714	0	0
13	5861	0	0
14	4807	0	0
15	130114	92177	0
16	5086	0	0
17	6328	0	0
18	5382	0	0
19	5420	0	0
20	6568	0	0
21	89283	66348	0
22	5871	0	0
23	11821	2304	0
TOTAL:	1096242	789026	0
		GRAND TOTAL (kg):	1885269

Table G-34. PF 10 - LOX/SC$_2$H$_4$ with ISRU Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	293183	223422	0
2	1008	0	0
3	1095	0	0
4	1173	0	0
5	2292	0	0
6	367354	299658	0
7	11470	6195	0
8	29732	18662	0
9	170362	135499	0
10	4648	0	0
11	4715	0	0
12	5930	0	0
13	4990	0	0
14	6121	0	0
15	157082	121130	0
16	5327	0	0
17	6573	0	0
18	5636	0	0
19	5676	0	0
20	6826	0	0
21	78954	47150	0
22	6152	0	0
23	7338	0	0
TOTAL:	1183639	851717	0
		GRAND TOTAL (kg):	2035356

Table G-35. PF 11 - LOX/LCH$_4$ with Terrestrial Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	17248	55190	188
2	183	0	129
3	199	0	140
4	1307	0	150
5	221	0	152
6	20632	91787	484
7	2071	1703	490
8	993	3685	504
9	4385	17653	562
10	1057	0	540
11	2216	2255	569
12	2235	4674	586
13	2271	5017	602
14	1137	0	585
15	4560	17916	664
16	1240	0	645
17	2368	0	662
18	10580	4994	682
19	1312	1370	686
20	1324	2075	693
21	2467	8312	721
22	2497	6451	745
23	2514	3425	757
TOTAL:	85019	226506	11937
		GRAND TOTAL (kg):	12248413

Table G-36. PF 11 - LOX/SCH$_4$ with Terrestrial Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	18355	58227	197
2	192	0	135
3	1301	0	147
4	225	0	157
5	231	0	160
6	22862	97062	507
7	1025	1749	513
8	2185	11186	550
9	4491	18661	611
10	1107	0	566
11	3362	0	596
12	1197	24	614
13	2327	5260	631
14	1191	0	612
15	13898	18971	695
16	1298	0	676
17	1336	0	693
18	2457	5211	714
19	1374	1419	719
20	2478	2191	726
21	2531	8778	756
22	2562	6831	780
23	1488	3603	793
TOTAL:	89470	239173	12547
		GRAND TOTAL (kg):	12875825

Table G-37. PF 12 - LOX/LCH$_4$ with ISRU Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	315392	199245	0
2	183	0	0
3	199	0	0
4	1307	0	0
5	221	0	0
6	455100	295402	0
7	9978	6076	0
8	23703	14154	0
9	96822	62340	0
10	1007	0	0
11	14843	7852	0
12	1042	0	0
13	20309	11595	0
14	7951	4642	0
15	130421	83760	0
16	1139	0	0
17	2268	0	0
18	1202	0	0
19	2762	749	0
20	13690	7075	0
21	90762	53376	0
22	3413	1019	0
23	20515	12289	0
TOTAL:	1214231	759575	0
		GRAND TOTAL (kg):	1973806

Table G-38. PF 12 - LOX/SCH$_4$ with ISRU Hydrogen

Cycle	Total Production Plant Mass (kg/cy)	Total Power System Mass (kg/cy)	Total Hydrogen Mass Required (tonnes/cy)
1	330476	209035	0
2	192	0	0
3	1301	0	0
4	225	0	0
5	231	0	0
6	477081	310348	0
7	10177	6197	0
8	62483	39819	0
9	63965	40716	0
10	1054	0	0
11	1071	0	0
12	5359	2086	0
13	28718	18063	0
14	9285	4785	0
15	135838	88282	0
16	1192	0	0
17	2323	0	0
18	2351	0	0
19	2469	580	0
20	13208	7323	0
21	95727	56084	0
22	3742	1149	0
23	22542	12869	0
TOTAL:	1271011	797335	0
		GRAND TOTAL (kg):	2068346

G.2.2 – Ground Vehicle Propellant Family Masses

Table G-39. G1 – LOX/LH_2 from Earth

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Oxygen Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Mass (kg/cy)
1	6000	18500	2708	338	24973
2	0	0	750	94	37971
3	0	0	1710	214	19677
4	0	0	2248	281	17101
5	0	0	2248	281	17101
6	0	0	3339	417	37106
7	0	0	4393	549	33522
8	0	0	3443	430	37787
9	0	0	5484	685	53527
10	0	0	5391	674	38818
11	0	0	6482	810	58823
12	0	0	6125	766	51632
13	0	0	7376	922	63438
14	0	0	7479	935	64118
15	0	0	8032	1004	86699
16	0	0	9268	1158	73348
17	0	0	9164	1146	72668
18	0	0	9464	1183	88738
19	0	0	9624	1203	80539
20	0	0	11356	1420	98648
21	0	0	11609	1451	105159
22	0	0	11412	1427	89769
23	0	0	12607	1576	110454
TOTAL:	6000	18500	151712	18964	1361615
				GRAND TOTAL:	1556790

Table G-40. G2 – LOX/LH_2 with Terrestrial Hydrogen

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Mass (kg/cy)
1	12000	18500	6975	24973
2	0	0	1383	37971
3	0	0	1212	19677
4	0	0	1189	17101
5	0	0	1430	17101
6	0	0	1144	37106
7	0	0	1442	33522
8	0	0	1265	37787
9	0	0	1340	53527
10	0	0	1255	38818
11	0	0	1335	58823
12	0	0	1339	51632
13	0	0	1233	63438
14	0	0	1296	64118
15	0	0	1345	86699
16	0	0	1232	73348
17	0	0	1217	72668
18	0	0	1290	88738
19	0	0	1246	80539
20	0	0	1334	98648
21	0	0	1289	105159
22	0	0	1340	89769
23	0	0	1231	110454
TOTAL:	12000	18500	35362	1361615
			GRAND TOTAL:	1427477

Table G-41. G3 – LOX/LH_2 with ISRU Hydrogen

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Mass (kg/cy)
1	17528	18500	0	24973
2	0	0	0	37971
3	0	0	0	19677
4	0	0	0	17101
5	0	0	0	17101
6	0	0	0	37106
7	0	0	0	33522
8	0	0	0	37787
9	0	0	0	53527
10	0	0	0	38818
11	0	0	0	58823
12	0	0	0	51632
13	0	0	0	63438
14	0	0	0	64118
15	0	0	0	86699
16	0	0	0	73348
17	0	0	0	72668
18	0	0	0	88738
19	0	0	0	80539
20	0	0	0	98648
21	0	0	0	105159
22	0	0	0	89769
23	0	0	0	110454
TOTAL:	17528.4	18500	0	1361615
			GRAND TOTAL:	1397643

Table G-42. G4 – LOX/CO

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Mass (kg/cy)
1	6000	18500	0	27971
2	0	0	0	38670
3	0	0	0	21539
4	0	0	0	19631
5	0	0	0	19631
6	0	0	0	40835
7	0	0	0	38477
8	0	0	0	41621
9	0	0	0	59681
10	0	0	0	44909
11	0	0	0	66113
12	0	0	0	58559
13	0	0	0	71759
14	0	0	0	72544
15	0	0	0	95656
16	0	0	0	83836
17	0	0	0	83051
18	0	0	0	99394
19	0	0	0	91390
20	0	0	0	111472
21	0	0	0	118240
22	0	0	0	102682
23	0	0	0	124672
TOTAL:	6000	18500	0	1532335
			GRAND TOTAL:	1556835

Table G-43. G5 – LOX/CH_4 with Terrestrial Hydrogen

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Mass (kg/cy)
1	6000	18500	208	25549
2	0	0	57	38142
3	0	0	132	20056
4	0	0	173	17586
5	0	0	173	17586
6	0	0	258	37828
7	0	0	340	34492
8	0	0	265	38509
9	0	0	424	54734
10	0	0	416	39985
11	0	0	500	60227
12	0	0	473	52945
13	0	0	570	65039
14	0	0	577	65719
15	0	0	619	88431
16	0	0	716	75343
17	0	0	708	74663
18	0	0	730	90773
19	0	0	743	82625
20	0	0	876	101078
21	0	0	897	107679
22	0	0	882	92249
23	0	0	973	113172
TOTAL:	6000	18500	11710	1394412
			GRAND TOTAL:	1430622

Table G-44. G6 – LOX/CH_4 with ISRU Hydrogen

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Mass (kg/cy)
1	15607	18500	0	25549
2	0	0	0	38142
3	0	0	0	20056
4	0	0	0	17586
5	0	0	0	17586
6	0	0	0	37828
7	0	0	0	34492
8	0	0	0	38509
9	0	0	0	54734
10	0	0	0	39985
11	0	0	0	60227
12	0	0	0	52945
13	0	0	0	65039
14	0	0	0	65719
15	0	0	0	88431
16	0	0	0	75343
17	0	0	0	74663
18	0	0	0	90773
19	0	0	0	82625
20	0	0	0	101078
21	0	0	0	107679
22	0	0	0	92249
23	0	0	0	113172
TOTAL:	15607	18500	0	1394412
			GRAND TOTAL:	1428519

Table G-45. G7 – LOX/C_2H_5OH with Terrestrial Hydrogen

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Mass (kg/cy)
1	6000	18500	146	26711
2	0	0	38	38415
3	0	0	92	20781
4	0	0	122	18570
5	0	0	122	18570
6	0	0	181	39279
7	0	0	239	36423
8	0	0	186	39995
9	0	0	298	57132
10	0	0	294	42353
11	0	0	353	63062
12	0	0	334	55637
13	0	0	402	68276
14	0	0	407	68993
15	0	0	435	91913
16	0	0	505	79421
17	0	0	500	78704
18	0	0	515	94916
19	0	0	524	86846
20	0	0	618	106061
21	0	0	632	112769
22	0	0	622	97274
23	0	0	686	118700
TOTAL:	6000	18500	8253	1460803
			GRAND TOTAL:	1493555

Table G-46. G8 – LOX/C_2H_5OH with ISRU Hydrogen

Cycle	Processor Mass (kg/cy)	Power Mass (kg/cy)	Hydrogen Mass (kg/cy)	Rover Mass (kg/cy)
1	10803.5	18500	0	26711
2	0	0	0	38415
3	0	0	0	20781
4	0	0	0	18570
5	0	0	0	18570
6	0	0	0	39279
7	0	0	0	36423
8	0	0	0	39995
9	0	0	0	57132
10	0	0	0	42353
11	0	0	0	63062
12	0	0	0	55637
13	0	0	0	68276
14	0	0	0	68993
15	0	0	0	91913
16	0	0	0	79421
17	0	0	0	78704
18	0	0	0	94916
19	0	0	0	86846
20	0	0	0	106061
21	0	0	0	112769
22	0	0	0	97274
23	0	0	0	118700
TOTAL:	10803.5	18500	0	1460803
			GRAND TOTAL:	1490106