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Life Support System Trade Study for SpaceX Mars Mission

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Elon Musk's 2016 SpaceX Interplanetary Transport System (ITS) presentation of an interplanetary spaceship and multiple launch vehicles designed to transport 450 tons of cargo and 100 passengers to Mars excluded specifications for habitation on the surface of Mars and a life support system design. Assumptions for a Life Support System (LSS), Biomass Production System (BPS), In Situ Resource Utilization (ISRU), and Power Supply System (PSS) are presented in this paper. A parametric analysis of an Initial Mass in Low Earth Orbit (IMLEO) for the SpaceX Mars mission including the assumed LSS, BPS, ISRU, and PSS showed LSS and ISRU were very effective in decreasing IMLEO, thus decreasing mission costs. ISRU was the key system in producing propellant needed to return to Earth, eliminating the need to transport it from Earth. In addition, biomass production was vital for long-term missions and large populations of over 100 people. However, as biomass production increased, BPS mass and PSS mass increased, meaning the ratio of BPS mass per kilogram of the biomass production and the ratio of PSS mass per kilowatt must be decreased even when using LSS and ISRU.

Nomenclature

BPS = Biomass Production System
CM = Crewmember
DAV = Descent and Ascent Vehicle
DRM = Design Reference Mission
ER = Electrochemical Reduction
EVA = Extra-Vehicular Activity
G = gear ratio
GSS = Gas Storage System
HAB = Habitat
IMLEO = Initial Mass in Low Earth Orbit
ISRU = In Situ Resource Utilization
ISS = International Space Station
ITS = Interplanetary Transport System
I_{sp} = specific impulse
LED = Light-Emitting Diode
LEO = Low Earth Orbit
LiOH = Lithium hydroxide
LSS = Life Support System
MOI = Mars Orbit Insertion
MP = Methane Pyrolysis
MTV = Mars Transfer Vehicle
NASA = National Aeronautics and Space Administration
PSS = Power Supply System

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RWGS = Reverse Water Gas Shift
SOCE = Solid Oxide CO_2 Electrolysis
TEI = Trans-Earth Injection
TMI = Trans-Mars Injection
WE = Water Electrolysis
d = duration of stay
f_b = BPS mass factor of BPS mass to baseline BPS mass
f_p = PSS mass factor of PSS mass to baseline PSS mass
m = mass of spacecraft
m_0 = initial mass of spacecraft
m_f = final mass of spacecraft
n = number of crewmembers
r_a = ratio of payload mass to entry mass (vehicle mass prior to entry of atmosphere)
r_b = ratio of biomass produced by the BPS to total food consumption mass
r_c = ratio of crew oxygen and water produced by ISRU to crew consumption
r_l = ratio of LSS recycled mass to crew consumption mass
r_p = ratio of propellant produced by ISRU to total propellant consumption
Δv = delta velocity

I. Introduction

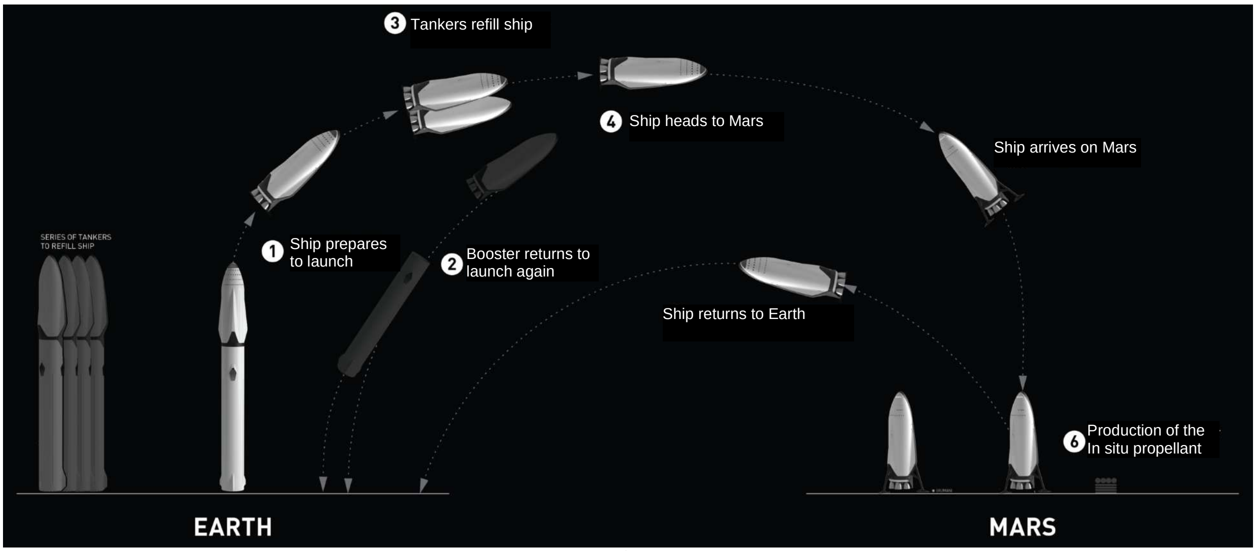
In September 2016, Elon Musk's SpaceX presented their Interplanetary Transport System (ITS) consisting of an interplanetary spaceship and multiple launch vehicles.[1] The spaceship measured 49.5 m in length, 17 m in diameter at its widest point, and 12 m in width for its hull. The launch vehicle consisted of 550 tons of expendable payload in low Earth orbit (LEO) and a fully reusable payload in LEO. With a propellant refill in Earth orbit before the interplanetary journey, ITS was designed to be capable of transporting 450 tons of cargo and 100 passengers to Mars. The size of the spaceship is considerably larger than any spaceship proposed before.[2, 3] The journey was designed to require 80 to 150 days depending on the launch date, which will occur during one of nine synodic periods between 2020 and 2037. The trip time is based on a trans-Mars injection (TMI) delta velocity of 6 km/s and a Mars entry velocity of 8.5 km/s. The average length of a trip to Mars is approximately 115 days. Although the design of the transport system was well covered, the presentation did not mention the surface habitat of Mars and a life support system.[1] Both are very important systems for long-term habitation on Mars. The spaceship lands on Mars and is to be used as the Mars surface habitat in the early stages of the mission. The Life Support System (LSS), Biomass Production System (BPS), In Situ Resource Utilization (ISRU), and Power Supply System (PSS) will be expanded as the population on Mars increases.

A LSS consists of air, food, thermal, waste, and water subsystems. The subsystems are complex and highly interactive when recycling rates are maximized. Crew size and mission duration have the largest impact on designing the size and configuration of a LSS.[4] In addition to those two parameters, mission location, which is usually described by the distance or the delta velocity from Earth, is the primary factor for a trade study. In particular, ISRU is the key system for long-term habitation on the surface of Mars.[5, 6] ISRU is necessary for collecting water in the soil and carbon dioxide from the atmosphere, and for producing oxygen from carbon dioxide. Although ISRU technology is immature, it is possible to decrease the initial mass in LEO (IMLEO) by producing oxygen, methane, and water from carbon dioxide in the atmosphere and water in soil. As ISRU also interacts with LSS, BPS, and PSS, the design and operation of those systems should be considered as a whole system. Therefore, a parametric analysis measured the impact that LSS has on cost by changing carbon dioxide and water recycling ratios, the impact that ISRU has on oxygen and water production ratios, and the impact that BPS has on biomass production ratio. The development cost of the LSS and ISRU, which may be very high, were not included in the IMLEO calculations for this paper. The focus of this research was on the launch cost by doing a sensitivity analysis on IMLEO including supply cost.

This paper presents trade studies for a Mars mission plan, including Mars surface habitat, LSS, BPS, ISRU, and PSS, adapting Musk's ambitious SpaceX Mars journey by using a mission mass analysis tool.

II. SpaceX Mars Architecture

Figure 1 shows the SpaceX Mars architecture presented in September 2016.[1] The mission architecture consists of seven steps: 1) the ship prepares to launch, 2) the booster returns to Earth to launch again, 3) the tankers refill ship, 4) the ship heads to Mars, 5) the ship arrives on Mars, 6) the production of the in situ propellant, and 7) the ship returns to Earth. A new launch vehicle, with an expendable LEO payload of 550 metric tons, is being developed that can be reused and refilled to decrease the mission's transportation costs. The spaceship is supported by a main booster rocket and some tanker rockets for refilling the fuel. The amount of propellant needed to return to Earth from Mars is approximately five times greater than the amount required for the ship to depart from Earth.[1] Hydrogen, which is the most common propellant for rockets today will not be used; instead, methane will be used. Methane can be produced from the atmosphere and water on Mars. It may drastically decrease the total transportation cost. The new interplanetary spaceship has a ship dry mass of 150 tons and a tanker dry mass of 90 tons, which can carry 450 tons to Mars. The spaceship enters the atmosphere of Mars either by being captured in an orbit or by proceeding directly from interplanetary space. The spaceship will have a propellant plant to use on Mars so it can secure unlimited carbon dioxide and water to produce resources, such as oxygen and methane. This strategy is the main idea for decreasing the costs of the SpaceX Mars mission, as well as reusing the vehicle, refilling in orbit, and using methane as the propellant.



1 Ship prepares to launch, 2 Booster returns to launch again, 3 Tankers refill ship, 4 Ship heads to Mars, 5 Ship arrives on Mars, 6 production of the In situ propellant, and 7 Ship returns to Earth.

Figure 1. SpaceX Mars architecture.[1]

III. Parametric Analysis Tool

A. Mission Concept Model

Figure 2 shows the general mission concept model in this paper used as a parametric analysis tool. It can be applied to a mission consisting of three phases using a separate vehicle for each phase: 1) interplanetary outbound and inbound transits, 2) descent and ascent, and 3) habitation on the surface of Mars. Moreover, a Mars transfer vehicle (MTV) for interplanetary outbound and inbound transits, a descent and ascent vehicle (DAV), and a habitat (HAB) on the surface of Mars are defined. To evaluate the cost, the tool can calculate the IMLEO. The IMLEO is calculated based on the designed system mass on the surface of Mars and the payload mass to be returned to Earth multiplied by the specific gear ratios,[7] as shown in the next section. The delta velocity based on the trajectory derived from interplanetary propulsion affects the gear ratio. Additionally, IMLEO is impacted by the cargo deployment method, the Mars capture method, the LSS method, the BPS method, the PSS method, the ISRU method, and the Mars ascent propellant that are used. In the SpaceX Mars mission, all three phases are conducted using the same, single spaceship.

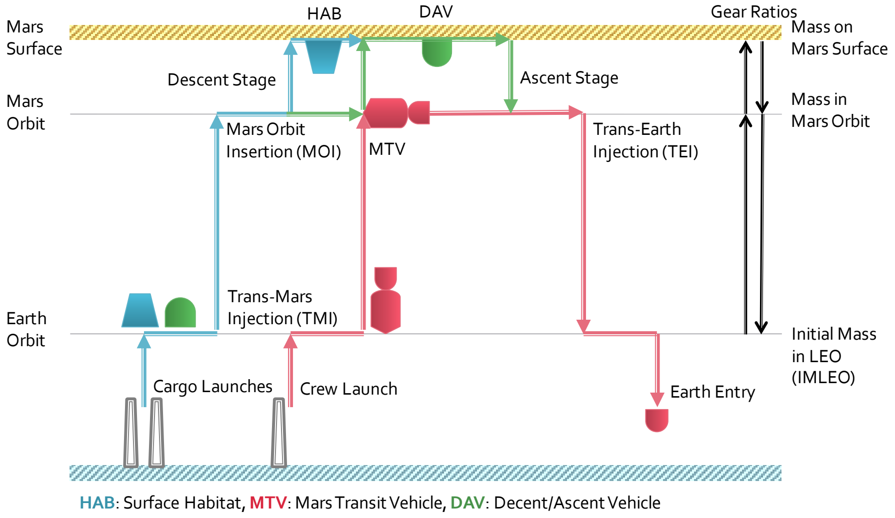


Figure 2. General mission concept and components of parametric analysis tool.

B. IMLEO Analysis using Gear Ratio

One of the first and most important requirements in planning space missions is making a preliminary estimate of IMLEO.[2-4] IMLEO depends on hardware mass, resupply mass, propulsion, and delta velocity (Δv). The delta velocity is derived using the insertion method from one location to another location. The gear ratio has been defined as the propulsive mass fraction, or m_f/m_0 (ratio of the final mass after maneuver to the initial mass).[7] Gear ratios can reveal how the mission architecture affects the mission costs, and it can provide reasons to consider innovative approaches to the mission architecture that will reduce the mission costs. An example of two different technologies performing the same function that can be strongly affected by gear ratios was shown in previous research.[8]

The method used to calculate the gear ratio is described as follows:

Step 1: Calculate the gear ratio, G_i, from i-1 to i.

$$G_i = m_{i\text{-}1} / m_i = 1 / \exp(- \Delta v_i / (g\, I_{sp})) \quad (1)$$

m_i = mass at location i

Δv_i = delta velocity from location i-1 to i

g = acceleration of gravity

I_{sp} = specific impulse

Step 2: Calculate mass at location i-1

$$m_{i\text{-}1} = G_i\, m_i \quad (2)$$

Similarly, the final mass m_f for a mission with *ith* boosters is:

$$m_0 = \Pi\, G_i\, m_f \quad (3)$$

Some cases are more complex. Some boosters may not be carried and used in a serial fashion. For instance, the return booster from the Mars orbit to the Earth orbit may be left in the Mars orbit while the astronauts take a separate smaller spacecraft down to the Martian surface.[8]

The gear ratios derived from the delta velocity, the propellant, and I_{sp} for the SpaceX Mars mission are shown in Table 1. The TMI delta velocity 6,000 m/s is assumed to be larger than that of the National Aeronautics and Space Administration (NASA) Design Reference Mission (DRM).[2]

Table 1. Delta velocity and gear ratio for Mars mission.

Mission Segment	Delta velocity, m/s	Propellant	I_{sp}	$G(m_o/m_f)$, kg/kg
1. Trans-Mars injection (TMI)	6,000 [1]	LOX/LCH4	382	4.97
2. Mars orbit insertion (MOI) propulsive	1,934 [3]	LOX/LCH4	382	1.68
3. Mars orbit insertion (MOI) aerocapture	260 [3]	LOX/LCH4	382	1.07
4. Mars de-orbit, landing, and touchdown	615 [3]	LOX/LCH4	382	1.18
5. Mars ascent to orbit	5,625 [3]	LOX/LCH4	382	4.49
6. Trans-Earth injection (TEI)	1,588 [3]	LOX/LCH4	382	1.53
7. LEO insertion (propulsive), deorbit, entry, and landing	6,813 [3]	LOX/LCH4	382	6.17
8. LEO insertion (aerocapture), deorbit, entry, and landing	0 [3]	LOX/LCH4	382	1.00

LOX: Liquid oxygen, LH2: Liquid hydrogen, LCH4: liquid methane

C. Mass Analysis Model

The HAB, MTV, and DAV models are shown in Figure 2. In the previous mass analysis model, the HAB does not ascend from Mars and return to Earth after the Mars landing. The MTV does not land on the surface of Mars after entering the Mars orbit; it stays in orbit until the crew leaves Mars. The DAV is used for descending from the Mars orbit to the planet's surface and for ascending from its surface back to its orbit. In the SpaceX Mars architecture, the interplanetary spaceship lands on the surface of Mars, and it is used for descending from the Mars orbit to its surface and for ascending from its surface back to its orbit. Therefore, the DAV model has the same payload mass as the MTV model. The IMLEOs for HAB, MTV, and DAV are described using a gear ratio as follows:

1. *IMLEO for HAB*

The HAB mass on the surface of Mars (m_{HABonMS}) consists of the HAB payload to the surface of Mars ($payload_{\mathrm{HAB}}$), the LSS mass (m_{LSSinHAB}), the BPS mass (m_{BPSinHAB}), the ISRU mass ($m_{\mathrm{ISRUinHAB}}$), and the PSS mass (m_{PSSinHAB}). It also consists of the consumable mass ($m_{\mathrm{consumableinHAB}}$) and the crew supply mass ($m_{\mathrm{crewsupplyinHAB}}$), minus the recycled mass ($m_{\mathrm{recycledinHAB}}$) multiplied by the number of crewmembers (n_{crew}) and the duration of stay in the HAB (d_{inHAB}).

$$\begin{aligned} m_{\mathrm{HABonMS}} = {} & payload_{\mathrm{HAB}} + m_{\mathrm{LSSinHAB}} + m_{\mathrm{BPSinHAB}} + m_{\mathrm{ISRUinHAB}} + m_{\mathrm{PSSinHAB}} \\ & + (m_{\mathrm{consumableinHAB}} + m_{\mathrm{crewsupplyinHAB}} - m_{\mathrm{recycledinHAB}})\, n_{\mathrm{crew}}\, d_{\mathrm{inHAB}} \end{aligned} \tag{4}$$

The LSS, ISRU, BPS, and PSS mass models are described as follows:

$$m_{\mathrm{LSSinHAB}} = m_{\mathrm{LSSinHABbaseline}}\, r_{\mathrm{l}} \tag{5}$$
$$m_{\mathrm{ISRUinHAB}} = m_{\mathrm{ISRUCbaseline}}\, r_{\mathrm{c}} + m_{\mathrm{ISRUPbaseline}}\, r_{\mathrm{p}} \tag{6}$$
$$m_{\mathrm{BPSinHAB}} = m_{\mathrm{BPSinHABbaseline}}\, r_{\mathrm{b}}\, f_{\mathrm{b}} \tag{7}$$
$$m_{\mathrm{PSSinHAB}} = (m_{\mathrm{PSSinHABbaseline}} + m_{\mathrm{PSSforLSS}}\, r_{\mathrm{l}} + m_{\mathrm{PSSforISRUO2}}\, r_{\mathrm{c}} + m_{\mathrm{PSSforISRUCH4}}\, r_{\mathrm{p}} + m_{\mathrm{PSSforBPS}}\, r_{\mathrm{b}})\, f_{\mathrm{p}} \tag{8}$$

The LSS mass (m_{LSSinHAB}) consists of the baseline LSS mass ($m_{\mathrm{LSSinHABbaseline}}$) multiplied by the ratio of the LSS recycled mass to the crew consumption mass (r_{l}). The ISRU mass consists of the ISRU for crew and propellant. The baseline mass of ISRU for crew ($m_{\mathrm{ISRUCbaseline}}$) is multiplied by the ratio of the oxygen and water produced by ISRU to the total oxygen and water consumption (r_{c}). The baseline mass of ISRU for propellant ($m_{\mathrm{ISRUPbaseline}}$) is multiplied by the ratio of the oxygen and methane produced by ISRU to the total oxygen and methane consumption (r_{p}). The BPS mass (m_{BPSinHAB}) consists of the baseline BPS mass ($m_{\mathrm{BPSinHABbaseline}}$) multiplied by the biomass production ratio of the BPS to the total food consumed by the crew (r_{b}) and the BPS mass factor of the BPS mass to the baseline BPS mass (f_{b}). The PSS mass (m_{PSSinHAB}) is the sum of the baseline PSS mass ($m_{\mathrm{PSSinHABbaseline}}$) and additional PSS masses for LSS ($m_{\mathrm{PSSforLSS}}$) multiplied by r_{l}, ISRU ($m_{\mathrm{PSSforISRUC}}$) multiplied by r_{c}, ISRU ($m_{\mathrm{PSSforISRUP}}$) multiplied by r_{p}, and BPS ($m_{\mathrm{PSSforBPS}}$) multiplied by r_{b} and then multiplied by the PSS mass factor of the PSS mass to the baseline PSS mass (f_{p}). Because it is difficult to clarify all aspects of BPS and PSS, which are developing technologies, the BPS mass factor and the PSS mass factor were introduced to describe the uncertainty in this mass estimation model. The factors were used to conduct a parametric sensitivity analysis of the degree of influence on IMLEO.

The LSS recycled mass model is described as follows:

$$m_{\mathrm{recycledinHAB}} = m_{\mathrm{H2Ocrew}}\, r_{\mathrm{l}} + m_{\mathrm{O2crew}}\, r_{\mathrm{l}} + m_{\mathrm{biomass}}\, r_{\mathrm{b}} \tag{9}$$

The LSS recycled mass ($m_{\mathrm{recycledinHAB}}$) consists of the crew use water (m_{H2Ocrew}) multiplied by ratio r_{l}, the crew oxygen (m_{O2crew}) multiplied by ratio r_{l}, and the biomass (m_{biomass}) multiplied by ratio r_{b}.

The HAB mass in the Mars orbit from the interplanetary outbound transit (m_{HABinMO}) is the HAB mass on the surface of Mars (m_{HABonMS}) multiplied by the gear ratio of the descent (G_{descent}) and divided by the ratio of the payload mass to the entry mass (the vehicle mass prior to entry into the atmosphere) (r_{a}). The ratio is less than 1 for aerocapture and the ratio is 1 for propulsive capture.

$$m_{\mathrm{HABinMO}} = m_{\mathrm{HABonMS}}\, G_{\mathrm{descent}} / r_{\mathrm{a}} \tag{10}$$

r_a aerocapture: <1
propulsive capture: 1

The HAB initial mass in LEO ($m_{HABIMLEO}$) is the HAB mass in the Mars orbit ($m_{HABinMO}$) multiplied by the gear ratios of the Mars orbit insertion (MOI) and the TMI (G_{MOI} and G_{TMI}).

$$m_{HABIMLEO} = m_{HABinMO}\, G_{MOI}\, G_{TMI} \tag{11}$$

2. IMLEO for MTV

The MTV mass in LEO ($m_{MTVinLEO}$) consists of the MTV payload returned to LEO ($payload_{MTV}$) and the LSS mass ($m_{LSSinMTV}$), as well as the consumable mass ($m_{consumableinMTV}$) and the crew supply mass ($m_{crewsupplyinMTV}$) minus the recycled mass ($m_{recycledinMTV}$) in the MTV multiplied by the number of crewmembers (n_{crew}) and the duration of stay in the MTV (d_{inMTV}).

$$m_{MTVinLEO} = payload_{MTV} + m_{LSSinMTV} + (m_{consumableinMTV} + m_{crewsupplyinMTV} - m_{recycledinMTV})\, n_{crew}\, d_{inMTV} \tag{12}$$

The LSS mass and the LSS recycled mass are described as follows:

$$m_{LSSinMTV} = m_{LSSinMTVbaseline}\, r_l \tag{13}$$
$$m_{recycledinMTV} = m_{H2Ocrew}\, r_l + m_{O2crew}\, r_l \tag{14}$$

The MTV mass in the Mars orbit ($m_{MTVinMO}$) is the MTV mass in LEO ($m_{MTVinLEO}$) multiplied by the gear ratio of the trans-Earth injection (TEI) (G_{TEI}).

$$m_{MTVinMO} = m_{MTVinLEO}\, G_{TEI} \tag{15}$$

The MTV initial mass in LEO ($m_{MTVIMLEO}$) is the MTV mass in the Mars orbit ($m_{MTVinMO}$) multiplied by the gear ratios of the MOI and the TMI (G_{MOI} and G_{TMI}). If the MTV does not return to Earth, $m_{MTVinMO}$ becomes the final mass.

$$m_{MTVIMLEO} = m_{MTVinMO}\, G_{MOI}\, G_{TMI} \tag{16}$$

3. IMLEO for DAV

The DAV mass in the Mars orbit for the interplanetary inbound transit ($m_{DAVinMOin}$) consists of the DAV payload from the surface of Mars ($payload_{DAV}$), plus the consumable mass ($m_{consumableinDAV}$) and the crew supply mass ($m_{crewsupplyinDAV}$) in the DAV multiplied by the number of crewmembers (n_{crew}) and the duration of stay in the DAV (d_{inDAV}).

$$m_{DAVinMOin} = payload_{DAV} + (m_{consumableinDAV} + m_{crewsupplyinDAV})\, n_{crew}\, d_{inDAV} \tag{17}$$
$$m_{DAVonMS} = \begin{cases} m_{DAVinMOin}\, G_{ascent} & \text{(no ISRU)} \\ m_{DAVinMOin} & \text{(ISRU)} \end{cases} \tag{18}$$

The DAV mass on the surface of Mars ($m_{DAVonMS}$) is the DAV mass in the Mars orbit ($m_{DAVinMO}$) multiplied by the gear ratio of the ascent (G_{ascent}) without ISRU. The DAV mass in the Mars orbit equals the DAV mass on the surface of Mars with ISRU, because ISRU produces the ascent propellant.

The DAV mass in the Mars orbit from the interplanetary outbound transit ($m_{DAVinMOout}$) is the DAV mass on the surface of Mars ($m_{DAVonMS}$) multiplied by the gear ratio of the descent ($G_{descent}$) and divided by the ratio of the payload mass to the entry mass (r_a).

$$m_{DAVinMOout} = m_{DAVonMS}\, G_{descent} / r_a \tag{19}$$

r_a aerocapture: <1
propulsive capture: 1

The DAV initial mass in LEO ($m_{DAVIMLEO}$) is the DAV mass in the Mars orbit ($m_{DAVinMOout}$) multiplied by the MOI and TMI gear ratios (G_{MOI} and G_{TMI}).

$$m_{\mathrm{DAVIMLEO}} = m_{\mathrm{DAVinMOout}}\, G_{\mathrm{MOI}}\, G_{\mathrm{TMI}} \tag{20}$$

D. LSS Technology Options

A LSS consists of air, food, thermal, waste, and water subsystems. The subsystems are complex and highly interactive when recycling rates are maximized. A LSS can be either a storage LSS or a recycling LSS depending on the recycling ratio (0 to 1); for example the recycling ratio for a storage LSS (no recycling) is 0; and the ratio for the recycling LSS ranges from 0 to 1. The requirements of the LSS subsystems are estimated by the crew input and output, and the crew supply, as shown in Table 2 and Table 3, respectively.

The size of the crew consumable mass for a LSS operation is estimated by the crew input and output, and the crew supply, as shown in Table 2 and Table 3, respectively.[11] The input and output of each crewmember is defined as 5.01 kg/CM-day and 6.57 kg/CM-day, respectively. The logistics for the crew's daily life needs in the International Space Station (ISS) is defined as 6.35 kg/CM-day, as shown in Table 3. This is estimated using current operation data of the ISS. [12-14] The final crew supply in transit and on Mars is 4.53 kg/CM-day and 3.92 kg/CM-day, respectively. It is assumed that some minimal activities are performed in transit and self-sustaining activities are performed on Mars.

Table 2. Crewmember input and output.

Input	kg/CM-day	Output	kg/CM-day
Oxygen	0.84	Carbon dioxide	1.00
Drinking and food preparation water	2.38	Respiration and perspiration condensate	2.28
Urine flush water	0.5	Used urine flush water	2.00
Wash water	1.29	Used wash water	1.29
Total supplies	5.01	Total output	6.57

Table 3. Crew supply.

Crew supply	ISS, kg/CM-day	In transit, kg/CM-day	On Mars, kg/CM-day
Food	2.51	2.30	2.30
Crew supply	1.19	0.95	0.95
Maintenance	2.56	1.28	0.64
EVA support	0.09	0	0.03
Total	6.35	4.53	3.92

The two LSS options, a storage LSS with 10% spares and a recycling LSS with 10% spares, are used to estimate the LSS mass. The recycling LSS subsystem mass per crewmember is estimated, as shown in Table 4, based on advanced LSS technology.[15] The LSS for the SpaceX Mars mission is designed based on the mass of the LSS subsystems using the linear scaling method as a function of the number of crew.

Table 5 shows the masses for the LSS operations, which are estimated based on the crewmember input and output, as shown in Table 2. The oxygen, water, nitrogen, and LiOH masses per crewmember are shown. The tankages of oxygen, water, and nitrogen are used as coefficients 0.364 kg/kg, 0.2 kg/kg, and 0.556 kg/kg, respectively.[16] The oxygen and nitrogen leak rate are set at 0.0005%/m^3 per day.[17]

Table 4. LSS subsystem mass on Mars surface.

Subsystem or Component	Mass, kg/CM	Power, kW/CM
Air Subsystem	188	0.27
Food Subsystem	0	0.00
Thermal Subsystem	41	0.06
Waste Subsystem	31	0.00
Water Subsystem	185	0.19
Human Accommodations	53	0.04
Total	498	0.55

Table 5. Mass for LSS operation.

Subsystem	Mass, kg/CM-day
Oxygen	0.84
Oxygen tankage	0.31
Water	5.31
Water tankage	1.06
LiOH and packaging	1.75
Oxygen leak	0.0088
Oxygen leak tankage	0.0032
Nitrogen leak	0.0353
Nitrogen leak tankage	0.0196

E. BPS Technology Options

The BPS mass and power requirement are estimated based on the biomass production system design for BIO-Plex.[17] The power system mass and production system mass were assumed at 2.6 kW/m^2 and 101.5 kg/m^2, respectively, based on 1990s technology. In this estimation, a downsized design is used based on 2000s technology, such as a light-emitting diode (LED). To calculate the required power estimation, the required power of the LED per biomass production by photosynthesis is assumed to be 0.4 g/mol.[18] If 706 g of food (dry mass) is required per crewmember per day, the photosynthetic photon flux is 1,765 mol. Then, the photosynthetic photons per joule of electrical energy are assumed to be 1.66 μmol/J,[11] and the photosynthetic photon flux is 1,063,253 kJ. The electrical energy supplied per day (86,400 s) is 12.3 kW/CM-day, which is 16% of 78 kW (2.6 kW/m^2 x 30 m^2/CM) using 1990s technology. To estimate the BPS mass, the baseline BPS mass is set at 1.0 mT/CM, which is one third of 3 mT/CM (101.5 kg/m^2 x 30 m^2/CM) using 1990s technology. These BPS and PSS values were set as the baseline design values for this parametric analysis.

F. ISRU Technology Options

ISRU consists of an atmosphere collection system to collect carbon dioxide from the atmosphere of Mars and a water mining system to produce water from the planet's soil. ISRU could reduce the propellant mass or consumable mass by producing oxygen (O_2) and/or methane (CH_4) from the Mars's atmosphere and/or soil of Mars. There are three proposed options, as shown in Table 6. The first option is O_2 propellant produced from Mars' atmospheric CO_2 and CH_4 from Earth. The second option is O_2 and CH_4 produced from Mars' atmospheric CO_2 and hydrogen (H_2) from Earth. The third option is O_2 and CH_4 produced from Mars' atmospheric CO_2 and H_2O in the soil. The chemical conversion equations can be performed in several different ways. The first option has three processes: Solid Oxide CO_2 Electrolysis (SOCE), Reverse Water Gas Shift (RWGS) with Water Electrolysis (WE), and Sabatier with WE and Methane Pyrolysis (MP). The second option has two processes: Sabatier with WE and RWGS. The third option has two processes: Sabatier with WE and Electrochemical Reduction (ER).

Table 6. ISRU option and process.

Option	Production	Process
1	O_2 only production with Earth CH_4	Solid Oxide CO_2 Electrolysis: $2CO_2 \rightarrow 2CO + O_2$ or Reverse Water Gas Shift: $2CO_2+2H_2 \rightarrow 2CO + 2H_2O$ 2nd Water Electrolysis: $2H_2O \rightarrow 2H_2 + O_2$ or Sabatier: $CO_2+4H_2 \rightarrow CH_4 + 2H_2O$ 2nd Water Electrolysis: $2H_2O \rightarrow 2H_2 + O_2$ 2nd Methane Pyrolysis: $CH_4 \rightarrow C+2H_2$
2	O_2/CH_4 production with Earth H_2	Sabatier: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ 2nd Water Electrolysis: $4H_2O \rightarrow 4H_2 + 2O_2$ or Reverse Water Gas Shift: $2CO_2+2H_2 \rightarrow 2CO + 2H_2O$
3	O_2/CH_4 production with Mars H_2O	Sabatier: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ 2nd Water Electrolysis: $2H_2O \rightarrow 2H_2 + O_2$ or Electrochemical Reduction: $CO_2 + 2H_2O \rightarrow CH_4 + 2O_2$

As each reaction has a different reaction temperature, each process requires a different amount of power for its chemical reaction. The CO_2 concentration in Mars' atmosphere is 95%, CO_2 can be stably collected from the atmosphere. However, the H_2O content of the soil on the surface of Mars depends on the region, and it ranges between 3% and 8%.[5] This could strongly affect the efficiency of producing H_2O from the planet's soil.

Table 7 shows the ISRU mass and power using Option 3 (Sabatier and WE) based on the ISRU design developed by Donald Rapp.[6] If oxygen and methane of 1,100 mT is produced in 720 days for an interplanetary return spaceship flight to Earth, then the production rate is 61.8 kg/hr (49.5 kg O_2 and 12.3 kg CH_4) from 34.0 kg CO_2 and 27.8 kg H_2O. The ISRU mass is estimated to be 4,170 kg for O_2 production and 20,535 kg for H_2O production. The ISRU power is estimated to be 467 kW for O_2 production and 260 kW for H_2O production.

Table 7. ISRU mass and power

Process	Unit feedstock rate	Mass, kg	Power, kW
CO_2 acquisition	1 kg/hr of CO_2	50	1.2
Sabatier conversion	1 kg/hr of CO_2	12.5	0.16
Water electrolysis	1 kg/hr of water	11.2	2.4
Liquefying O_2	1 kg/hr of O_2	35	1.1
Liquefying CH_4	1 kg/hr of CH_4	85	3
Regolith excavation and water extraction	1 kg/hr of water recovered	700	8
Total		894	16

G. Power Supply System Options

This paper assumes the ISRU plant would be operated continuously with nuclear power. The baseline power requirement was assumed to be 1 kW/CM. A baseline assumption was used for a PSS mass per power of 267 kg/kW because the mass of a single 8 kW fission is estimated to be 8,000 kg.[5] The PSS mass for LSS and ISRU were calculated by multiplying the power requirement by 267 kg/kW.

H. Integrated System

The ISRU, PSS, LSS, WE, and propulsion systems should be optimized when considering system operation because their functions are interconnected and complementary. Figure 3 shows the integrated fluids and interfaces in a surface system consisting of ISRU, PSS, LSS, WE, a propulsion system, and a Gas Storage System (GSS). O_2 is produced by ISRU from CO_2 in Mars' atmosphere. H_2O is produced by ISRU from the soil on the surface of Mars. CO_2 is produced by ISRU from trash and waste. CH_4 is produced from CO_2 and H_2O, or H_2. A portion of H_2O is decomposed into O_2 and H_2 by an electric current. O_2 is consumed and CO_2 is produced by humans, and then CO_2 is regenerated into CH_4 by the LSS. Waste H_2O is regenerated into clean H_2O by the LSS. Trash is transferred to ISRU from the LSS. PSS generates power using O_2 and CH_4, and then it produces CO_2 and H_2O, which are used by ISRU. O_2 is also used for respiration in the cabin. O_2 and CH_4 are used to produce propulsion.

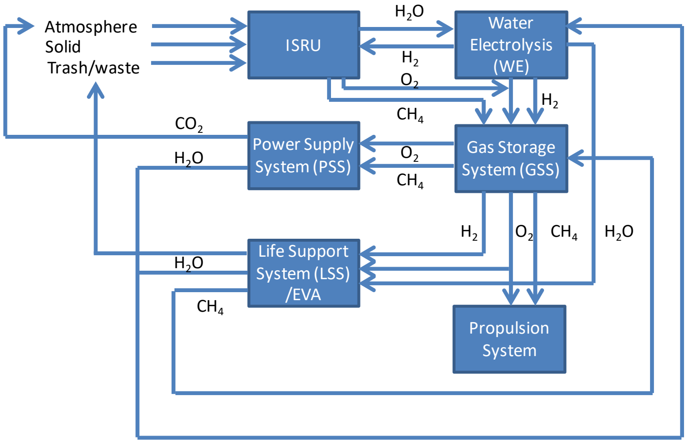


Figure 3. Integrated Fluids and Interfaces

IV. Parametric Analysis for SpaceX Mars Architecture

A. Conceptual Architecture

Table 8 shows the mission architecture trade tree and parameter ranges. The trade options consist of LSS recycling on the surface of Mars, LSS recycling in transit, ISRU on the surface of Mars, and BPS biomass production on the planet's surface described by the LSS recycling ratios, the ISRU production ratios, or the BPS production ratios.

There are up to eight possible combinations broken down into three categories: 1) ISRU on the surface of Mars, 2) LSS recycling, and 3) BPS biomass production on the planet's surface. ISRU on the surface of Mars has two options: ISRU (Y) or no ISRU (N). LSS has two options: storage (N) or recycling (Y). BPS has two options: production (Y) or no production (N). In addition, biomass production is described by using the BPS mass factor (designed mass/baseline mass) and the PSS mass factor (designed mass/baseline mass). The parametric analysis uses a range of ratios (r_l, r_p, r_c, r_b, f_b, and f_p) for LSS recycling, ISRU propellant, ISRU crew, BPS production, BPS mass factor, and PSS mass factor, respectively, as shown in Table 8.

Table 8. Mission architecture trade tree and parameter ranges.

Case	ISRU on surface	LSS recycling	BPS biomass production on surface	ISRU production ratio r_p, r_c	LSS recycling ratio r_l	BPS production ratio r_b	BPS mass factor f_b	PSS mass factor f_p
1	Y	N	Y	1	0	0-1	0-2	0-2
2			N			0	0	0
3		Y	Y		0-1	0-1	0-2	0-2
4			N			0	0	0
5	N	N	Y	0	0	0-1	0-2	0-2
6			N			0	0	0
7		Y	Y		0-1	0-1	0-2	0-2
8			N			0	0	0

B. IMLEO for Eight Cases Based on the SpaceX Mars Architecture

Based on the SpaceX Mars architecture, the exploration phase consists of three phases: transportation, ascent/descent, and surface HAB. The transportation and ascent/descent phases are both conducted by a single ITS spaceship. However, the SpaceX mission plan does not include any specifications about the surface HAB. According to the SpaceX mission plan, the spaceship will not remain in Mars orbit; instead it will land on Mars with the crew. It will be used as an interplanetary transfer vehicle that will provide support for the round trip mission from Earth to Mars orbit. It is assumed that the surface HAB dry mass is 150 mT and the cargo mass is 50 mT, because the interplanetary spaceship is used for the surface HAB. Table 9 shows the baseline architecture and the mass budget used in this study. The surface HAB was designed using the scaling factor method.

This paper assumes a fixed mass decided on by the SpaceX Mars architecture. The four variable subsystem masses of LSS, ISRU, BPS, and PSS were assumed for each case in the mission architecture trade tree with the variable ratios shown in Table 8. The technology assumptions of LSS, BPS, ISRU, and PSS are defined in Section II.

Table 9. Baseline mass budget assumption for SpaceX Mars mission.

Function	Dry mass, mT	Mission descriptions
Surface Habitat (HAB) function provided by SpaceX spaceship 520-day	Fixed mass 200 mT	**Fixed mass**: Spaceship dry mass (Habitat): 150 mT **Variable mass**: maximum 50 mT LSS (Storage or Recycling): Section II D, BPS (production or no production): Section II E, ISRU plant (ISRU or no ISRU): Section II F, additional PSS (Solar or Nuclear): Section II G, and Life support consumable and crew supply: 572-day (10% margin of 520-day)
Mars Transfer Vehicle (MTV) function provided by SpaceX spaceship 300-day	Fixed mass 300 mT	**Fixed mass**: Spaceship dry mass: 150 mT, Mars landing system margin: 100 mT **Variable mass**: maximum 50 mT LSS (Storage or Recycling): Section II D, Life support consumable and crew supply: 330-day (10% margin of 300-day)
Descent/ Ascent Vehicle (DAV) function provided by SpaceX spaceship 10-day	Fixed mass 200 mT	**Fixed mass**: Spaceship dry mass: 150 mT **Variable mass**: maximum 50 mT LSS (Storage or Recycling): Section II D, Life support consumable and crew supply: 10-day

Spaceship mass, Mars landing system margin mass, and maximum payload are based on reference 1

Figure 4 shows the IMLEO in eight baseline mission cases derived from the trade tree shown in Table 8. The cases show the eight combinations of use of ISRU or no ISRU, Storage LSS or Recycling LSS, and BPS or no BPS.

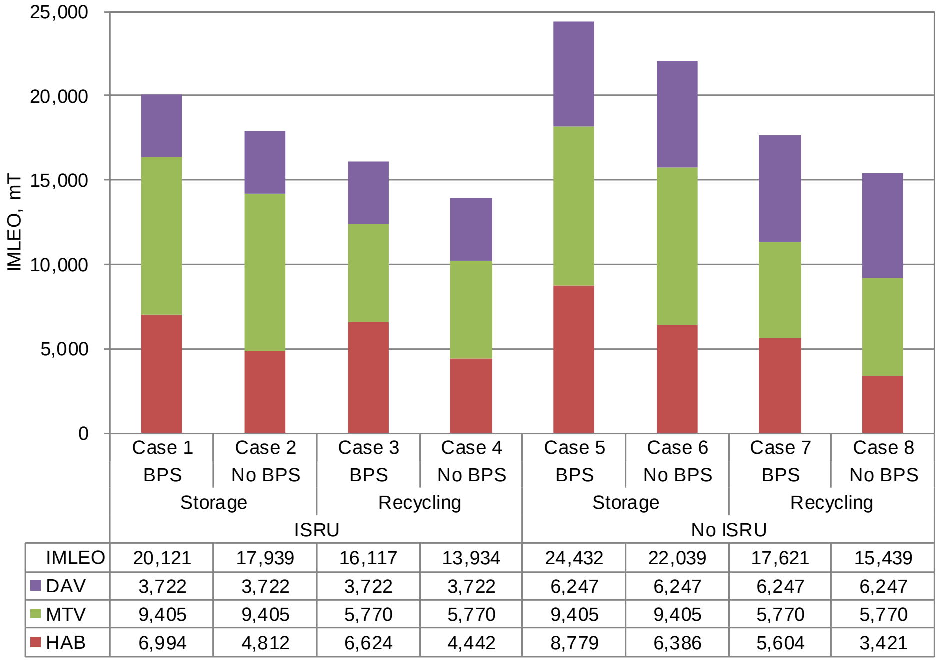
IMLEO can be decreased 4,310 mT when using ISRU, Storage LSS, and BPS (Case 1) as opposed to no ISRU, Storage LSS, and BPS (Case 5) and 1,505 mT when using ISRU, Recycling LSS, and BPS (Case 3) as opposed to no ISRU, Recycling LSS, and BPS (Case 7).

IMLEO can be decreased 4,100 mT when using ISRU, Storage LSS, and no BPS (Case 2) as opposed to no ISRU, Storage LSS, and no BPS (Case 6) and 1,505 mT when using ISRU, Recycling LSS, and no BPS (Case 4) as opposed to no ISRU, Recycling LSS, and no BPS (Case 8).

The results confirm these differences are derived whether or not ascent propellant is produced for DAV on Mars. ISRU is effective in decreasing the IMLEO in all cases and especially effective in decreasing the IMLEO when Recycling LSS is not used.

IMLEO can be decreased 4,005 mT when using ISRU, Recycling LSS, and BPS (Case 1) as opposed to ISRU, Storage LSS, and no BPS (Case 3) and 6,811 mT when using no ISRU, Recycling LSS, and BPS (Case 5) as opposed to no ISRU, Storage LSS, and BPS (Case 7). IMLEO can be decreased 4,005 mT when using ISRU, Recycling LSS, and no BPS as opposed to ISRU, Storage LSS, and no BPS (comparing Case 2 and Case 4) and 6,600 mT when using no ISRU, Recycling LSS, and no BPS as opposed to no ISRU, Storage LSS, and no BPS (comparing Case 6 and Case 8). The recycling efficiency is assumed to be at 100% in all these calculations; thus, the Recycling LSS is largely effective in decreasing the IMLEO in all cases.

IMLEO increases with BPS as opposed to no BPS (Case 1 and Case 2, Case 3 and Case 4, Case 5 and Case 6, and Case 7 and Case 8) because biomass production increases the BPS mass and the PSS mass.



	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
	BPS	No BPS	BPS	No BPS	BPS	No BPS	BPS	No BPS
	Storage		Recycling		Storage		Recycling	
	ISRU				No ISRU			
IMLEO	20,121	17,939	16,117	13,934	24,432	22,039	17,621	15,439
🟪 DAV	3,722	3,722	3,722	3,722	6,247	6,247	6,247	6,247
🟩 MTV	9,405	9,405	5,770	5,770	9,405	9,405	5,770	5,770
🟥 HAB	6,994	4,812	6,624	4,442	8,779	6,386	5,604	3,421

Δv margin = 10%, $r_l = 1.0$, $r_p = 1.0$, $r_c = 1.0$, $r_b = 1.0$, $f_b = 1.0$, and $f_p = 1.0$

Figure 4. IMLEO in eight baseline mission cases.

C. Sensitivity Analysis

Biomass production on Mars did not decrease the IMLEO in all cases. Therefore, a sensitivity analysis was conducted to determine how much the BPS mass had to be decreased and the best method of accomplishing it.

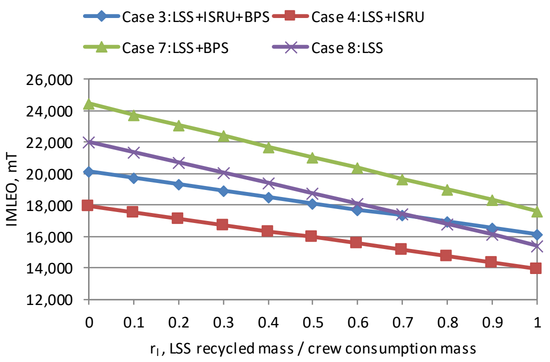
1. *Single-section analysis*

A sensitivity analysis was conducted to examine the influence that different parameters, such as the LSS recycling ratio (r_l), the biomass production ratio (r_p), the BPS mass factor (f_b), and the PSS mass factor (f_p), had on IMLEO for the eight cases.

Figure 5 shows the IMLEO versus various ratios of LSS recycled mass to crew consumption mass. In Case 3, Case 4, Case 7, and Case 8, the IMLEOs decreased as the ratio of the recycled mass to consumption mass increased from Recycling LSS. The IMLEO in Case 8 (LSS) dips under the IMLEO in Case 3 (LSS+ISRU+BPS). Therefore, when the recycling ratio is greater than 0.7, ISRU does not decrease the IMLEO when using LSS and BPS.

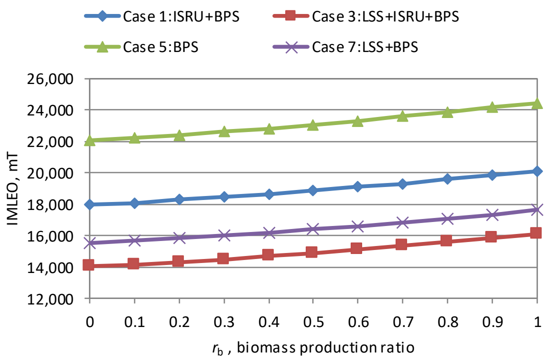
Figure 6 shows the IMLEO versus various biomass production ratios. As expected, in Case 1, Case 3, Case 5, and Case 7 (with BPS), the IMLEOs increase as the biomass production ratio increases.

Figure 7 shows the IMLEO versus various PSS mass factors. In Case 1, Case 2, Case 3, and Case 4 (with ISRU), the IMLEOs increase as the PSS mass factor increases. Case 1 starts to exceed Case 2 at 0.1 of f_p. Case 3 starts to exceed Case 4 at 0.1 of f_p. In Case 1 and Case 3 (with BPS), the IMLEOs increase in comparison to Case 2 and Case 4 (without BPS) as the PSS mass factor increases. In addition, in Case 3, the IMLEO starts to exceed that of Case 2 at 1.8 of f_p. This means the combination of Recycling LSS and biomass production is less than the combination of Storage LSS and no biomass production when the PSS mass increases.



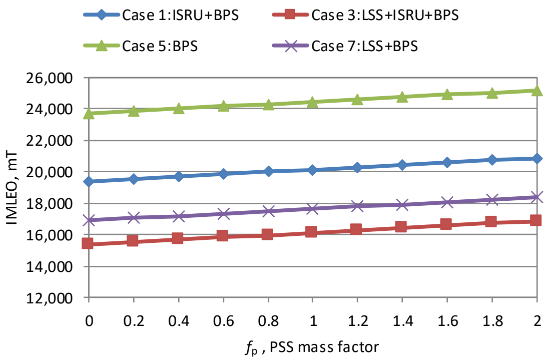
r_p = 1.0, r_c = 1.0, r_b = 0, f_b = 1.0, and f_p = 1.0

Figure 5. IMLEO versus ratios of LSS recycled mass to crew consumption mass.



r_l= 1.0, r_p = 1.0, r_c = 1.0, f_b = 1.0, and f_p = 1.0

Figure 6. IMLEO versus biomass production ratio.



r_l= 1.0, r_p = 1.0, r_c = 1.0, r_b = 0, and f_b = 1.0

Figure 7. IMLEO versus PSS mass factor.

2. *Cross-section analysis*

A cross-section analysis was conducted to examine the influence that varying two parameters had on IMLEO in Case 3 (LSS+ISRU+BPS) because BPS and PSS are developing technologies, and it is difficult to clarify all their aspects. The BPS mass factor and the PSS mass factor were introduced to show the uncertainty of developing technology in this mass estimation model. This cross-section analysis also evaluated the influence that different BPS and PSS mass sizes had on IMLEO.

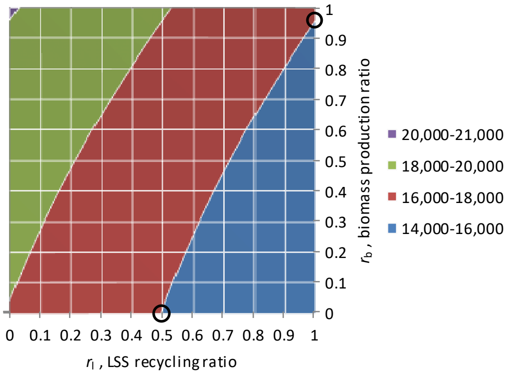
Figure 8 shows the IMLEO of Case 3 versus the LSS recycling ratio and the biomass production ratio. The IMLEO remains low when the biomass production ratio is high as long as the LSS recycling ratio is high. For example, when the IMLEO is at 16,000 mT and the recycling ratio is 0.5, the biomass production ratio is 0. When the LSS recycling ratio is 1.0, the acceptable biomass production ratio is 0.95. In addition, this figure shows that the LSS recycling ratio and the biomass production ratio work together to change the IMLEO.

Figure 9 shows the IMLEO of Case 3 versus the ISRU production ratio and biomass production ratio. This figure presents the same characteristics as seen in Figure 8. The IMLEO remains low when the biomass production ratio is high as long as the ISRU production ratio is high. For example, when the IMLEO is at 16,000 mT and the ISRU production ratio is 0, the biomass production ratio is 0.27. When the ISRU production ratio is 1.0, the biomass production ratio is 0.95. In addition, this figure shows that the ISRU production ratio and the biomass production ratio work together to change the IMLEO.

Figure 10 shows the IMLEO of Case 3 versus the PSS mass factor and biomass production ratio. As the PSS mass factor increases, the IMLEO increases earlier when the biomass production ratio is low (close to 0.2). For example, when the IMLEO is at 16,000 mT and the PSS mass factor is near 1.0, the biomass production ratio is 1.0. When the PSS mass factor is 2.0, the biomass production ratio is 0.2. That proves that the increase of PSS mass greatly affects the increase of IMLEO by biomass production. In addition, this figure shows that the PSS mass factor and the biomass production ratio work together to change the IMLEO.

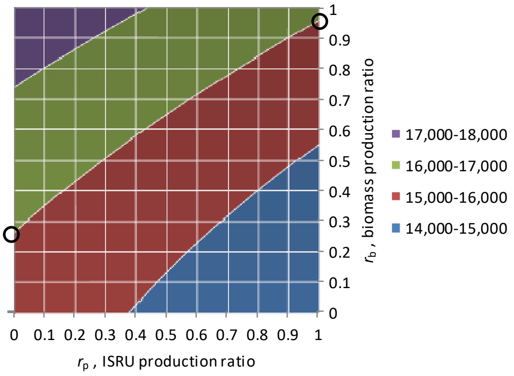
Figure 11 shows the IMLEO of Case 3 versus the BPS mass factor and the biomass production ratio. As the BPS mass factor increases, the IMLEO increases when the biomass production ratio is high (close to 1.0), and the IMLEO does not increase when the biomass production ratio is low. For example, when the biomass production ratio is 1.0, the IMLEO starts to exceed the 16,000 line at 0.8 of the BPS mass factor. When the biomass production ratio is less than 0.48, the IMLEO remains between 14,000 and 15,000 for any BPS mass factor. This proves that the increase in the BPS mass affects the increase in the IMLEO when the biomass production ratio is high.

Finally, Figure 12 shows the IMLEO ratio of Case 3 and Case 4 versus the PSS mass factor and BPS mass factor. When the number is 1.0, it shows a break-even point between BPS and no BPS. The biomass production can decrease the IMLEO when both the PSS mass factor is less than 1.3 and the BPS mass factor is less than 0.4. For example, a design of 0.3 times the mass of BPS and 0.3 times the mass of PSS is feasible.



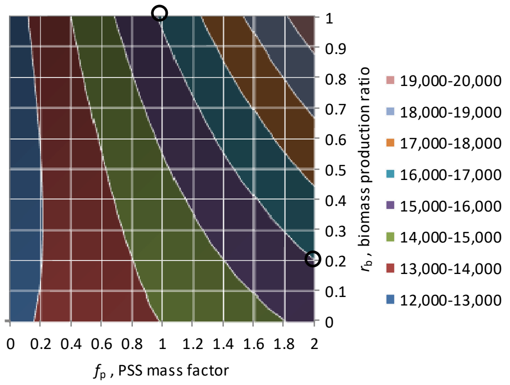
r_p = 1.0, r_b = 0, f_b = 1.0, and f_p = 1.0

Figure 8. IMLEO versus LSS recycling ratio and biomass production ratio.



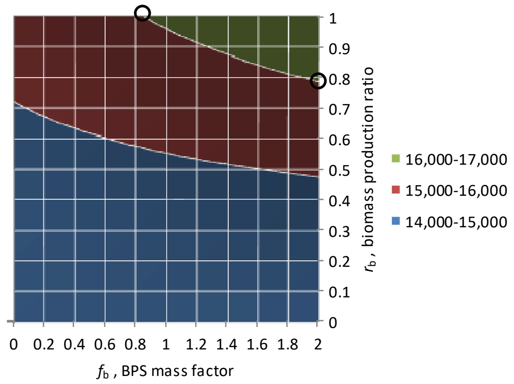
r_l= 1.0, r_c = 1.0, r_b = 0, and f_b = 1.0

Figure 9. IMLEO versus ISRU production ratio and biomass production ratio.



r_l= 1.0, r_p = 1.0, r_c = 1.0, and f_b = 1.0

Figure 10. IMLEO versus PSS mass factor and biomass production ratio.



r_l= 1.0, r_p = 1.0, r_c = 1.0, and f_p = 1.0

Figure 11. IMLEO versus BPS mass factor and biomass production ratio.

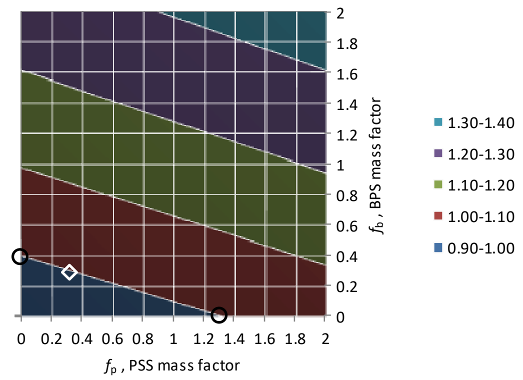
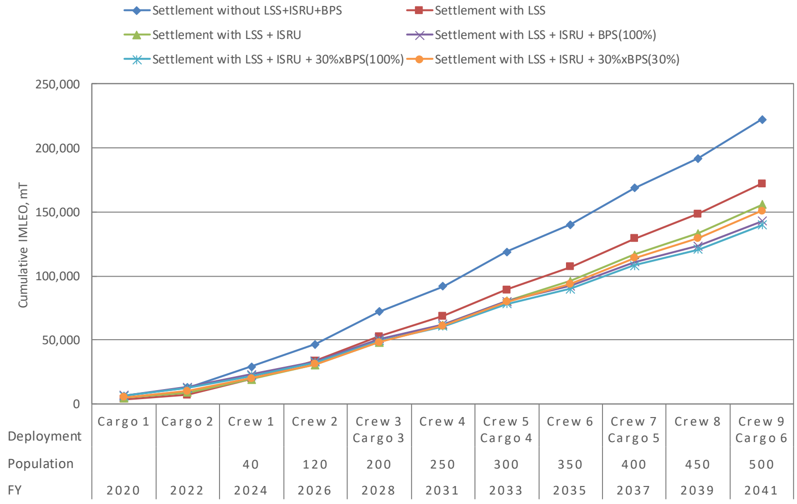


Figure 12. IMLEO ratio of Case 3/Case 4 versus PSS mass factor and BPS mass factor.

Next, we compared the cumulative IMLEOs between several Mars settlement missions. In a settlement mission, all crewmembers land on Mars for a 520-day mission. Then 50% of the crew remains on the Mars while the other 50% returns to Earth. After two consecutive crew flight missions, a cargo ship is sent for increasing the HAB for the additional 100 crewmembers who arrived on the previous two flights. The cargo flights are scheduled after every odd number crew flight i.e. Crew 3, Crew 5, etc. Figure 13 shows the cumulative IMLEO lines of settlement without LSS+ISRU+BPS, the settlement with LSS, the settlement with LSS+ISRU, the settlement with LSS+ISRU+BPS (100% biomass production), the settlement with LSS+ISRU+30% mass of BPS (100% biomass production), and the settlement with LSS+ISRU+30% mass of BPS (30% biomass production). The settlement mission sequences, consisting of cargo and crew departures, are shown at the bottom of Figure 13. Every two or three years, 100 additional crewmembers will join the HAB on Mars and leave behind 50 crewmembers, except for Crew 1 (20 members leave Mars on Crew 2) and Crew 2 (20 members leave Mars on Crew 3). It is assumed that additional supplies that cannot be recycled or produced will be sent in every mission sequence. The supply mass is less than the maximum payload of 50 mT for the ITS flight. As a part of ITS, the spaceship becomes an ascent vehicle with propellant produced by ISRU. The IMLEO of the settlement without LSS+ISRU+BPS is the highest of the six missions. The IMLEO of the settlement with LSS+ISRU+30%xBPS (100%) is the lowest of the six missions. The IMLEOs of the settlement in FY2041 with LSS, with LSS+ISRU, with LSS+ISRU+30%xBPS (30%), with LSS+ISRU+BPS (100%), and with LSS+ISRU+30%xBPS (100%) are presented in descending order. This figure shows that the IMLEO of the settlement with LSS+ISRU+30%xBPS (30%) is less than that of the settlement with LSS+ISRU, even if its biomass production ratio is only 30%. A Mars settlement mission requires a downsized BPS as well as a LSS and an ISRU for long-term habitation.



Δv margin = 10%, r_l = 1.0, r_p = 1.0, r_c = 1.0, r_b = 1.0, f_b = 0.3, and f_p = 0.3

Figure 13. Growth of IMLEO of SpaceX Mars mission.

V. Conclusion

Elon Musk’s SpaceX 2016 ITS proposal lacked a design for a habitation facility and LSS on Mars for long-term habitation. This paper assumes the spaceship lands on Mars and is used as the Mars surface habitation facility for the mission’s initial stage. Assumptions for a LSS, BPS, ISRU, and PSS were made in conducting a parametric analysis of IMLEO for the SpaceX mission. LSS and ISRU were very effective at decreasing IMLEO, thus decreasing mission costs. ISRU can produce the propellant needed for returning to Earth thus decreasing the IMLEO drastically. Biomass production reduces the amount of cargo needed for the long-term mission with a large population of over 100 people. However, biomass production increases the BPS mass and the PSS mass, so decreasing the ratio of BPS mass per kilogram to biomass production and PSS mass per kilowatt is necessary even with a LSS and ISRU. The results showed that a design using 30 % of the baseline mass of BPS and 30 % of the baseline mass of PSS was feasible, and less than the break-even point of biomass production on Mars. In order to realize the goal of long-term habitation, the SpaceX Mars settlement mission will require new and better technology for a considerably lighter BPS than currently available today.

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