Proposed ITS Pressurized Cargo Modules To Initiate a Chemical Industry on Mars

Roy A. Paul[1]
Mars Pioneers, Mebane, NC 27302 USA

and

Michel Lamontagne[2]
CIMA+ Consulting Engineers, Montreal, QC, H3C 3X Canada

and

Bernardo Senna[3]
Mars Pioneers, Rio de Janeiro, 20540-050 Brazil

Abstract

In 2016 Elon Musk revealed the SpaceX architecture for an Interplanetary Transport System (ITS). It included a second stage spacecraft to be produced as a tanker or a passenger transporter to Mars. In this paper, we propose that a cargo version of the ITS spaceship should also be produced to deliver large pressurized cargo vessels to Mars' surface. A specialized crane or grappler would unload each vessel from its spaceship. After supplies and equipment were removed, the shell of the pressure vessel itself would be employed as a storage tank for chemicals. Some of the modules would be customized on Earth as high-volume chemical reactors or processing units and delivered to Mars as ready-to-use processing modules. To implement this approach, we offer six methods for delivering a module to Mars and their respective unloading machines. We also offer four examples of customized modules that include an atmospheric dust remover, a Sabatier reactor and electrolysis unit, an oxygen generator, and an air separation unit. To illustrate the employment of modules in an initial chemical industry, we laid out a tank farm for rocket propellants. We estimated the O_2 and CH_4 production rates for the reactors and used them to determine the numbers of reactor and storage modules required to provide propellants to spaceships for their return trips to Earth. We discovered that a very large number of storage modules would be required to support various sizes of launch campaigns, given the present assumptions in this paper.

Nomenclature

CG = Center of gravity
CDRA = Carbon Dioxide Removal Assembly
CRA = Carbon Dioxide Reduction Assembly
ECLSS = Environmental control and life support system
FOD = Foreign object debris
FRP = Fiber reinforced polymer
g = Earth's gravitational acceleration
gm = grams
GHSV = Gas hourly space velocity (incoming volumetric flow rate per hour / volume of catalyst bed)
GNC = Guidance, navigation and control
ISRU = In-situ resource utilization

[1] Senior Collaborator, marspioneers@twc.com, AIAA Member
[2] Engineering Collaborator, michel.residence@gmail.com
3 Design Collaborator, bernasenna@gmail.com

ISPR = International Standard Payload Rack
ISS = International Space Station
ITS = Interplanetary Transport System
LEO = Low Earth orbit
LCH4 = Liquid methane
LOX = Liquid oxygen
MOXIE = Mars Oxygen ISRU Experiment
MSFC = Marshall Space Flight Center (NASA)
OGS = Oxygen Generator System
OGA = Oxygen Generator Assembly
PICA = Phenolic impregnated carbon ablator
SE = Sabatier reactor combined with Electrolysis unit
SLPM = Standard liters per minute
SLS = Space Launch System
STP = Standard conditions of temperature and pressure
t = metric tonnes
TPS = Thermal protection system
TMI = Trans-Mars injection

I. Introduction

In 2016 Elon Musk revealed the SpaceX architecture for an Interplanetary Transport System (ITS) that will be used to colonize Mars[1,2]. It included a first stage super heavy lift vehicle and a second stage spacecraft, as shown in Figure 1. The first stage will loft the spacecraft to the point of stage separation and return to the launch site to be reused frequently. The second stage spacecraft will take the form of a specialized tanker or a passenger transporter to Mars. The tanker version will deliver propellants to low Earth orbit (LEO) and then return to the launch site to be reused. The spacecraft version will receive a fill-up of liquid oxygen (LOX) and liquid methane (LCH4) propellants while parked in LEO and then proceed to trans-Mars injection (TMI). After delivering its payloads to Mars' surface it will return to Earth to be reused.

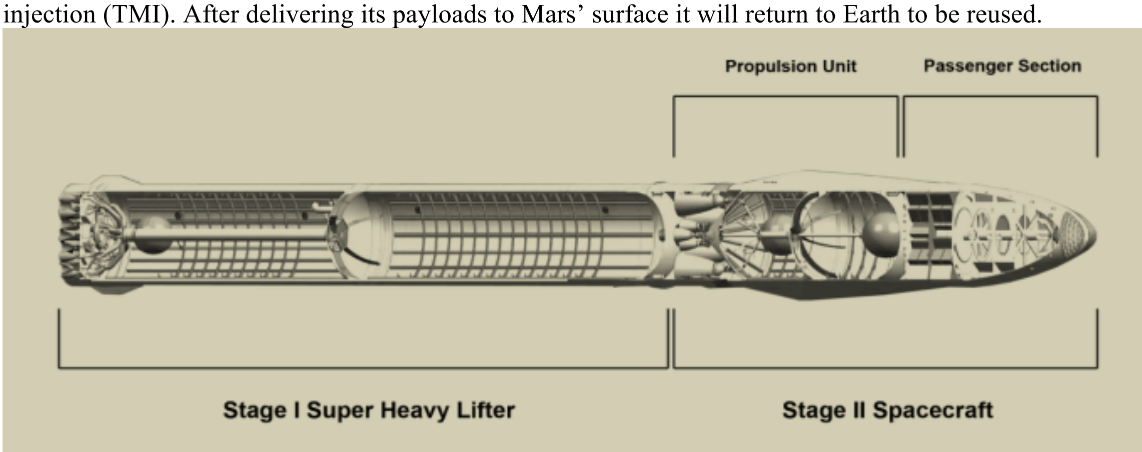

Figure 1. Principal Components of the Passenger Version of the Interplanetary Transport System (ITS) Revealed by SpaceX.[1,2]

SpaceX have repeatedly expressed the need to send large masses of supplies and equipment to Mars before and during the colonization effort.[3,4,5] The number of cargo missions may outnumber the passenger trips by as much as 10 to 1.[6] From these statements, we deduce that a cargo carrier version of the spacecraft will be required. We expect this version to be a specialized cargo carrier to consist of the same outer shell and employ the same propulsion system as the passenger version, but adjustments may be made to enhance its cargo carrying capability. Given that a cargo carrier will be developed, it is the view of the authors that enhancing the usable payload for each mission will be desirable.

We propose that a cargo version of the spaceship should be produced. It would be specialized to deliver a standard cargo module consisting of a pressurized vessel (module) maximized for interior volume. Its purpose would be to deliver to Mars ' surface the maximum feasible usable mass and volume of equipment in each cargo mission. In addition, the outer shell itself would be employed on Mars as a chemical storage tank for cryogenic liquids and pressurized gases. Alternatively, the module may be customized on Earth with built-in reactors, tanks, and plumbing to be delivered to Mars as a ready-to-use chemical processing unit. This type of module would be connected to other modules by plumbing pipes that together would form a chemical processing complex on Mars.

II. ITS Pressurized Cargo Vessel as a Standard Module

In developing a chemical industry on Mars, the expected cargo version of the ITS spaceship is the focus of interest. It should be a cargo carrier for hauling supplies and equipment to Mars, but carry all its cargo within a pressurized vessel. The cargo section would have the same exterior shape and shell materials as the passenger version that was revealed by SpaceX. The interior, however, would be stripped of ECLSS equipment, walls, floors, and any storage compartments for passengers. It would consist solely of bare walls and empty volume, all of which can be occupied by the cargo module. To exploit all the available volume, we propose that the pressurized vessel should take the same shape as the external surface and fit tightly within it.

Note that an analysis of chemical production needs of the colony might find that a smaller vessel would suffice. However, the SpaceX viewpoint of Mars colonization entails a continually growing population that may eventually reach 1 million people[1]. Such an analysis would address a given point in time, whereas "need" would keep expanding into the foreseeable future. Therefore, any volume we may choose for a standard storage vessel will not be large enough. Any surplus production would soon be consumed as the colony expands, so that there would soon be a need for more production. We believe that employing vessels of the largest feasible volume will best support colony growth.

A. Configuration of the Cargo Module

The proposed cargo vessel is derived from concepts originating in NASA. Figure 2 shows a NASA/MSFC pressurized tank employed as a habitat module[8]. This module is designed to be loaded onto the SLS Exploration Upper Stage (EUS); it consists of a cylinder with rounded ends welded onto the top and bottom. The end weld joints are reinforced by a metal bands around the top and bottom. The cylinder consists of two sections that are welded together in the middle and reinforced by an additional metal band. An added vertical cylinder is attached on the top end as a connector to other modules.

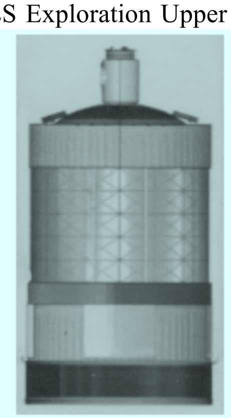

Figure 2. NASA Pressure Vessel Employed as Habitat[8].

The NASA pressure vessel (Fig. 2) is an analogue for the proposed ITS pressure vessel shown in Figure 3. The principal difference is that the top of the module is not rounded, but assumes the same nosecone shape as the shell of the ITS spacecraft. With a maximum external diameter of 10.8 m it will fit snugly within the 12.0 m diameter spacecraft shell that has an assumed 0.6 m wall thickness. Sharply rounded corners would be reinforced by bands of structural material inside the vessel rather than around the exterior. This design approach provides the maximum feasible volume of usable cargo space. To accommodate this cargo vessel, the interior wall of the ITS cargo section may contain longerons and stringers, but no structures running across the middle of the cargo volume; the middle of the cargo section will be completely occupied by the cargo vessel. The vessel itself, however, may utilize structural supports across the interior volume, but they must be carefully spaced to allow for loading and unloading of the equipment payload from the vessel.

Figure 3 below shows how the proposed pressurized cargo module fits within the ITS spaceship. Image (A) shows the exterior of the spaceship as presented by Elon Musk[1] with the added feature of a fairing over the cargo section. The second image (B) reveals the interior of the propulsion unit and the cargo section with the proposed cargo vessel fitted inside the fairing. The third image (C) shows some of the features of the vessel, including a large removable hatch door for loading and unloading cargo and a

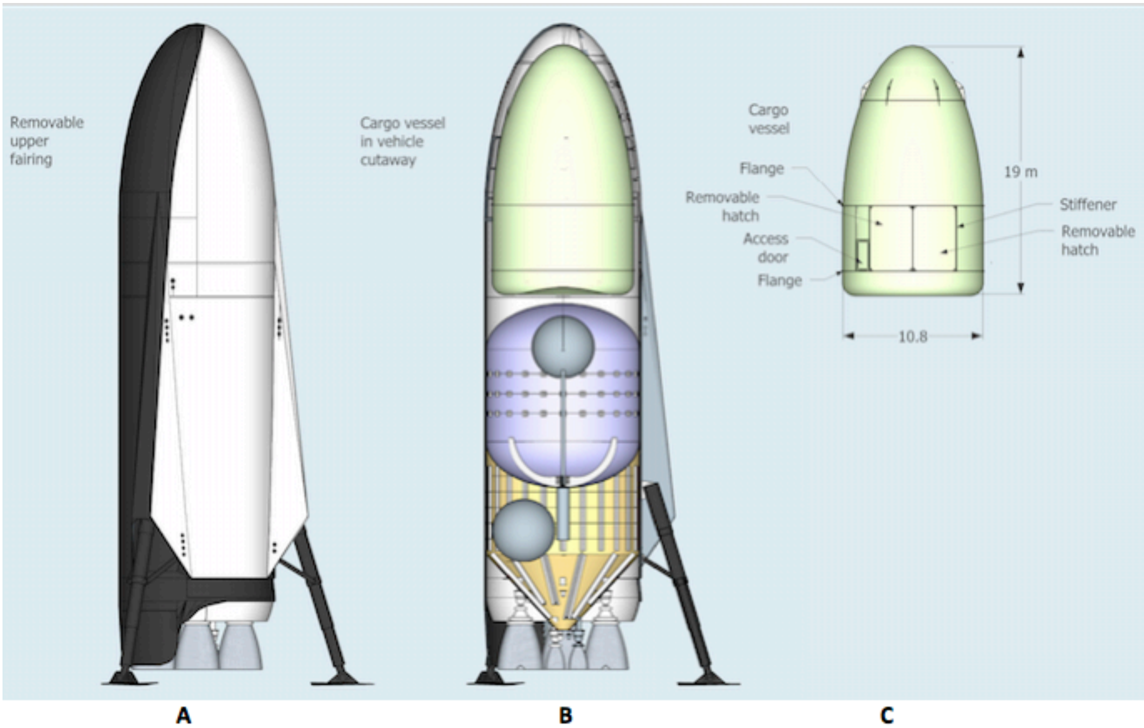

Figure 3. The ITS Cargo Spaceship and its Pressurized Cargo Module: *(A) Exterior view of the ITS Spaceship; (B) Cutaway view showing the cargo module inside its fairing; and (C) Features and dimensions of the cargo vessel (module).*

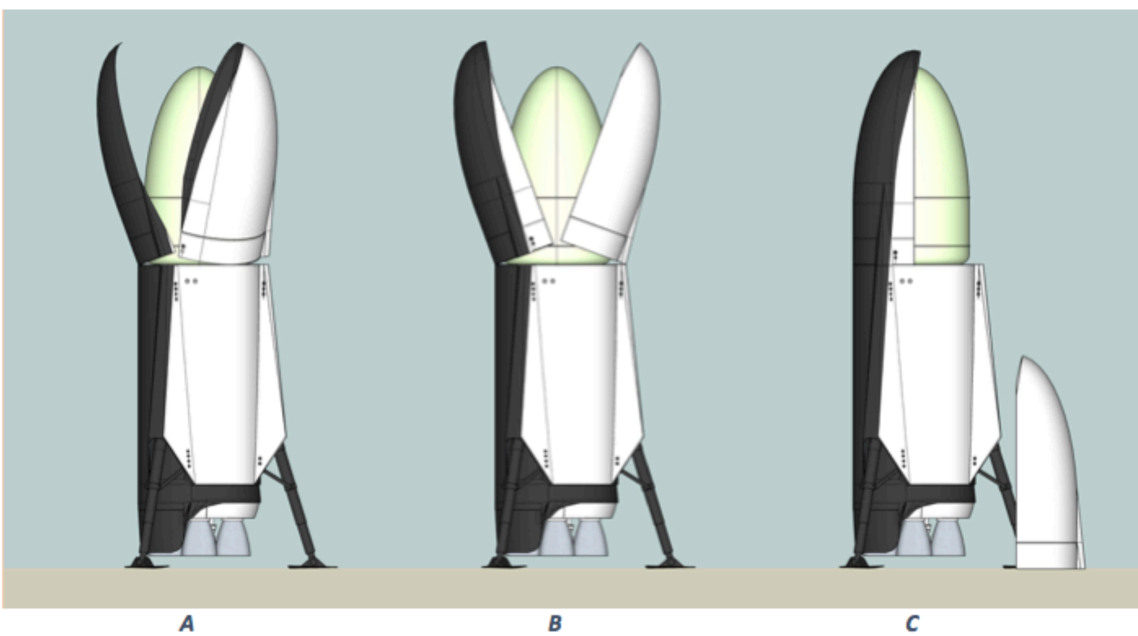

Figure 4. Three Optional Types of Fairings to Deliver a Cargo Module to Mars: *(A) Three-panel fairing that matches the three panels on the propulsion unit. The bottom of each panel is hinged for opening and closing; (B) Two-panel fairing with each panel hinged on the bottom; and (C) One-panel removable half-fairing with a non-removable heat shield on the opposite side.*

person-sized door for gaining access to the interior. Such access may or may not be needed, depending on how the module will be employed on Mars

B. Six Methods for Delivering a Cargo Vessel to Mars.

Six methods for delivering a cargo module involve two different approaches. The first approach is to enshroud the module within a fairing in the same way that a fairing enshrouds a satellite payload before a launch. Figure 4 exhibits three types of reusable fairings that may be employed: a three-panel clamshell (Method 4A), a two-panel clamshell (Method 4B), and a half-fairing (Method 4C). A spaceship designer may select the three-part fairing if he wanted the fairing panels to match the three surfaces on the propulsion unit below. One of the three fairing panels will encompass a PICA–x ablative heat shield for aero-braking, and the other two panels will be composed of multi-layer thermal protection. After the spaceship lands, the three panels would open on hinges located on the bottom of each panel, like a budding trillium, to expose the cargo module inside. A designer may choose the two-panel fairing option to reduce the number of vertical seams between panels from three to two; however, both these options will require a horizontal seam between each panel bottom and the propulsion unit below. These seams allow the panels to fold back to expose the cargo vessel for unloading. A designer would choose the third option to eliminate any seams in the heat shield; the Pica-x surface would extend continuously from the propulsion unit upward across the cargo section and over the nose cap. A removable half-fairing panel would complete the encapsulation of the cargo vessel.

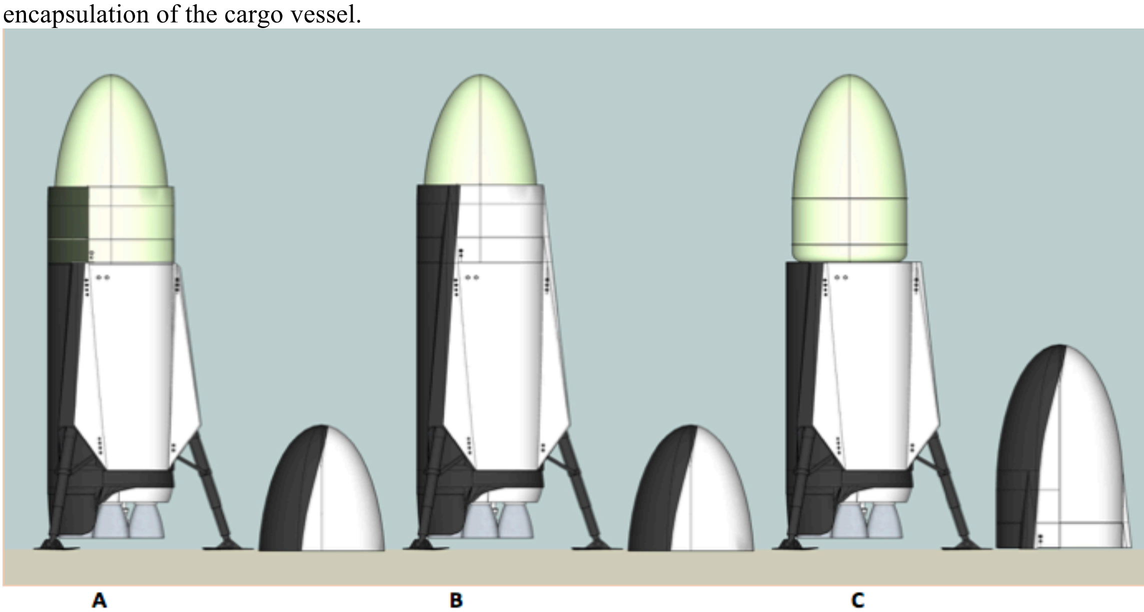

Figure 5. Three Optional Types of Nose Caps May Deliver a "Matryoshka" Cargo Vessel: *(A) Short nose cap reveals the top of the cargo vessel. The lower segment of the vessel is the lower part of the wall of the cargo section of the spaceship and is unloaded as part of the vessel; (B) Short nose cap with bottom segment of the vessel nestled inside the extended wall of the propulsion unit, and (C) Long nose cap covering the entire vessel.*

The other general approach to deliver a cargo module would entail a removable and reusable nose cap rather than a fairing (See Figure 5). The first of three optional versions of vessels and nose caps would include a short cap that covers only the top portion of the module (Method 5A), whereby the cylindrical portion of the module is the cylindrical portion of the cargo section. The purpose is to enlarge the volume of the cylindrical section and to reduce the mass carried on each trip. When the vessel is unloaded, the sidewall goes with it. The second method (5B) also features a short cap that covers only the nose portion of the module. In this case, the bottom segment is nestled inside the wall of the cargo section, which is an extension of the sidewall of the propulsion unit. Method 5C features a long cap that covers the entire module. In each version, a crane will remove the nose cap vertically to reveal the cargo module underneath, a motion resembling the revealing of a Matryoshka doll inside another doll.

Method 5A has an analogue in the options offered by NASA/MSFC[8] for loading a habitat module onto the SLS. As shown in Figure 6, the module on the left has a diameter of 7.2 m and is completely covered by an 8.4 m fairing, such that the surface of the *fairing* is continuous with the surface of the rocket below. The habitat on the right is 8.4 m in diameter, such that the surface of the *module* is continuous with the surface of the rocket below and is topped by a nose cap having the same 8.4 m (maximum) diameter. This option is analogous to method 5A for delivering a cargo module to Mars. In both the NASA module and the ITS module the purpose is to enlarge the usable payload volume and to save on the mass required to deliver a payload to its destination. If the length of each of the two modules in Figure 6 were 10 m, then the module on the right would have a volume 28.9 percent greater than the one on the left (disregarding wall thickness).

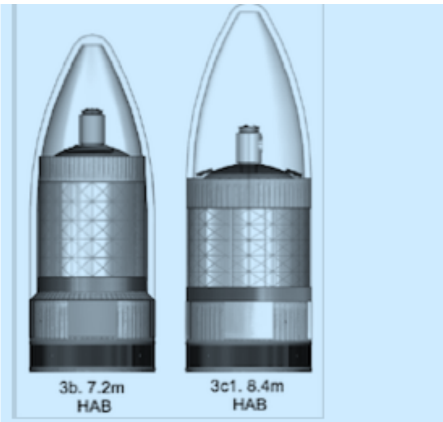

Figure 6. Two Options for Enshrouding a Habitat Module to be Loaded onto the SLS Second Stage ***(from Smitherman***[8]**).**

Note that in Method 5A the module will be removed from the spaceship and the nose cap replaced back onto the rocket for the return trip to Earth. In this instance, the spaceship will be made shorter, so the question will be whether the area of the remaining heat shield (m^3) is sufficient to withstand the aerodynamic pressure and heating upon re-entering Earth's atmosphere. This question will require additional analysis not covered in this report.

C. Alternative Methods for Unloading the Cargo Module

Upon landing on Mars' surface, the cargo vessel will be unloaded. In this paper, two options are presented for unloading: a specialized "vessel-grappler" (VG) and a jib crane. Either machine must have a lifting capacity of 400t (150t when employed on Mars). Which machine is chosen will depend on the style of vessel and the delivery method chosen.

The featured delivery method 5C (the half-fairing) requires a specialized "vessel grappler" (VG) mounted on a mobile base as shown in Figure 7. It has the capability to grab the vessel using a six-armed grappler around the lower cylindrical segment and a single arm and finger over the top of the vessel. The lengths of the bottom grappler arms will be limited by the width of the opening created by removing the half-fairing. Each fingertip will sport an extendable rod that slides into a hole in the vessel wall that is reinforced from inside. VG translates the vessel horizontally before lowering it via a double-acting mast,

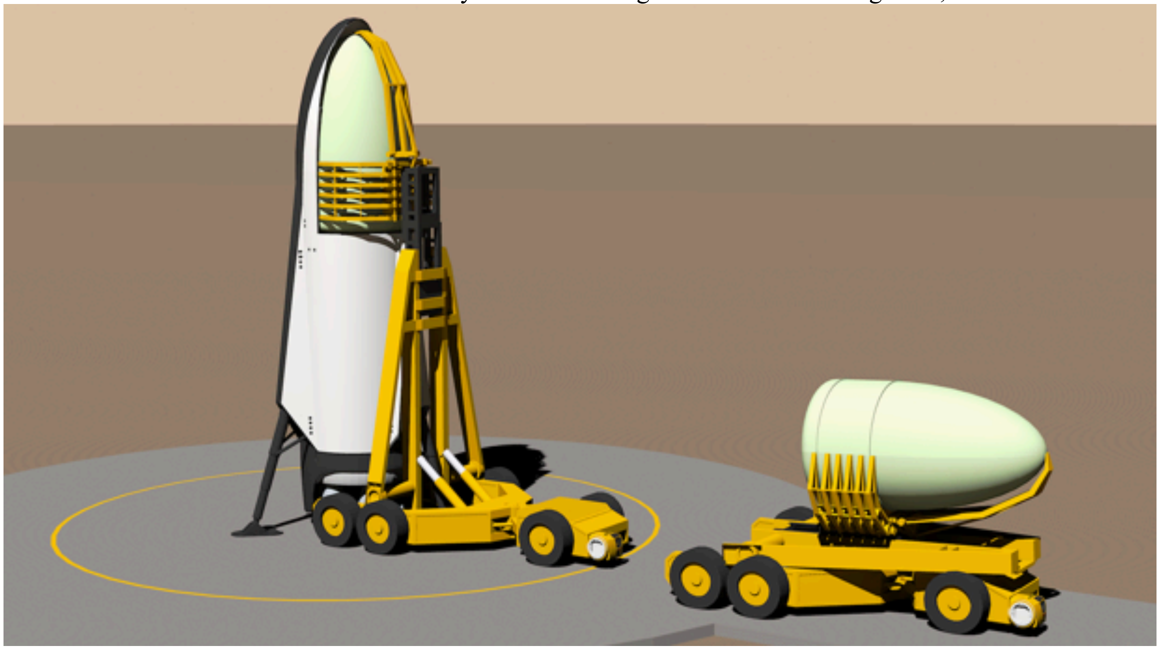

Figure 7. Specialized Vessel Grappler: *VG attaches to a cargo vessel, loads it onto its mobile base, and transports it to a cargo unloading station.*

like a tall forklift. The mast is hinged at the bottom so it can fold the vessel onto the base in horizontal position, like a transporter-erector. Figure 7 illustrates the process of unloading a vessel using this machine, which entails the following steps:

1) The VG autonomously backs up to the front of the spacecraft.
2) A radio signal to the fairing latch system causes the latches on the lower horizontal edge of the half-fairing to unlock.
3) A second signal causes the latches on the two vertical edges of the fairing to unlock.
4) Pusher rods separate the fairing from the spaceship shell about 4 cm.
5) VG moves forward to grab the fairing, inserting its extensible rods into the small space between the fairing panel and the spaceship shell.
6) The VG drives away with the fairing and sets it aside. Then it returns to its position in front of the spaceship.
7) VG grapples the vessel that is now exposed. It adjusts arm positions until the six fingers on both sides and the single finger on top are positioned above their respective finger-holes and inserts their extensible rods into the holes.
8) VG pulls away from the spacecraft, raising the vessel slightly to clear the floor of the cargo section and the nose cone heat shield. As it backs further away, it simultaneously lowers the vessel down the mast and closes the mast hinge, keeping the vessel's center of gravity above the center of the base. The vessel settles into horizontal position on the mobile base, as suggested in Figure 7.
9) Mobile VG carries the module to an unloading station. The vessel is turned to upright position and lowered to the ground for easy unloading.
10) The empty cargo vessel, now a chemical storage module, is carried to its final location in the growing chemical complex.

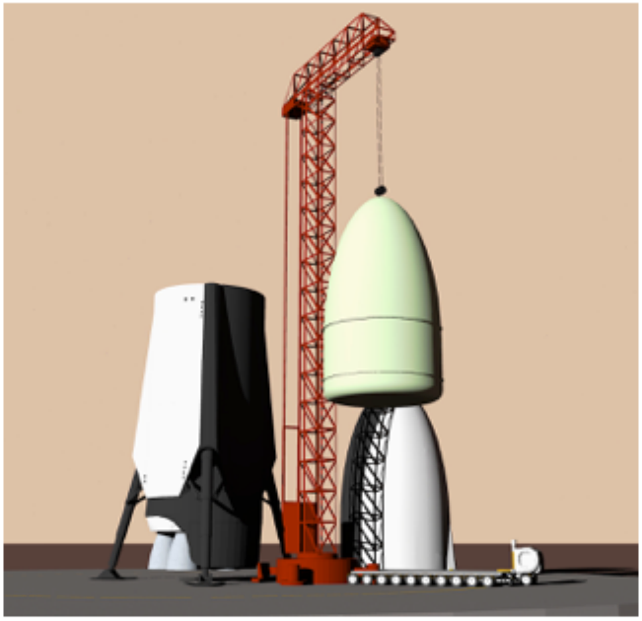

Figure 8. Jib Crane Unloading a Cargo Vessel: *Crane unloads the long-nose cone followed by unloading the module onto a module carrier (flat-bed truck).*

Note that SpaceX have shown three vertical clines as integral parts of the surface of the ITS spaceship[1,2]. One may assume they form nacelles to cover the legs and their pneumatic valves and plumbing lines. For delivery method 4C we assume that the upper part of the clines that extend onto the cargo section will only serve to streamline airflow during takeoff and landing. We assume that no equipment exists behind this segment of the clines that would interfere with the removal of the cargo vessel. Otherwise the horizontal removal of the vessel would be less practical due to interference with equipment.

The second approach, using a nose cap, will employ a jib crane to unload the cargo vessel as shown in Figure 8. Currently, employing a crane may be the preferred approach[2]. To separate the nose cap from the spaceship (Methods 5A, 5B or 5C) the same type of latch system currently employed to separate the Falcon 9 stage two fairing from stage one will be employed here. It consists of a set of four separation collets and pneumatic pushers in four interfaces connecting the two stages.[9,10] Using the jib crane, the unloading steps are as follows:

1) A cargo spaceship will land precisely on a landing pad that was previously equipped with a jib crane.
2) A remote signal will cause the nose cap to unlatch from the spaceship.
3) The crane arm (jib) will position over the spaceship, lower a robotic hook, and attach to the nose cap.

4) The autonomous crane hook will remove the nose cap vertically, and place it on the ground.
5) The hook will attach to a hook-eye (or equivalent) on the top of the module.
6) The crane will lift the module vertically and lower it onto the mobile transporter base.
7) The transporter will carry the cargo vessel to a dock where equipment and supplies may be easily unloaded.
8) The transporter will then carry the empty vessel, now a chemical storage module, to its final location in a chemical complex.
9) At the landing site, the jib crane will reattach the nose cone onto the spaceship, which is now ready to be carried to a launch pad.

D. Estimated Volumes of Alternative Cargo Modules

Later in this report we employ projections based on estimated volumes of prototypes and modules. For the volume of the proposed module, begin with the cargo section. Applying a cargo wall thickness of 0.6 m for the wall of the cargo section gave interior dimensions of 10.8 m diameter by 19.4 m height. The cargo vessel will fit snugly within the cargo section, so we gave the exterior of the module the same 10.8 by 19.4 m dimensions with a nominal 2 cm margin. The cargo module will suffer less dynamic and static loads during its lifetime than the cargo section of the spaceship, therefore we applied a reduced wall thickness of 0.4 m for the module. Then we applied a half-ellipsoid model to the nose segment, which was found to adhere closely to the outline of the spaceship passenger section as presented by SpaceX[1,2]. The following formula was used:

$V = 4/3\pi(a)\,(b)\,(c)/2$, where

V = interior volume of the nose segment of the vessel in m^3;
a = x axis from ellipsoid center = (5.4 - 0.4} m;
b = y axis from ellipsoid center = (5.4 - 0.4) m; and
c = z axis of ellipsoid end-to-end = (18) m.

The bottom segment was identified as a standard cylinder with rounded corners on the bottom. Optionally, the bottom may be rounded or concave, i.e. a Coke® bottle bottom.) The volume of this segment was estimated as follows:

$V = \pi r^2\,(h)$ where

V = volume of barrel section in m^3;
r = interior radius of the vessel in m; and
h = interior height of the segment in m.

Table 1. Estimated Volumes of Optional Vessels, by Vessel Segment.

Vessel Interior Specifications	**20 m Vessel**[1]	**19 m Vessel**[2]	**20 m Plus**[3]
Half-Ellipsoid Segment			
a (x radial-m)	5.00	5.00	5.00
b (y radial-m)	5.00	5.00	5.00
c (height =1/2 of full ellipsoid ht. of 18.00m)	9.00	8.00	9.00
Volume (m^3)	942	890	942
Cylindrical Segment			
r (radius-m)	5.00	5.00	5.40
h (height-m)	9.60	9.60	9.60
Volume (m^3)	754	754	879
Bottom Chamfer Adjustment (m^3)	-2	-2	-2
Total Volume Rounded (m^3)	**1690**	**1640**	**1720**

[1]The 20m vessel is employed with delivery methods 4A, 4B, 5B, and 5C.
[2]The 19m vessel is employed with delivery method 4C.

[2]The 20m plus vessel with enlarged cylindrical segment is employed with delivery method 5A.

The results of these calculations are posted in Table 1.

Note that the bottom of the vessel is flat with chamfered (rounded) edges. Rounding requires the removal of material that reduces the volume of the vessel by a small amount. A torus model was fit to the rounded corners to calculate the removed volume, which was minor compared to other factors.

III. Priorities for the Mars Chemical Industry

For decades, the NASA plan for the exploration of Mars included the production of chemical propellants on the surface of Mars[11,12]. These chemicals would sustain the lives of the crew and produce propellants to fuel a rocket returning to Earth. The SpaceX architecture includes the production of propellants; but also includes the production of chemicals to support a colonization project.

The initial Mars chemical industry would produce only the most rudimentary and most critical chemicals, but the basic facilities will provide a foundation for producing a sophisticated assortment of products in the future. The highest priority chemicals are as follows:

1) H_2O and O_2 for immediate human survival;
2) CH_4 and O_2 rocket propellants for the return trip to Earth; and
3) Basic chemicals O_2, CH_4, H_2, and CO as chemical building blocks to create many other chemical species.

Beyond the critical chemicals for short-term survival, colonists would establish facilities to develop a chemical industry for the long-term goal of self-sufficiency. Each landing of a cargo spaceship would bring equipment, supplies and a pressure vessel to add another module to a growing industrial complex.

Table 2. Essential Chemicals for the Chemical Industry[13]

Ammonia	Fluorine	Phenol
Benzene	Hydrogen	Phosphoric acid
Bromine	Hydrogen chloride	Phosphorous
Buta-1,3-diene	Hydrogen fluoride	Propanone (acetone)
Calcium carbonate	Hydrogen peroxide	Propene (propylene)
Chlorine	Iodine	Sodium carbonate (soda ash)
Epoxyethane (ethylene oxide)	Methanol	Sodium hydroxide
Ethane-1,2-diol/Ethylene glycol	Methyl t-butyl ether (MTBE)	Sulfur
Ethanoic acid (acetic acid)	Nitric acid	Sulfuric acid
Ethanol	Nitrogen	Titanium dioxide
Ethene (ethylene)	Oxygen	Urea

CICE Promoting Science at the University of York, United Kingdom, have developed a list of 33 essential chemicals for the chemical industry[13], which are listed in Table 2. The goal of Mars self-sufficiency will require all the chemicals of Table 2 to be produced on Mars eventually; however, showing all the processes and all the steps toward achieving that goal is beyond the scope of this paper. Table 2 may represent a long-term goal for developing the Mars chemical industry.

IV Example Modules

In this section, we will show how SpaceX may offer ITS standard pressurized modules to their customers. We assume customers will acquire individual vessels and convert the interior of each one for their own application on Mars. For these customers, the following examples of chemical reactors and a standard chemical storage vessel will illustrate how applications may be adapted to a standard ITS cargo module.

A. A Standard Module for Chemical Storage

The most common application for a standard pressurized module will be a tank for storing chemicals. A pressurized vessel will be required for each cryogenic liquid, such as LOX and LCH4, and for each pressurized gas, such as H_2 (assuming liquid H_2 would usually require too much energy to maintain).

Each chemical storage module should be equipped to accommodate plumbing pipes or ducts for gases or liquids; these pipes will carry chemicals to and from other modules for storage or for further processing.

Each module would have three openings in standard locations, as shown in Figure 9. These openings would be placed at the top, bottom and middle of the vessel, which are the locations necessary to accommodate a wide range of chemical processing applications. Openings should be large enough to accept the largest combination of pipes and ducts that may be required for any one customized module; this may require a diameter of 150 cm for each opening. A temporary plug should be inserted into each opening to protect it from damage during handling and transport to the customer's location.

Each customer would replace the temporary plug in each opening with his own same-diameter fitting as part of customization. This fitting will consist of a solid plug for unused openings or an adapter plate with drilled holes to accommodate the plumbing pipes for his application. Figure 9 shows four examples of hole patterns that may be bored through such an adapter plate. Example A shows two large and two small holes that could accommodate input and output liquids (large holes) and two input and output gases (small holes). In this case, the inflow and outflow pipes are in the same opening of the vessel, whereas in other applications inflow and outflow may proceed in different directions. Example B shows four openings of the same size. This pattern could accommodate inputs and outputs of different chemicals having the same volumes of flow. Example C shows one large square opening for a large duct, presumably for a large gas flow in one direction. Example D shows the maximum size opening for one pipe carrying liquid or gas. Once the customer produces adapter plates they should be permanently fused into their respective ports.

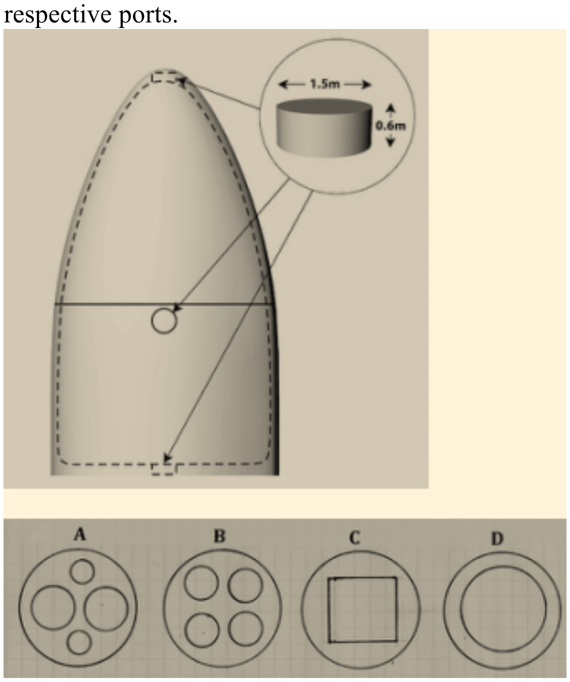

Figure 9. Plumbing Ports at Three Standard Locations and Examples of Inserts: *(A) For gases and liquids; (B) For inputs and outputs; (C) For one large duct; and (D) For a large single pipe.*

Each chemical storage module will be composed of composite material[2], which is one the best options for many chemical storage tanks[14,15,16]. Various types of Fiber Reinforced Polymer (FRP) are resistant to a wide variety of corrosive chemicals used in the chemical industry[21]. Innocuous species such as CO_2, N_2 and Ar are easily handles and reactive species like CO, O_2, Cl_2, or NaOH can be stored with the proper selection of composite material[39]. For example, Polyesters and vinyl esters have excellent acid resistance. A reducing acid such as HCl is very corrosive to carbon steel, but FRP can tolerate the acid at high temperatures and concentrations up to 37%. On the other hand, concentrated H_2SO_4 is much more aggressive toward FRP.

Each chemical is different and must be evaluated differently to determine whether the composite material of a standard ITS tank will be appropriate. In the case of an especially severe species like concentrated H_2SO_4, the customer will require an additional technique to handle it. In some cases, a specialized coating may be applied to the inside walls of the storage vessel or it may be necessary to build a separate tank within the standard ITS storage tank. In this case, the space between the exterior of the inside tank and the interior of the outside tank may become useful; it can be designed to provide access for the maintenance crew. The space around fittings, joints, and motors should be sufficient to allow a person in a spacesuit to perform repair work. Alternatively, if the interior space can remain pressurized and temperature controlled, then the work may be performed in shirtsleeves and much less space will be required.

B. An Atmospheric CO_2 Cleaning Process

Mars' atmosphere is 96.0 percent carbon dioxide, 1.9 percent nitrogen, 1.9 percent argon, and trace amounts of H_2O, CO, O_2 and CH_4[17]. Atmospheric CO_2 will provide the carbon to produce organic chemicals; however, Mars atmospheric CO_2 should not be introduced directly into industrial machinery

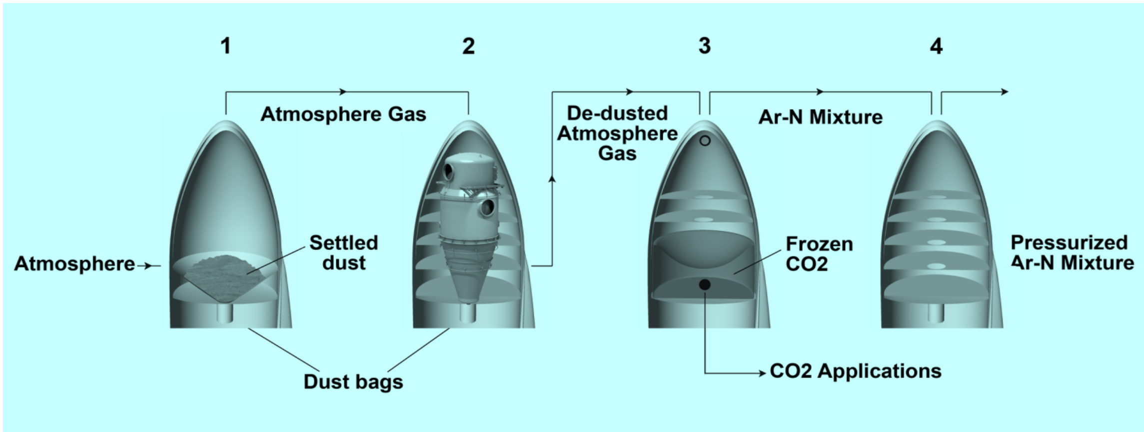

Figure 10. Four-step CO2 Cleaning*: (1) Dust-settling chamber; (2) Clean-in-place dust filter/bag-house; (3) Clean CO2 freezing and storage; (4) N and Ar byproduct gas storage.*

because it carries a heavy burden of dust that can damage machinery and interfere with chemical processing.

On Earth, atmospheric dust particles adhere to water droplets, which scrub dust out of the atmosphere during rainfall or morning dew. Mars, on the other hand, has almost no moisture in the atmosphere[17,18]. In addition, Mars' lower gravitational acceleration allows dust particles to remain suspended in the atmosphere and travel long distances. Martian atmospheric dust particles are generally 3 µm in diameter and can remain in suspension indefinitely at most wind speeds, while particles up to 20 µm diameter can enter into suspension with a surface wind speed as low as 2 m/s and remain in suspension at 0.8 m/s[18]. Cleaning the atmospheric CO_2 for industrial use will involve the removal of dust and unwanted gases from an atmospheric gas stream. Figure 10 shows this process in four steps.

The Step 1 module is a dust-settling chamber that provides a quiet zone where airborne particles slow down to a speed significantly less than 0.8 m/s so that dust particles settle out of the air. Fine dust will accumulate at the bottom of the settling chamber where it will be collected periodically, placed in {polyethylene} dust bags, and stored for other applications. In step 1 a standard pressure vessel is customized as a settling chamber, but only the outside air pressure is involved. This step only requires a large enclosed volume with an opening on one side for atmospheric gas to enter the chamber; a tube at the top of the chamber to remove partially cleaned gas; and a dust collection device at the bottom. A chamber built from ISRU materials could easily replace this ITS vessel. The advantage of a settling chamber is that very little energy is required to operate it and the particles removed in this step will reduce the dust load and energy required for the next step.

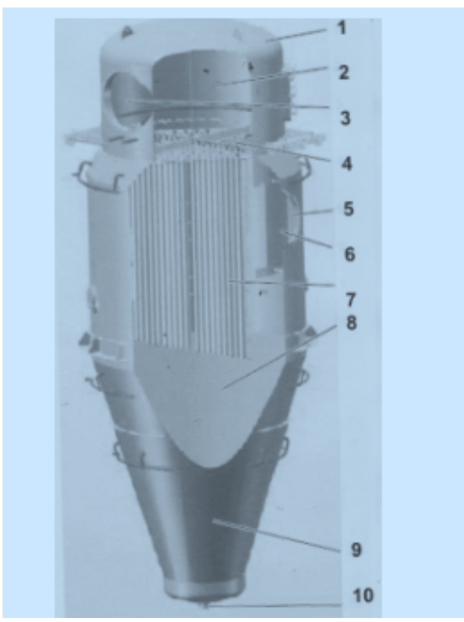

Figure 11. Components of a large Clean-In-Place (CIP) filter unit: *(1) housing, (2) clean gas chamber; (3) clean gas outlet; (4) filter plate; (5) raw gas inlet; (6) raw gas baffle plate; (7) filter bags; (8) raw gas chamber; (9) filter cone; and (10) discharge [dust] (Courtesy Intensiv-Filter Company,* Germany].

The second step is comprised of a large clean-in-place (CIP) particulate filter unit, as illustrated in Figure 11. During routine operations, atmospheric gas flows from the outside of the filter bags through small pores to the inside of the bags, allowing dust particles to be trapped on filter surfaces. The filter bags are de-dusted by a high-intensity reverse flow of gas to dislodge the dusty filter cake from the filters. Occasionally the autonomous operation must be shut down and the equipment cleaned and inspected by the crew.

As an alternative to a bag-house, an electrostatic precipitator (ESP) may be employed. An ESP features thin wire electrodes hanging inside a chamber where air passes through. When an electrical current is applied to the wires, dust particles in the atmospheric stream are attracted to the charged wires and adhere to them. To remove accumulated dust from the wires, gas flow through the ESP chamber is turned off and the charge on the electrodes is reversed. Dust is repelled from the wires and settled to the bottom of the chamber where it is bagged periodically. An ESP can achieve very high efficiency (>99.5%) of dust removal, but requires very high usage of electrical energy[22]. For this reason, the bag house was chosen; but an ESP will be appropriate for special applications where very high purity of input gas is required. To minimize its usage, the ESP should be employed only for a specific industrial process and downstream from other less expensive dust-removing equipment.

When adapted to a Mars chemical industry, this type of CIP bag-house will be sized (large) to just fit into a standard module. Alternatively, an assembly of smaller and easier-to-manufacture filter units may be employed. This approach will maximize the volume of clean CO_2 provided by one CO_2 cleaning module to the downstream chemical processing modules.

In Step 3 the de-dusted CO_2 stream flows into a multistage compressor that elevates atmospheric gas pressure. It draws gas through the preceding two steps and forces pressurized gas through the next two steps. The atmospheric stream flows into a refrigeration unit at the top of the Step 3 module. As the temperature drops below -56.6 degrees C, the CO_2 freezes out of the gas stream and collects at the bottom of the chamber. The remaining atmospheric gases, Ar, N, and CO, could be wasted to the outside; however, this will be an opportunity to capture these gases for further usage.

In Step 4 the remaining gas stream is diverted into a pressurized gas storage module. As shown in Table 3 the byproduct airstream (after CO_2 removal) contains a substantial amount of Argon and Nitrogen, which is a chemically neutral combination that can be mixed with O_2 and a small amount of CO_2 to make up breathable air for habitats and greenhouses. Before this application can be implemented, however, the CO component must be completely removed because CO is potentially fatal, even in small quantities. One remedy may be to elevate the gas temperature and expose the mixture to a catalyst until the O_2 component reacts completely with the remaining CO, which should eliminate the hazard. For added safety, CO detectors should also be installed in habitats. The N_2 and Ar mixture may also be sent to an air separation module to isolate the two gases as pure N_2 and pure Ar.

Table 3. CO_2 Cleaning (Step 3) alters the distribution of components in the remaining gas stream.

Gas Components of the Incoming Mars Atmosphere	Component Percent of Atmos. gas[10]	Component Percent of Remaining Gas Stream by Percent Removal of CO2 from Atmos. Gas				
		80.0 Pct.	90.0 Pct.	99.0 Pct.	99.9 Pct.	100.0 Pct.
Carbon dioxide (CO_2)	95.97	82.68	70.48	19.28	2.33	0.00
Argon (Ar)	1.93	8.32	14.17	38.75	46.84	47.99
Nitrogen (N_2)	1.89	8.14	13.88	37.95	45.87	46.99
Oxygen (O_2)	0.146	0.63	1.07	2.93	3.54	3.63
Carbon monoxide (CO)	0.0557	0.24	0.41	1.12	1.35	1.38
Totals:	99.99	100.01	100.01	100.03	99.93	99.99

Table 3 shows that a high rate of CO_2 removal is required to achieve an acceptable CO_2 concentration. For human habitation, the level should be less than 5.5 percent. According to this table, such a low concentration will only be achieved as the CO_2 removal efficiency approaches 99.9 percent. At the same time, the CO_2 freeze-out of step 3 may or may not achieve a high removal efficiency. The goal in this step should be to substantially reduce the percent of CO_2 in the remaining air stream, not to remove it entirely. Regardless of the CO_2 removal efficiency, an additional air separation process will be required to completely remove lethal CO and to reduce other contaminants before introducing the remaining gas into habitats. Air separation requires high energy usage to bring down the temperatures of all gases, including Ar and N_2, below their triple point. The cost of air separation will be substantially reduced by removing the largest constituent (CO_2) at a higher temperature and lower energy cost. In step 4, the remaining air steam will be stored for further processing.

C. A Sabatier Reactor and Electrolysis (SE) Module

For a long time, we have known that oxygen and methane will be the preferred rocket propellants to fuel a return trip from Mars[23]. Using these propellants, SpaceX will refuel the ITS spaceships and propulsion units for their trips back to Earth[2]. To synthesize methane, the Sabatier reaction[24,25] (also called methanation) will be the primary method of producing CH_4. It involves an exothermic chemical reaction of hydrogen with carbon dioxide at elevated temperature (300–400 °C) and elevated pressure and activated by a catalyst. The over-all reaction is:

$$CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O + \text{energy} \qquad \text{Eq (1)}$$
$$\Delta H = -165.0 \text{ kJ mol}^{-1}$$

To start up this exothermic reaction, an initial input of heat energy is required. A resistance heater located inside the reactor module will initiate the reaction, but once the reaction begins it will produce its own heat to continue the process and provide surplus heat for other applications.

The input chemicals for this reaction are carbon dioxide and hydrogen. The CO_2 input will derive from Mars' atmosphere and will be cleaned via the four-step CO_2 cleaning process before entering the Sabatier reactor. The H_2 input may initially be brought from Earth to start up the process, but after start-up the H_2 will be derived from water electrolysis, the second process to take place within an SE module.

Water electrolysis will employ a DC power source connected to two electrodes, usually consisting of two plates composed of inert metal, such as platinum, that are immersed in water[26]. In more modern technology the electrodes may be polymer electrolyte membranes[27]. Electrons at the cathode cause H_2 gas to be generated whereas O_2 gas is generated at the anode. Adding an electrolyte and an electro-catalyst accelerates the process to a high rate of gas production. Following is the over-all reaction[26] for water electrolysis:

$$H_2O_{(l)} + \underset{\text{Electricity}}{237.2\text{kJ mol}^{-1}} + \underset{\text{heat}}{48.6\text{kJ mol}^{-1}} \rightarrow H_{2\,(g)} + 1/2\ O_{2\,(g)} \qquad \text{Eq (2)}$$

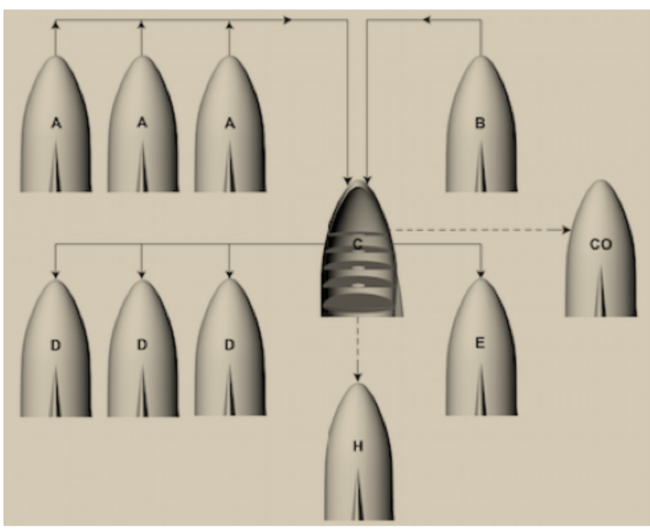

Figure 12. Modules Employed for the Sabatier Reactor and Water Electrolysis (SE) Process: *(A) Input H_2O storage including extra modules for extended runs; (B) Chemical storage module for input CO_2; (C) Reaction vessel for Sabatier reaction and H_2O electrolysis; (D) Storage for output O_2 including extra capacity modules; (E) Storage module for output H_2O that may be used or recycled; (H) Byproduct H_2 storage; and (CO) Byproduct CO storage as input to the chemical industry*

The input H_2O will derive from a water mining operation. Water is known to be abundant on Mars, but unlike Earth, it occurs in solid state rather than liquid. Water mining for underground ice would proceed by employing soil-moving machines analogous to strip mining equipment. Alternatively, wells may be drilled to reach buried glacial ice, heat and pressurize the water to liquid state, and pump the liquid into a storage module. In either approach, further heating would distill H_2O to separate it from soil detritus and from frozen gases, such as CO_2. The product of distillation would be stored as cleaned water in a standard chemical storage module. Another source would be H_2O byproduct from the Sabatier reaction.

Like the carbon dioxide reduction assembly (CRA) inside ISS Destiny module[28], the Sabatier reaction and water electrolysis unit will live together in a symbiotic relationship within the SE module. The Sabatier reaction is exothermic while water electrolysis is endothermic. By co-locating the two processes together, the excess heat generated by the Sabatier reaction can be easily employed to drive electrolysis. Conversely, water electrolysis will produce H_2 for the Sabatier reactor.

Figure 12 shows how ITS cargo vessels may be employed as modules for an initial Sabatier-electrolysis process. Module A is an ITS pressurized cargo vessel converted into a standard chemical storage module. It is employed to store clean water (or water ice) prior to its introduction into the SE reactor. Module B is a second storage vessel for clean CO_2 from the 4-step process prior to sending it into the SE module. Module C is the SE (combined Sabatier reactor and electrolysis) module. Module D is a storage module for the output product CH_4 and module E is a storage vessel for the byproduct H_2O. Alternatively, water may be recycled back to H_2O storage (Module A) or directly to the SE unit. One reason for capturing the H_2O in a tank separate from the input water is that it will be of higher purity (due to additional processing) and may be employed for a different purpose, such as drinking water or a chemical process that requires high purity H_2O.

Figure 12 also shows how supplemental modules may be added to an initial layout. Extra H_2O storage modules (A) were added to facilitate a longer batch processing run. Extra CH_4 storage tanks (D) were added to accumulate rocket propellant in larger quantities. Modules "H" and "CO" were added to accumulate H_2 and CO byproducts that may be useful to the chemical industry.

In a perfectly balanced setup the volumes of storage vessels A, B, C, and D would exactly match the throughput rate of reactor C. However, there are various reasons why this will not be (and should not be) the case, such as the following:

1) Batch processing at various steps may take place at different times from other steps. For any process to proceed, there must be sufficient input chemicals and sufficient storage capacity for inputs and outputs. Interruptions in processing can be reduced by having sufficient storage modules available before start-up.

2) Routine maintenance will halt processing. For example, catalytic beds will require regular change-out as they become used up or contaminated.

3) Utilization of each storage vessel will grow as the colony grows. Storage capacity (and reactor capacity) will increase until the maximum storage limit is reached. At that point, it may be necessary to add additional storage modules.

4) Throughput capacity of the reactor may change over time. The number of SE reactors inside a reactor module may start out few and increase as additional reactors are added to accommodate colony growth.

5) Each chemical may be stored for multiple purposes in addition to serving the SE processing module. For example, O_2 storage will may serve habitats as well as a propellant tank farm.

6) Certain chemicals, especially H_2O and O_2 required for human survival, will require backup storage. If for any reason chemical production were halted, there must be stored surplus on hand to carry the colony until the emergency can be resolved.

Note that the Sabatier and electrolysis processes using ITS cargo modules will be simpler than the analogous process in the ISS. Chemical reactions in the SE module may proceed at a high rate for an extended period because adequate numbers of input modules buffer the SE unit from variations in the production of the inputs. Also, adequate chemical storage modules are available for outputs. This luxury is not available in the ISS where other systems, such as cyclical power generation, trace contaminant removal, and CO_2 removal, with their own variable rates, connect directly with the CH_4 production system with no buffering[29]. Conversely, the reactor in the SE module can proceed until (a) one of the input modules A or B are emptied; or (b) one of the output modules D or E reaches capacity; or (c) the catalysts within the reactor module C reach end-of-life; or (d) some component in the system fails.

Also note that O_2 production for human habitats will occur primarily within each habitat. The smaller systems for dwellings will be the primary generators; SE modules will only supplement the O_2 supply for habitats as emergency back-up.

D. Production Rate of the SE module

To plan for expansion of chemical facilities, one needs to estimate the rate of production of all the reactors, including the SE module(s). One needs to calculate the kg per day of CH_4 generated from a Sabatier-electrolysis system that fully utilizes the volume of one ITS cargo module.

To begin the estimate, consider the rate of production of CH_4 from the Sabatier reactor installed in the ISS. Its purpose is to utilize waste byproducts H_2 and CO_2 from other air treatment units to produce drinking water and reduce CO_2 levels[29]. This reactor, called the Carbon Dioxide Reduction Assembly (CRA), is a component added to an existing air revitalization system(ARS)[25]. Prior to installing the CRA,

CH_4 produced by the ARS was wasted to space. Nevertheless, its production of CH_4 may be used as a guide to estimating the potential CH_4 production rate on a larger Sabatier reactor employed on Mars.

The "prototype" Sabatier reactor [24] consisted of a 1-inch diameter stainless steel tube approximately 8" long that contained 12 ml (~0.73 in^3) of catalyst bed. The catalyst bed volume was sized to handle a gas hourly space volume (GHSV) of 30,000 to 60,000 hr^{-1} with an inlet gas flow to the reactor of 6 – 12 standard liters per minute (SLPM). However, one of the units providing chemical feedstock only operated during orbital daylight periods at a limited production rate of 25 to 100 percent of full capacity[24].

The CRA receives CO_2 inputs from a Carbon Dioxide Removal Assembly (CDRA)[28]. The CDRA consists of desiccant beds and zeolite CO_2 adsorbent beds that operate on a cycle. The on/off cycle corresponds to the orbital day/night periods when the ISS solar panels are generating or not generating power. When CDRA is turned on it adsorbs CO_2 up to the capacity of their adsorbent beds; when turned off the beds are heated and the CO_2 is driven off and piped to the CRA reactor.

The CRA also receives H_2 from an electrolysis unit called the Oxygen Generator Assembly (OGA). It generates O_2 to replace the amount consumed by breathing of the crew. It also generates H_2, which is piped to the CRA as an input.

In 2010, the flight CRA was installed into the air revitalization system of the ISS[28].To date, none of the published data included the actual hourly or daily CH_4 production rate, however, Takada, Ghariani and Kheuren[30] stated the production rate of O_2 from the OGA. It is designed to generate oxygen at a nominal rate of 5.4 kg/day when operated under variable ISS conditions or at a selectable rate between 2.3 and 9.2 kg/day when operated continuously. One may use this data to estimate the production rate of CH_4 from the ARS. From Section C, equations 2 and 1 may be rewritten as interconnected mass-balanced equations that proceed simultaneously. (Molecular mass shown below each species):

$$\underset{72}{4H_2O} \rightarrow \underset{8}{4H_2} + \underset{64}{2O_2} \qquad \text{Eq (2)}$$

$$\underset{44}{CO_2} + \underset{8}{4H_2} \rightarrow \underset{16}{CH_4} + \underset{36}{2\,H_2O} \qquad \text{Eq (1)}$$

In this idealized scenario, 100 percent of H, O and C are utilized. When 64kg of O_2 is produced in equation 2, exactly 16 kg of CH4 is produced simultaneously in equation 1. The mass ratio between production rates is 4:1. Thus, a continuous O_2 production rate may be converted to a simultaneous CH_4 production rate as follows:

$P_{CH4} = P_{O2}(M_{CH4}/M_{O2}) = P_{O2}\,(.25)$ where P_{CH4} and P_{O2} are CH_4 and O_2 production rates respectively, and M_{CH4}/M_{O2} = mass ratio of CH_4 to O_2.

Thus, for the continuous maximum O2 production rate of 9.2 kg/day, the simultaneous CH_4 production rate would be 2.3 kg/day.

The second part of projecting from the prototype to the proposed SE module requires one to know the volume of the Sabatier-electrolysis unit within the ISS. The NASA ISS User's Guide[31] explains that the agency allocates space for equipment by specifying the configuration of an International Standard Payload Rack (ISPR), which is a set of shelves handled as a unit. Each ISPR provides 1.571 m^3 of internal volume and has a curved back-plate to accommodate the curved interior surface of an ISS cylindrical module, such as the US Destiny module.

The CRA is installed in one ISPR along with the OGA, as shown in Figure 13. The OGA occupies the right half of the rack space where it conveniently provides H_2 directly to CRA via a physical plumbing connection. The CRA and a CO_2 control assemblies occupy the left side. The CRA receives its CO_2 input from the CDRA, which in an adjacent, but separate

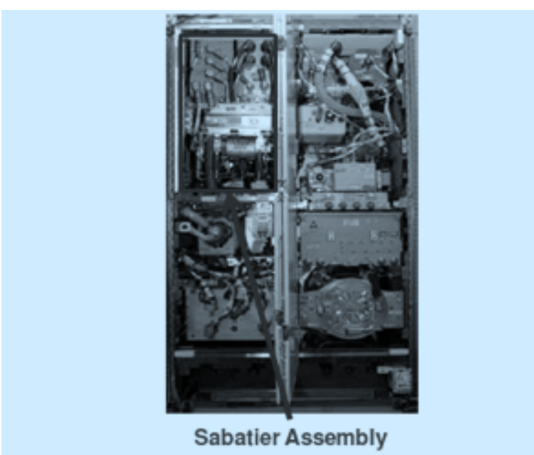

Figure 13. The CO2 Reduction Assembly (CRA): *A Sabatier reactor located inside an ISPR, sharing the left side with a CO2 Control Assembly, while the Oxygen Generator Assembly (OGA) occupies the right side.*

ISPR[28]. The CRA and OGA together may be considered a prototype for the two processes in the SE chemical processing module. Thus, for this paper the volume of one ISPR (1.571m^3) will be considered as the volume of a prototype unit preceding the SE module.

Two aspects of this simplifying assumption may require explanation. First, the CDRA is not included in the volume of the prototype, which may be reasonable because there will be no processing unit comparable to a CDRA in the SE module; the SE module will receive its CO_2 directly from a clean CO_2 storage tank (a separate module). Second, the ISS prototype includes a CO_2 control assembly, which is necessary to accumulate CO_2 as it is received intermittently from the CDRA. However, there will be no comparable control unit in the SE module, so using the entire ISPR volume represents a conservative approach that allows for unknown plumbing or additional devices that may be necessary in the SE module.

To extrapolate the production rate of a small Sabatier unit to the SE module, one requires a linear volumetric expansion factor (F). This assumes that a compact plumbing arrangement will be found for the SE Module that is comparable to the plumbing efficiency of the prototype unit. Any near-term advances in design technology are not considered. For this exercise, use the estimated volume for the 20m module from Section II D above, which is 1690 m^3. Of this volume, one may allocate 600 m^3 for crew access and for additional plumbing to tie together multiple reactors (estimate by the Author). Thus, we have

$F_{CH4} = 1090\ m^3 / 1.571\ m^3 = \underline{694.}$

This is equivalent to saying 694 prototype Sabatier reactors would theoretically fit into one ITS module. One may further assume that the production rate of both O_2 and CH_4 are proportional to the volume of their respective production units. The highest continuous O_2 rate is 9.2 kg/day for the prototype, so the projected O_2 production rate for the SE module is:

$P_{O2} = (694)\ (9.2kg/day) = 6385kg/day = \underline{6.385}t/day$ of O_2.

The projected CH4 production rate is:

$P_{CH4} = (694)\ (2.3kg/day) = 1596.2kg/day = \underline{1.596}\ t/day$ of CH_4**.**

E. An Oxygen-Generating Module

The SE modules will generate CH_4 and O_2 propellants required for launching spaceships back to Earth. Beyond fulfilling these requirements, the budding chemical industry will require additional O_2 to create many additional chemicals, including some of those listed in Table 2.

The example of an oxygen-generating module presented here is based on MOXIE (Mars Oxygen ISRU Experiment)[32,33]. It was developed by MIT and planned by NASA to be installed in the instrument package of the 2020 Mars Exploration Rover. It will generate O_2 from CO_2 taken from the Martian atmosphere by means of a solid oxide electrolysis (SOXE) process developed by Ceramatec, Inc. for this purpose. Its working elements are stacked cells containing a scandium-stabilized zirconia electrolyte. It features a thin-screen printed cathode coated with a catalyst on one side of each cell and an anode on the other side. These electrodes are separated by expansion-matched interconnects that direct the source gas, the exhaust gas, and product gases toward their respective manifolds. (Fig. 14)

In this field experiment, an electrical potential is applied to an electrode to electrolyze CO_2 and separate it into CO and O^- ions. The CO is exhausted and the oxygen ions are electrochemically driven through the SOXE elements to an anode. At the anode, oxygen atoms combine to produce O_2 gas that is released from the anode cavity. The strength of electrical current and the input CO_2 flow rate determine the rate of O_2 gas produced. The experimental process will produce 22gm of O_2 per hour when running at capacity[32].

According to NASA, the experimental prototype may be scaled up for a human expeditionary trip to Mars[33]. Scaling up by a factor of 100X would generate sufficient O_2 over a two-year period to fill a spacecraft capable of launching four persons on a return trip to Earth[32]. This scenario is consistent with the NASA architecture for an initial exploration foray to Mars' surface[11]. Applying the 100X expansion factor converts the experiment to an operational volume to16.6 m^3 and the expanded output rate would be 2.2kg/h.

To design an oxygen generator that fully occupies an ITS module, one may apply an even larger volumetric expansion factor (F_{O2}). First, one may estimate the O_2 production rate of a scaled-up MOXIE process. As a first order estimate, one will replicate the volume of the experimental unit until the available volume of the O_2 generator module is filled up. The volume occupied by the experimental MOXIE unit (Fig. 14) is 0.016568 m^3 (0.235m by 0.235m by 0.300m). The volume of the ITS cargo module was previously estimated as 1690 m^3. One may allow 600 m^3 for maintenance crawlways to access the machinery and for extra plumbing to tie together the production units. This will leave 1060 m^3 for numerous MOXIE units. Then a crude multiplier would be $1090m^3$ / $0.016568m^3$ = 65,789. The output rate for the module under continuous operation would be:

P_{O2} = (22gm/h) (65,789) = 1.44736E6gm/h = 1447.36kg/h = <u>34.7</u> t/day

at the highest continuous production rate. This estimate does not consider any economy of scale, improved plumbing layout, or any other technical improvement that is presently unknowable.

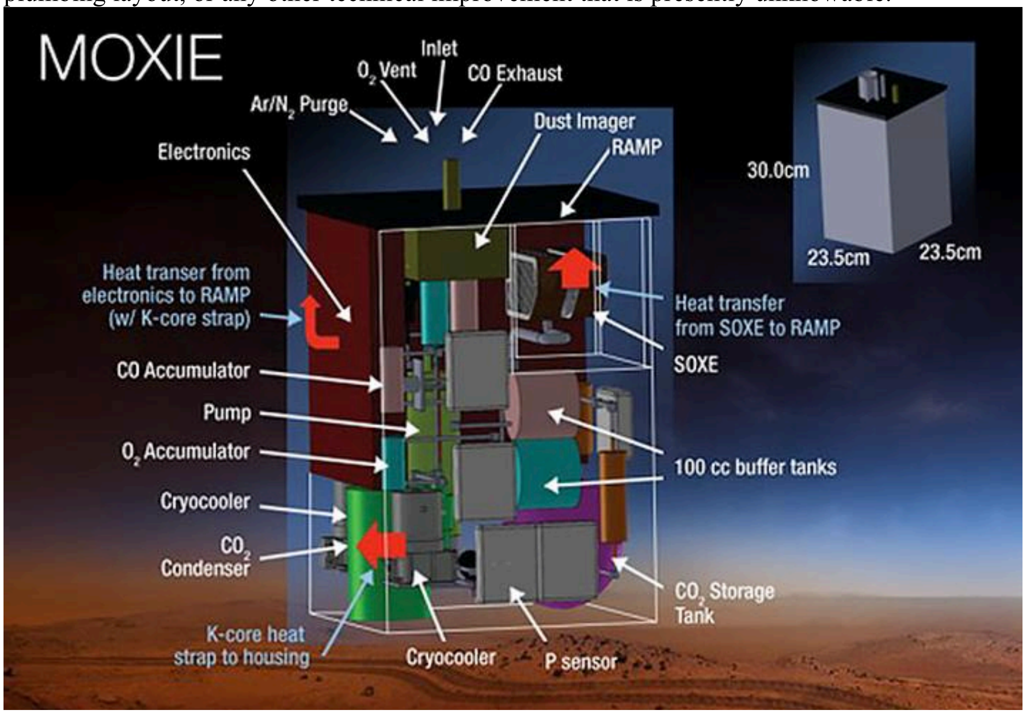

Figure 14. Components of the Mars Oxygen ISRU Experiment *(Courtesy of NASA and Wikipedia Commons).*

To design an O_2 generator module to achieve the maximum feasible production rate, new engineering studies will be required. The objective would be to determine the size of an individual reactor or group of reactors and their related equipment that would deliver the highest ratio of O_2 production rate per volume (or mass) of equipment, given the constraints of size and configuration of the module and the volume allocated for maintenance access and plumbing.

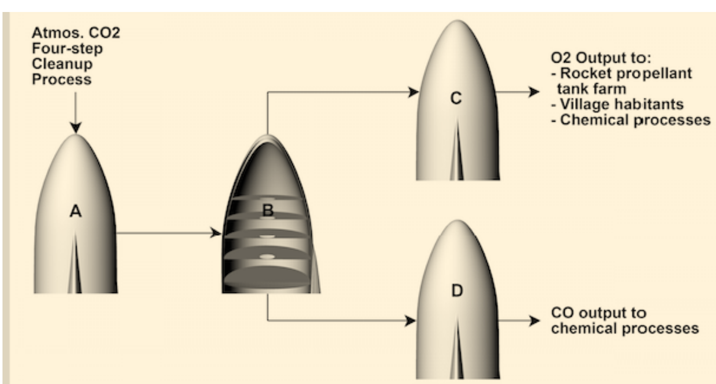

Figure 15. Modules Needed for a Scaled-up (MOXIE) O2 Generating Process: *(A) Input CO_2 storage; (B) O_2 generator module;(C) Output O_2 storage; and (D) Byproduct CO storage.*

Figure 15 shows how four ITS modules may be employed in a MOXIE O_2 generating process. In this approach, the input CO_2 is taken from the four-step cleaning process described earlier and stored in a storage module (A) prior to entering the O_2 generator (Module B). The output O_2 is stored in another storage vessel (Module C) prior to sending to various applications. Such applications may include supplying large quantities of O_2 to a propellant tank farm near a launch facility, supplying an emergency backup O_2 tank at a habitat community, or supplying a chemical/industrial process that requires a large volume of oxygen. One such process could be a steelmaking plant.

A possible disadvantage of the MOIE-derived process is that a nuclear power plant may be required to operate the scaled-up facility. According to current information, the SpaceX architecture will only employ solar panels[7].

F. An Atmosphere Separation Module

On Earth, an air separation unit (ASU) separates the constituents of air into its component gases. It principally separates oxygen from nitrogen, but sometimes argon and other rare inert gases are isolated as byproducts. The most common method of air separation is cryogenic distillation. Cryogenic ASUs are designed to produce a single gas, such as nitrogen or oxygen, in a pure form. Cryogenic distillation is the only viable means of isolating the rare gases neon, krypton and xenon[35,36].

On Mars, the atmosphere is 96 percent carbon dioxide with nitrogen and argon comprising most of the residual gas. To process Mars' atmosphere, a preliminary freeze step in the CO_2 cleaning process would solidify most of the CO_2 and separate it from the remaining air stream, containing N_2, Ar and trace constituents.

To separate pure gases from an atmosphere, air must first be cooled down until it liquefies. Then the temperature is slowly raised, selectively distilling out the gases at their respective boiling temperatures. To achieve the extremely low temperatures, an ASU requires a refrigeration cycle that employs the Joule Thompson effect[37]. The energy for refrigeration is focused into the compression of air at the inlet to the machine and the cold equipment must be kept inside an insulated enclosure (a "cold box"). On Mars the cold box would be placed inside a pressurized and insulated module. Note that the ASU process produces high purity gases at the expense of high energy consumption. Most of the CO_2 component of the Mars air stream would be already removed, so much less energy will be required to cool down the small amount of remaining atmospheric gas to cryogenic temperature.

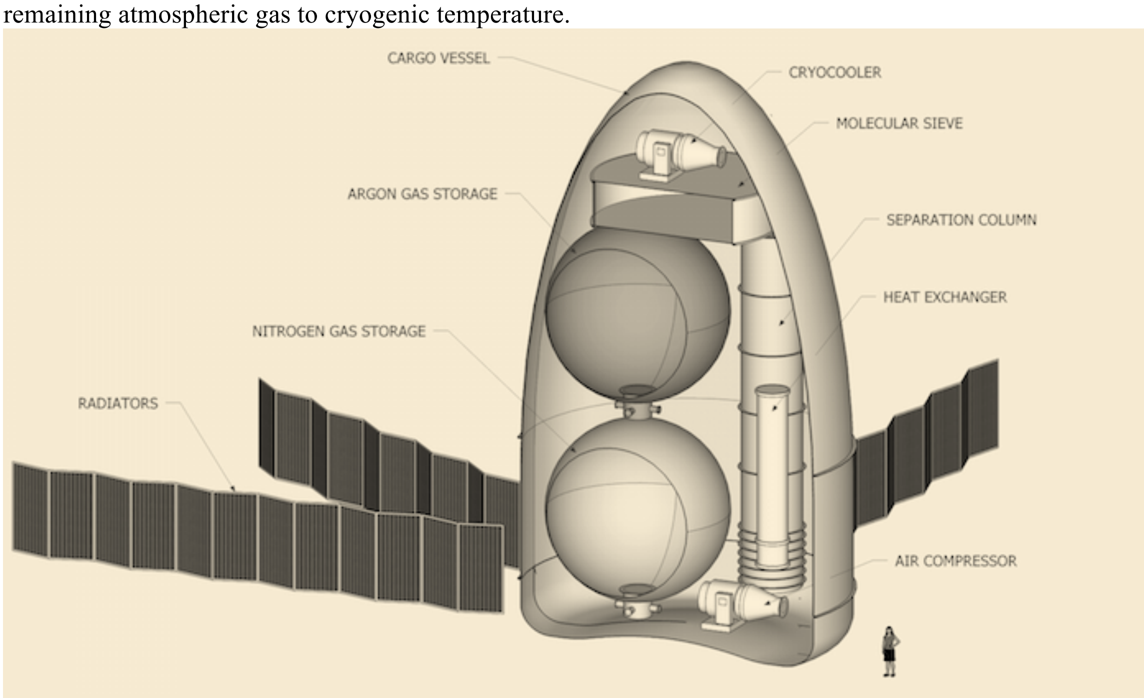

Figure 16. Air Separation Process Placed within One Module.

The cryogenic separation process for a Mars colony would require tight integration of the heat exchangers and separation columns to achieve energy efficiency. To help achieve this efficiency, modern ASUs may utilize expansion turbines for cooling and the output gas from the expander will help drive the air compressor[37]. The ASU process will consist of the following steps:

1) Dust removal. This is the first step for both Earth and Mars. The colony would employ the 4-step CO_2 cleaning process for the process gas prior to entering the ASU module.
2) Heat exchange. Incoming process gas is passed through an integrated heat exchanger and cooled by output cold gas streams.

3) Multi-stage air compression. The compression pressure is determined by the recovery rates of the various gases with typical pressures ranging from 0.5 to 1.0 mPa.
4) Molecular sieve. Process gas is passed through a molecular sieve bed to remove any remaining water vapor or carbon dioxide, which would freeze and plug up the cryogenic equipment.
5) Cryocooler. The refrigeration unit employs the Joule-Thompson effect in an expander unit to produce the desired cryogenic temperatures. Compressed liquefied air is fed to the low-pressure distillation column.
6) Distillation. Distillation columns remove various gasses from the gas stream as the temperature rises to their respective boiling points.
7) Heat exchange. The outgoing product gases are warmed to ambient temperature by the incoming air stream through the same heat exchanger as step 2.
8) Product storage. The principal output products are N_2 and Ar gases, which will be stored in two pressure vessels located inside one module, as indicated in Figure 16.

Note that the entire ASU process and output storage may be installed in one module. This is because the output volume is very low compared to the principal industrial products (O_2 and CH_4) and the demand for Ar, N_2, and trace constituents will also be lower.

V. The Initial Chemical Industry

In this proposal, the shells of empty cargo vessels would be employed as standard pressurized modules for an initial chemical industry on Mars. Modules would be adapted to three types of applications: chemical storage, chemical reactors, and industrial processing. For each module, it will be desirable to exploit its entire volume for operating equipment, to operate continuously near the maximum rated capacity, and to continue operating as long as feasible to maximize chemical production. One may assume that batch processing will stop only when a catalyst reaches end-of-life, an input chemical is depleted, the output storage capacity reaches zero, or equipment fails. Otherwise, production would proceed at the maximum feasible rate during each day of operation.

A. A Propellant Tank Farm

The goal of providing propellants for spaceships launching back to Earth would generate the greatest demand for chemical production and storage. Producing O_2 and H_2O for habitats would have the highest priority, but the volume required would be much less. We assume spaceships will launch only during a Mars-Earth conjunction that occurs only once during a synodic cycle of 26 months. The colony must produce and store LOX and LCH4 over the full 26 months to prepare for a short 2-1/2 month launch window. As the colony grows, the number of spaceships landing on Mars and returning to Earth will also grow. Over time, this growth will increase the mass of propellants required to service spaceships.

To plan a propellant tank farm, one needs to estimate the number of storage modules required, beginning with the specifications for one spaceship. According to Musk[1,] each ITS spaceship will carry 1950 t of propellant mass in its tanks. The mass and volume of propellant to fill each tank was not given, but may be estimated as follows:

$M_{O2} + M_{CH4} = 1950$ t — M_{O2} = mass of liquid O_2 (t); M_{CH4} = mass of liquid CH_4 (t)
$3.8M_{CH4} + M_{CH4} = 1950$ t — Mass ratio of combustion in Raptor engine = 3.8 to 1 (Wikipedia)
$M_{CH4} = 1950/4.8 = \underline{406\text{ t}}$
$M_{O2} = 1950 – 406 = \underline{1544\text{ t}}$

Based on the mass and density of each propellant, one may estimate the volume of propellant in each ITS spaceship as follows:
Density of liquid oxygen (D_{O2}) = 1141kg/m^3 = 1.141tm^{-3} at 1 atm. (Wikipedia)
Density of liquid methane (D_{ch4}) = 423kg/m^3 = 0.423tm^{-3} at 1 atm. (Wikipedia)
$V_{CH4} = 406\text{t} / 0.423\text{ t/m}^3 = \underline{960}\text{m}^3$ — Volume of CH_4 tank on spaceship
$V_{O2} = 1544\text{ t} / 1.141\text{ t/m}^3 = \underline{1353}\text{m}^3$ — Volume of O_2 tank on spaceship

Mass of each propellant stored in a storage module at maximum capacity:
$M_{CH4} = (1690\text{m}^3)(0.423\text{tm}^{-3}) = \underline{715}\text{t}$ — Mass of LCH4 stored in one module.
$M_{O2} = (1690\text{m}^3)(1.141\text{tm}^{-3}) = \underline{1928}\text{t}$ — Mass of LOX stored in one module.

B. Required Propellant Production and Storage Modules for a Propellant Tank Farm

When one designs the cargo ITS to exploit the full volume of each ITS module, many spaceships can be serviced. A high production rate will allow many propellant storage tanks to be filled during a 26-month synodic cycle. We have estimated that a fully utilized SE reactor module could produce 6.39t of O_2 and 1.596t of CH_4 per day of continuous production. Likewise, we estimated that a fully utilized O_2 generator module could produce 34.7t per day of continuous production. Using these estimates, an Excel worksheet was drawn up to calculate the number of modules required to service given numbers of spaceships, from 1 to 42. Figures 17a, 17b, and 17c are screenshots of different sections of the worksheet entitled "Modules Required to Produce and Store Propellants for Launching a Specified Number of Spaceships." (A download of the Excel spreadsheet may be obtained by email request to the principal author.)

3	Number of Martiam days in one synodic cycle (one period)	731	Google/NASA
4	Number of production (operating) days in one synodic period	487	Estimate 2/3 of days in one period
5	SE module production rate for CH4 (t/day)	1.596	From section III-D
6	SE module production rate for O2 (t/day)	6.39	From section III-D
7	O2 Generator production rate for O2 (t/day)	34.7	From section III-E
8	SE module CH4 production rate (t/synod)	777	G4 times G5
9	SE module O2 production rate (t/synod)	3112	G4 times G6
10	Number of input storage modules per SE module	2	H2O and CO2 (2) input modulles per reactor
11	Number of CH4 output storage modules for SE reactors	CH4	CH4 produced / mass stored in one module
12	Number of O2 output storage modules for SE reactors	O2	O2 produced / mass stored in one module
13	Number of input storage modules per O2 generator module	1	One for clean CO2 imput
14	Number of output storage modules per O2 generator module	1	One for O2 output
15	Mass of CH4 propellant stored in one storage module (t)	715	From section V-A
16	Mass of O2 propellant stored in one storage module (t)	1928	From section V-A
17	Mass of CH4 propellant in one ITS spaceship tank	406	From section V-A
18	Mass of O2 propellant in one ITS spaceship tank	1544	From swction V-A

Figure 17a. Screenshot of the Inputs and Assumptions for Tank Farm Worksheet 1 entitled **"***Modules Required to Produce and Store Propellants for Launching a Specified Number of Spaceships."*

Figure 17a lists the inputs and assumptions used in the worksheet. The number of days in a synodic cycle was a simple look-up via Google. The number of operating days was estimated as 2/3 of the days in the synodic cycle. The daily production rates of CH_4 and O_2 were taken from the calculations in the referenced sections and subsection of this paper. Total production of CH_4 and O_2 over one synodic period was calculated by multiplying the number of operating days in one synod by the respective daily production rate of each propellant. We assumed that each reactor module receives its inputs from chemical storage modules, one for each input chemical. The masses of propellants in storage tanks and in the spaceship propellant tanks were calculated in Section IV of this paper.

20	Modules Required to Produce and Store Propellants for Launching a Specified Number of Spaceships								
21	End-of-Synodic Period Launch Window				Sabatier-Electrolysis Modules			O2 Generators	
22			Propellants Required (t)		No. of	Production for Period (t)		No. of	Production
23	Convoys	Spaceships	CH4	O2	Modules	CH4	O2	Modules	O2 (t)
24	0	1	406	1544	1	777	3112	0	0
25	0	2	812	3088	2	1554	6224	0	0
26	0	3	1218	4632	2	1554	6224	0	0
27	0	4	1624	6176	3	2331	9336	0	0
28	0	5	2030	7720	3	2331	9336	0	0
29	1	6	2436	9264	4	3108	12448	0	0
30	2	12	4872	18528	7	5439	21784	0	0
31	3	18	7308	27792	11	8547	34232	0	0
32	4	24	9744	37056	14	10878	43568	0	0
33	5	30	12180	46320	18	13986	56016	0	0
34	6	36	14616	55584	21	16317	65352	0	0
35	7	42	17052	64848	24	18648	74688	0	0

Figure 17b. Screenshot of Columns A through I of Tank Farm Worksheet 1.

Figures 17b and 17c are screenshots of selected columns of the same worksheet. The scenario behind the worksheet assumes that the "fleet of spaceships" envisioned by Elon Musk will arrive at Mars in small convoys of six spaceships per convoy. The first two columns show the number of convoys and the number of spaceships to be analyzed. The CH_4 and O_2 propellants required were calculated as the capacity of each tank on one spaceship multiplied by the number of ships. The number of modules employed to produce CH_4 or O_2 is the tonnes of the respective propellant required divided by the total production over one synodic cycle, rounded up. This means that one whole module is required, even when only a small fraction of the module capacity is needed to meet the launch requirement. Propellant production is assumed to proceed over an entire synod during the days of operation, even when only a fraction of production is used for the nest launch window. Thus, total production is the production capacity for one reactor module times the number of such modules. O2 generator modules are only needed when the oxygen produced by the SE module is insufficient to meet the launch requirement. The table shows that no O2 generator whatsoever will be required to fulfill launch requirements under present assumptions. This is because the SE modules are assumed to produce O2 and CH$ in a perfect 4:1 ratio, which is more than the 3.8 to 1 ratio used in a Raptor engine. A more realistic scenario would show some of the byproducts CO and H_2 drawn off for industrial applications, which would change the ratio.

Number of Spaceships

O2 Generators		Extra Production		Propellant Storage Modules Required				
No. of	Production	At End of Period		For SE Modules		For O2 Gen Modules		Total
Modules	O2 (t)	CH4 (t)	O2 (t)	Input	Output	Input	Output	Modules
0	0	371	1568	2	4	0	0	7
0	0	742	3136	4	7	0	0	13
0	0	336	1592	4	7	0	0	13
0	0	707	3160	6	9	0	0	18
0	0	301	1616	6	9	0	0	18
0	0	672	3184	8	12	0	0	24
0	0	567	3256	14	20	0	0	41
0	0	1239	6440	22	30	0	0	63
0	0	1134	6512	28	39	0	0	81
0	0	1806	9696	36	50	0	0	104
0	0	1701	9768	42	57	0	0	120
0	0	1596	9840	48	66	0	0	138

Figure 17c. Screenshot of Columns H through P of Tank Farm Worksheet 1.

Figure 17c continues the calculations. When a reactor module operates throughout the synodic period, it produces a surplus (overage) beyond the requirement of the next launch window. The amount of overage is listed for both propellants. Next, the number of propellant storage modules required to store the propellants produced over the synod are listed. The numbers of modules are broken down by the input and output modules required for each type of propellant produced. One may assume that a minimum of one input module will be employed for each input chemical for each type of reactor module. The number of output modules employed will vary according to the mass and volume of propellant produced. It is calculated as the mass of propellant produced divided by the storage capacity of one storage module, rounded up. Finally, the total number of modules required is the sum of the previous four column entries plus the numbers of SE modules and O_2 generator modules.

To service these spaceships, the table shows the number of days of continuous operation of the SE reactor modules at their highest rate of output to produce the CH_4 required to fill the given number of spaceship methane tanks. Many events will cause interruptions in the number of days of continuous operation, such as:

1) Routine maintenance, e.g. replacing catalyst beds at the end of their service life;
2) Reduced effectiveness of catalysts over their (presently unknown) lifetime;
3) Unplanned maintenance when an equipment component fails;
4) Heating up and cooling down the SE nodule before and after an operating run;
5) Unplanned interruptions in the CO_2 cleaning procedure or clean H_2O production, or;

6) An accident.

These events, especially the unforeseen events, call for a random factor to allow leeway in scheduling the refueling of spaceships. One may assume that 2/3 of the calendar days in a synodic cycle will be available for producing propellants.

Note that the numbers of O_2 generators is zero in this iteration of the worksheet. The generous assumptions underlying the operation of the SE modules allowed all the carbon of the CO_2 input to be converted to CH_4. In a different scenario, some portion of the carbon may become CO and drawn off for use in the chemical industry. In this case, there may be a deficit in the O_2 produced for launching spacecraft and the O_2 generator would come into play.

VI. Summary and Conclusions

In this paper, we proposed a third version of the ITS spaceship: a cargo carrier to Mars. It would transport equipment and supplies inside a pressurized cargo vessel. After landing on Mars, the equipment would be unloaded and the shell of the vessel employed as a chemical storage tank. Alternatively, the cargo vessel would be customized on Earth and delivered to Mars as a ready-to-use chemical reactor vessel or processing unit.

We presented six methods for delivering a cargo vessel to the Red Planet. The first three methods utilized three different types of reusable fairings: three fairing panels, two fairing panels, or a half-fairing that allowed the heat shield to be produced in in one piece. The other three methods featured different styles of nose caps rather than fairings. A jib crane was employed to unload the packed cargo vessel onto a transporter. In the case of the half-fairing, a specialized vessel-grappler was employed to unload the vessel.

We presented five examples of how to employ pressurized cargo vessels: a standard chemical storage tank, a four-step CO_2 cleaning process, a Sabatier-electrolysis module, an oxygen generator, and an air separator module. The standard storage tank would feature standard plumbing access ports. The CO_2 cleaning process would employ four modules as a dust settling chamber, a dust filtering bag-house, a CO_2 freeze-out processor, and as a nitrogen-argon storage tank. The Sabatier-electrolysis module would receive H_2O and CO_2 inputs and produce CH_4 and O_2 with byproducts of H_2 and CO. An air separator module would remove contaminants from a nitrogen-argon mixture to produce high purity gases for habitats or for the chemical industry.

In a small colony, the chemicals required in largest volumes will be rocket propellants CH_4 and O_2 to launch spaceships back to Earth. To illustrate the modular approach, we chose to analyze the module requirements for a propellant tank farm such as diagrammed in Figure 18. We assumed propellants would be produced over a long 26-month synodic cycle, but loaded into spaceship tanks within a short 2-1/2 month launch window. Because the launch period is so short, many storage tanks would be required to accumulate enough propellants for each launch campaign. To implement the tank farm scenario, we used the production rates for the SE module and the oxygen generator in sections IV-C, D, and E. Using these production rates and other assumptions we developed a spreadsheet to calculate the numbers of various types of modules required to launch a given number of spaceships.

We found that as the number of launches grew, the number of required modules grew quite large. If the colony were to produce propellants to launch just one spaceship, one SE reactor module would be required along with 2 storage modules for inputs, 2 for outputs, and 2 to capture surplus production. To launch two convoys of six spaceships per convoy, 41 modules would be required. If the colony were to launch seven convoys of six spaceships per convoy, 138 modules would be required under the current assumptions. Although the volume of each cargo vessel was maximized, the high demand for propellant storage modules could potentially hinder the growth of the colony. This unexpected discovery represented the most important finding.

Because too many modules may be required under present assumptions, other methods to reduce the numbers of modules may be required, especially for chemical storage. In this regard, we offer these suggestions:

1) Employ ISRU construction techniques early in the colonization process. Build extra-large storage facilities that can replace ITS storage modules.

2) Implement landing and launch schedules that allow cargo spaceships to launch during the entire synodic period. This may require launching vehicles to Mars orbit and hovering there until the launch window opens. Another procedure would launch spaceships back to Earth in longer, low-energy orbits. The

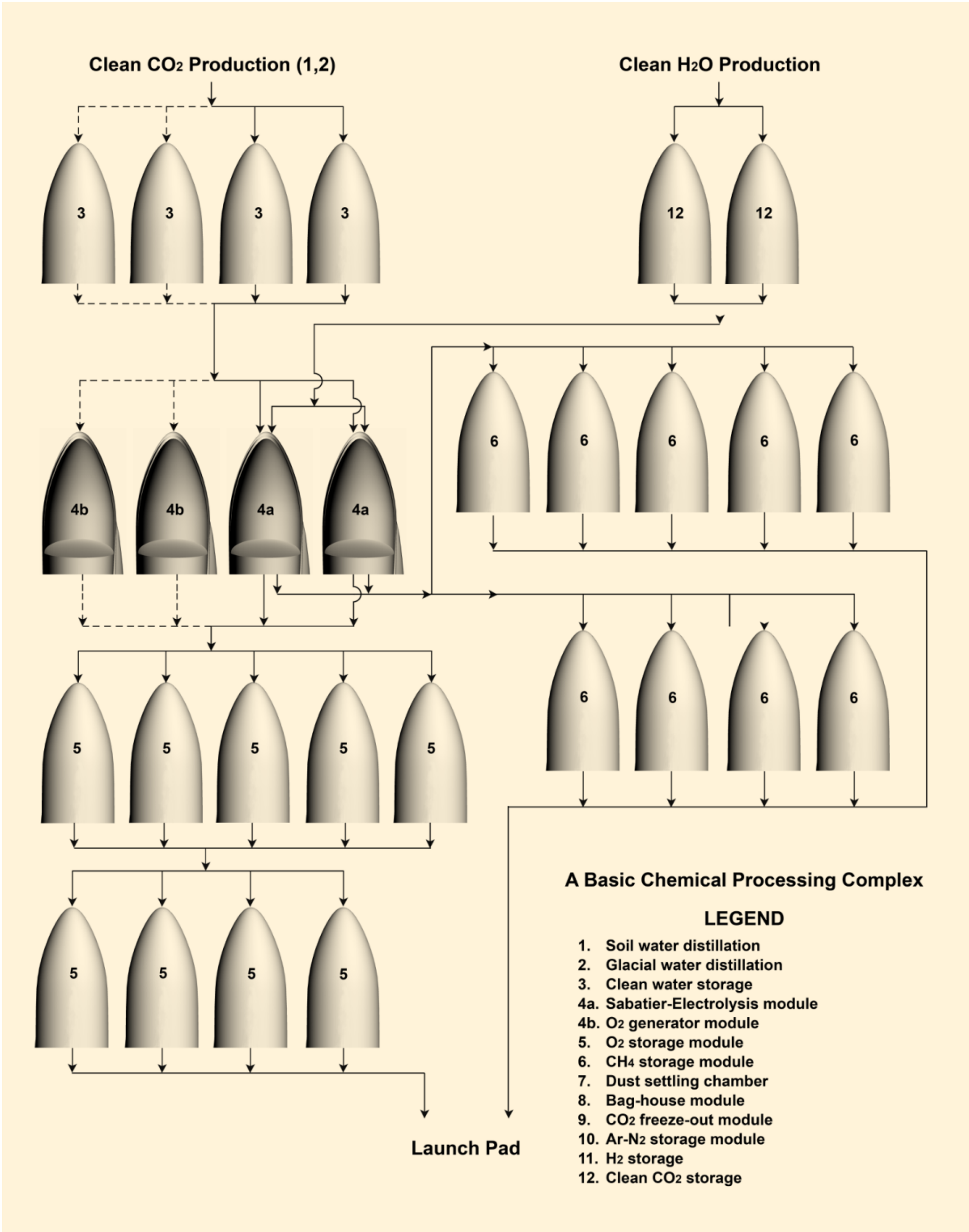

Figure 18. A Basic Chemical Processing Complex: *Production processing and storage modules to support a back-to-Earth launch campaign for 12 spaceships.*

slower launch rate would allow propellant storage modules to be emptied and reused over a longer period within each synodic cycle.

3) A third remedy would require modifying the SpaceX architecture. Each cargo vessel would incorporate a small, inexpensive propulsion unit and heat shield that would enable it to self-land onto Mars' surface. Instead of sending each cargo spaceship through TMI, each one would be propelled into a high Earth orbit, 0.1 to 0.2 m/s short of TMI. Then the vessel would be released into space, for example, by using a reusable fairing as shown in methods 4a or 4b in this paper. The vessel would initiate a burn through TMI and later, one or more burns when landing on Mars. A similar approach was recently recommended by Robert Zubrin[40] in his 2016 critique of the Mars architecture. This modification would avoid the necessity to return cargo spaceships from Mars to Earth. It would eliminate the need for most of the propellant storage modules in the propellant tank farm, leaving only a few to be used to store propellants for each launch window. The savings in spaceship launches should compensate for the cost of leaving propulsion units on Mars.

Acknowledgments

The authors would like to thank Chris Bergin, Managing Editor of NASAspacrflight.com, for facilitating the review of this paper through his extensive and well-organized forums. Special thanks to Karen Pease (Rei), Noel Munson (sghill), Wesley Wilson (wes_wilson), and Roland Winkler (Semmel) for their in-depth reviews. Other contributors (by pseudonym) were CraigLieb, IRobot and Johnnyhinbos. Monroe Smith served as Mathematics Reviewer.

Addendum

At a recent (July 2017) Symposium, Elon Musk indicated that the size of the initial ITS would be smaller than initially stated at the 2016 IAC speech[41]. He did not, however, provide specific data. When specifications for the updated ITS are published, projection data presented here could be updated. First, the volume estimates for the ITS cargo section and cargo module should be revised by using new size specifications in the 3-D shape models. Then updated propellant tank (mass) capacities should be inserted to determine propellant requirements for launch campaigns. Because the estimates in this paper employed linear projection models for both the ITS cargo modules and the ITS propellant tanks, the conclusions based on updated projections should remain the same

References

[1]Elon Musk (Sept 28, 2016) "Making Humans a Multi-Planetary Species," Presentation at the 49th Meeting of the International Aerospace Conference in Guadalajara, Mexico, http://www.spacex.com/mars Retrieved 1-5-2017.

[2]Derek Richardson (Sept 27, 2016) "Elon Musk shows off Interplanetary Transport System," Spaceflight Insider.com, http://www.spaceflightinsider.com/organizations/space-exploration-technologies/elon-musk-shows-off-interplanetary-transport-system/ Retrieved 1-5-2017.

[3]Carlo de Lacy (May 30, 2016) "SpaceX Mars Delivery Service: Elon Musk Opens Cargo Shipping to the Red Planet Because Why Not?" iTechPost. http://www.itechpost.com/articles/19625/20160530/spacex-mars-delivery-service-now-send-mail-red-planet.htm

[4]Tesla Motors Club (2013) Video: Elon Musk Panel BTA 2012. https://teslamotorsclub.com/tmc/threads/elon-musk-panel-bta-2012.13358/

[5]Elon Musk (April 22, 2011) "I'll put a man on Mars in 10 years," Interview with Alan Murray, The Wall Street Journal. http://www.wsj.com/video/elon-musk-ill-put-a-man-on-mars-in-10-years/CCF1FC62-BB0D-4561-938C-DF0DEFAD15BA.html

[6]Ross Anderson (Sep 30, 2014) "Exodus," Interview with Elon Musk, Aeon (Magazine) Essays. https://aeon.co/essays/elon-musk-puts-his-case-for-a-multi-planet-civilisation

[7]Elon Musk (11:59am, Sept 28, 2016) Twitter.com, @BArtusio https://twitter.com/elonmusk/status/781206685553528833

[8]David V. Smitherman (Sep 2016) "Habitation Concepts for Human Missions Beyond Low-Earth-Orbit," AIAA Space Forum, September 13 - 15 2016, Long Beach, California. AIAA 2016-5216.

[9]SpaceX.com (October 21, 2015) Falcon 9 Launch Vehicle Payload User's Guide Rev 2 http://www.spacex.com/sites/spacex/files/falcon_9_users_guide_rev_2.0.pdf

[10]Spaceflight 101.com/Launch Vehicle Library (2016) "Falcon 9 FTS (V1.2)." http://spaceflight101.com/spacerockets/falcon-9-ft/

[11]Mars Architecture Steering Group, NASA Headquarters [Bret G. Drake, Editor] (2009) Human Exploration of Mars Design Reference Architecture 5.0 Addendum, NASA/SP–2009–566-ADD, https://www.nasa.gov/pdf/373667main_NASA-SP-2009-566-ADD.pdf

[12]NASA (Oct 2015) "NASA's Journey to Mars," NP-2015-08-2018; https://www.nasa.gov/sites/default/files/atoms/files/journey-to-mars-next-steps-20151008_508.pdf

[13]CICE Promoting Science (undated) "The Essential Chemical Industry – Online: Essential Chemicals." http://www.essentialchemicalindustry.org/chemicals.html

[14]Reinhold, Inc. (2009) "FRP Material Selection Guide - An Engineer's Guide to FRP Technology," http://www.reichhold.com/corrosion/docs/Materials%20Selection%20Guide%20Final%20Version.pdf

[15]National Oilwell Varco (Feb 2015) "Chemical Resistance Guide," NOV Fiber Glass Systems, http://www.frpsolutions.com/PDF/Chemical%20Resistance.pdf

[16]Gevin McDaniel and Chase Knight (2014) Fiber "Reinforced Polymer (FRP) Composites," Florida Department of Transportation, 2014 FDOT Design Training Expo, http://www.fdot.gov/design/training/designexpo/2014/presentations/GevinMcDaniel-FRP%20Composites.pdf

[17]Wikipedia (Nov 2016) "Atmosphere of Mars." https://en.wikipedia.org/wiki/Atmosphere_of_Mars

[18]M.K. Mazumder et al (2004) "Mars dust: characterization of particle size and electrostatic charge distributions," NASA National Technical Report Server, Document ID 2012000263, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120003263.pdf

[19]Nilfisk Inc. (2011) "About Filtration / HEPA & ULPA Vacuum Filters," http://www.nilfiskcfm.com

[20]Champion Process, Inc. (Undated) "High Temperature and High flow bag filters," http://www.championprocess.com/bag-filters/

[21]Intensi-Filter Company (2009) "CIP – Cleaning in Place Filter," Technical Brochure. http://www.intensiv-filter.com/fileadmin/user_upload/downloads/files/TD.08.009.GB_view.pdf

[22]Dartmouth College Thayer School of Engineering (2017) "Electrostatic precipitators," http://engineering.dartmouth.edu/~d30345d/courses/engs37/esps.pdf

[22]Robert Zubrin (June 2011) The Case for Mars, Simon and Schuster, by way of Google Books, page 368 https://books.google.com/books?id=NC8XZEddojsC&pg=PA163&lpg=PA163&dq=hamilton+standard+sabatier&source=bl&ots=wHsWTv7S_9&sig=VT_lpqjjb-fkA-48tKZ1Qy2g4jw&hl=en&sa=X&ved=0ahUKEwjblsejm_TPAhUFdD4KHWxzCYwQ6AEIKTAC#v=onepage&q=hamilton%20standard%20sabatier&f=false

[23]K. Murdoch, J. Perry and F. Smith (2003) "Sabatier Engineering Development Unit," SAE International, 33rd International Conference on Environmental Systems, Vancouver, B.C., Canada, July 7-10, 2003; SAE Technical Paper 2003-01-2496.

[24]NASA (May 23, 2011) "The Sabatier System: Producing Water on the Space Station," https://www.nasa.gov/mission_pages/station/research/news/sabatier.html

[25]Marcelo Carmo, et al (April; 2013) "A comprehensive review on PEM water electrolysis," International Journal of Hydrogen Energy," Vol. 38, Issue 12, 22 April 2013, Pages 4901-4934, Downloaded from Science Direct Nov 25, 2016.

[26]Darren J. Samplatsky, et al (2011) "Development and Integration of the Flight Sabatier Assembly on the ISS," 41st International Conference on Environmental Systems," 17 - 21 July 2011, Portland, Oregon, Paper Number AIAA 2011-5151.

[27]Kevin C. Takada, A. E. Ghariani and S. V. Keuren (2015) "Advancing the Oxygen Generation Assembly Design to Increase Reliability and Reduce Costs for a Future Long Duration Mission,' 45th International Conference on Environmental Systems 12-16 July 2015, Bellevue, Washington, ICES-2015-115.

[28]Dina El Sheri and James C. Knox (2005) "International Space Station Carbon Dioxide Removal Assembly (ISS CDRA) Concepts and Advancements," SAE International Technical Paper 2005-01-2892

[29]Maxmillian Schalenbacha, W. Luekea, and D. Stoltena (2016) "Hydrogen Diffusivity and Electrolyte Permeability of the Zirfon PERL Separator for Alkaline Water Electrolysis," Journal of the

Electrochemical Society, J. Volume 163, Issue 14, http://jes.ecsdl.org/content/163/14/F1480.full [30]NASA (Undated) "ISS User's Guide-Release 2.0, http://www.spaceref.com/iss/ops/ISS.User.Guide.R2.pdf

[31]Jay L. Perry, Robert M. Bagdigian and Robyn L. Carrasquillo (2010) "Trade Spaces in Crewed Spacecraft Atmosphere Revitalization System Development," AIAA 2016-6061, AIAA 40th International Conference on Environmental Systems, http://arc.aiaa.org/doi/pdfplus/10.2514/6.2010-6061

[32]NASA (2008) "International Space Station Environmental Control and Life Support System," NASA Facts FS–2008– 05– 83– MSFC 8–368788; https://www.nasa.gov/centers/marshall/pdf/104840main_eclss.pdf

[33]Mike Wall (2014) "Oxygen-Generating Mars Rover to Bring Colonization Closer," Space.com August 1, 2014. http://www.space.com/26705-nasa-2020-rover-mars-colony-tech.html

[34]Maia Weinstock (2014) "Oxygen-creating instrument selected to fly on the upcoming Mars 2020 mission," Phys.org August 1, 2014. http://phys.org/news/2014-08-oxygen-creating-instrument-upcoming-mars-mission.html

[35]Sune Dalgaard Ebbesen and Mogens Mogensen (March 2009) "Electrolysis of carbon dioxide in Solid Oxide Electrolysis Cells," Journal of Power Sources 193 (2009) 349–358. https://www.researchgate.net/profile/Sune_Ebbesen/publication/235531472_Electrolysis_of_Carbon_Dioxide_in_Solid_Oxide_Electrolysis_Cells/links/541be9030cf2218008c4ceb7.pdf

[36]Tariq Malik (Feb 15, 2006) "Air Apparent: New Oxygen Systems for the ISS," Space.com http://www.space.com/2052-air-apparent-oxygen-systems-iss.html e

[37]Kevin C. Takada, A. E. Ghariani and S. Van Keuren (2015) "Advancing the Oxygen Generation Assembly Design to Increase Reliability and Reduce Costs for a Future Long Duration Mission," 45th International Conference on Environmental Systems July 2015, Bellevue, Washington, ICES-2015-115 12-16; https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150016494.pdf

[38]Michael J. Moran and H. N. Shapiro (2006) "Refrigeration and Heat Pump Systems," Fundamentals of Engineering Thermodynamics, 5th Edition. https://yidnekachew.files.wordpress.com/2012/04/fundamentals-of-engineering-thermodynamics-moran-j-shapiro-n-m-5th-ed-2006-wiley1.pdf

[39]Claudia Flavell-While (September 2010) "Cool Inventions," The Chemical Engineer, http://www.thechemicalengineer.com/~/media/Documents/TCE/Articles/2010/831/831%20cewctw.pdf

[40]Robert Zubrin (2016) "Colonizing Mars: A Critique of the SpaceX Interplanetary Transport System," The New Atlantis, Oct. 21, 2016. http://www.marssociety.org/colonizing-mars-a-critique-of-the-spacex-its-by-robert-zubrin/

[41]Elon Musk (July 19, 2017) "Elon Musk Keynote Address at ISSR&D Conference," NASA TV/ NASA Public-Education, http://www.ustream.tv/recorded/105920888