6801 - WR1

System Case Study: Mars One Program

Systems Engineering I

A review of the Mars One Program as a real-world system to research and evaluate as a SE case study throughout the term. The Mars One Program has developed an aggressive plan to launch 4 humans into space with the mission of establishing a human settlement utilizing existing technologies.

Kafi A. Joseph

Table of Contents

I. **Mars One Problem Statement.** The mission of the Mars One Program is to establish a human settlement on the planet Mars; the mission plan integrates technology components that are readily available from industry leaders worldwide to enable travel *to* and settlement *on* Mars (Mars One). To accomplish the mission, the Mars One team must establish a system which will satisfy three top-level system objectives: 1) the safe transport of human beings to Mars; 2) the establishment of a human settlement on Mars and 3) the establishment of communications between Earth and Mars (Figure 1).

a. Mars One Program Needs.

According to its founders, the Mars One program was established "to satisfy good old fashioned curiosity" (Mars One) that is, the inherent human need to explore. While the Mars One team acknowledges that there are secondary and tertiary benefits to be realized from the success of the program – to include advances in recycling, solar energy use and food production – the more detailed and defined needs statements found in the NASA Special Publication 6107 adds some clarity about why a Mars mission is needed. The special publication is a Mars Reference Mission which summarizes the work of several NASA field centers by outlining a plan for human missions to Mars with technically feasible approaches, reasonable risks and low costs (Hoffman & Kaplan, 1997, pp. 1-3).

One of the intended purposes of the Mars Reference Mission is to "[u]nderstand requirements for human exploration of Mars in the context of other space missions and research and development programs…" As such, the document is a reliable source when identifying the needs for Mars exploration. The publication succinctly outlines the needs for Mars exploration as: Human Evolution, Comparative Planetology, International Cooperation, Technological Advancement and Inspiration.

- "Human Exploration" suggests Mars exploration should be geared toward understanding the requirements to sustain a permanent human presence beyond Earth
- "Comparative Planetology" focuses on scientific exploration of Mars' history so that we may better understand Earth.
- "International Cooperation" highlights that a concerted international effort may be required for a sustained Mars program
- "Inspiration" asserts that the grandeur of Mars exploration will motivate the youth and excite the nations of the world.

Interestingly, at the time when the "Technology Advancement" need was identified in 1997, the Mars Exploration Study Team described the technical capabilities as "…either just available or on the horizon" and "[c]ommitment to the program will both effectively exploit previous investments and contribute to advances in technology" (Hoffman & Kaplan, 1997, pp. 1-5 - 1-6). As I address the technologies required to achieve the Mars One mission, one can only help but conclude that the authors of the 1997 document were correct and just 14 years later, in 2011 when the Mars One baseline mission design and architecture were developed, the program concept was designed on the premise that all the required technology already existed.

b. Mars One Capability Gaps.

While the technologies currently exist to address the top-level system objectives, it is important to note that in some cases, the existing technologies have yet to be tested on Mars. In other cases the technologies have been Mars tested, but lack a proven use for humans in the context of these Mars One mission requirements and in yet other cases have not been tested for either scenario. Table 1 contains the preliminary capabilities gap analysis I conducted where I reviewed the technologies identified to satisfy the top-level system objectives and overall mission and then reviewed the Mars One, NASA or specific manufacturer information to determine if capability gaps existed. In all, I found that of the nine technologies being fielded as system elements, seven have capability gaps related to lack of Mars testing and/or lack of proven use for humans on Mars (Figure 2).

1) Critical Capability Gaps. The most critical capability gap is the launcher. The launcher is required to conduct several launch missions to take payloads into Earth orbit and then on to Mars. The launch missions include the rovers, communications system, the cargo missions (i.e., living units, life support units and supplies), and finally, the Astronauts. Should any of the launches fail, the entire program is at risk for failure. The launcher of choice is the Falcon Heavy, manufactured by Space Explorations Technologies Corporation, or SpaceX. The selected launcher is an upgraded version of the Falcon 9 which has completed several successful launches taking items to the International Space Station (ISS), but the Falcon Heavy has yet to undergo real-world launches or test launches. In addition to the manufacturer test launches scheduled for 2014 (SpaceX, 2013), the Mars One team will address this critical capabilities gap by conducting a demonstration launch six years before the first human launch. These test and demonstration launches will provide valuable lessons learned about the selected launcher technology and in all, the launcher will have had eight real-world launches prior to conducting human crew launch (Mars One).

2) Significant Capability Gaps. Of the remaining capabilities gaps, the living units and the Marssuits are next in the line of criticality. Since these items have yet to be proven space-worthy, the technologies present a serious risk to both mission accomplishment and human life. I have ranked them as less critical in the overall mission accomplishment, because the items are not expected to launch for another five years (living units) and ten years (Marssuits). The living units that are proposed for deployment are inflatable habitats, which are regarded highly in the aerospace community because the inflatable properties present architectural and volume advantages over other more conventional structures (Edgecombe, dela Fuente, & Valle, 2009). The concept of inflatable spacecraft have been the subject of NASA research since the 1960s, and were pursued more seriously by the agency under the 1990s NASA TransHab program, which specifically targeted use of the structure for Mars missions. Budgetary constraints caused the TransHab program's cancellation and NASA to license the TransHab patent to Bigelow Aerospace. Bigelow Aerospace will launch an inflatable habitat into space in 2015, where the inflatable will be attached to the ISS for two years of suitability testing. Similar to the launcher, the ability to gather lessons learned from the inflatable habitat launches will reduce the risk and lessen the gap that currently exists for the living units. The testing period will end five years prior to the human launch, but only three years prior to the cargo launch – which is when the living units are expected to be Mars-worthy. Meanwhile, Marssuits are yet to be produced. These suits are required when the astronauts leave the living areas and will protect astronauts from exposure to the Martian atmosphere with temperatures ranging 1 – 161 °F, non-breathable air, and exposure to radiation and Mars dust. The only suits referenced in the documentation thus far are the Apollo-era space suits of the 1960s and 1970s (Mars One). This is not surprising, since even the most recent space station missions have not required suits suitable for utilization in gravity or on a planetary surface.

3) Other Capability Gaps. There are simply some risks associated with the remaining capability gaps that the Mars One team will need to accept and / or mitigate. Technologies for system elements such as the transit vehicle, landing capsule, and the supply units have been utilized for previous Mars missions, but not with human lives depending on their functionality. While the life support unit technology has been employed at the ISS, it has never been utilized on Mars or any planetary environment. These capabilities will be tested during the eight-year astronaut training period by leveraging scenarios and simulations in comparable environments such as arid locations and potentially the Arctic desert (Mars One). Employment of the technology in these analogous environments will provide the astronauts with

drills and skills to address potential failures or malfunctions of the technologies and increase the chances of program success.

II. The Mars One Concept of Operations (CONOPs).

The nine system elements of the Mars One Program critical to mission success as they must effectively function both internally and externally of the Mars One system boundaries. To date, the Mars One team has created a road map which outlines key milestones that are required to reach the desired end-state. These milestones are listed below (Mars One):

- 2011 - Mars One Founded
- 2013 - Crew Selection
- 2015 - Crew Training
- 2016 - Demo & Communications Satellite Mission
- 2018 - Rover Mission Launch
- 2020 - Cargo Missions Launch
- 2021 - Outpost Operational
- 2022 - Departure of Crew One
- 2023 – Landing of Crew One
- 2024 - Departure of Crew Two

From this roadmap, I've derived and created the CONOPs System Overview Diagram (Figure 3). The diagram, along with the below explanation, conveys the system objectives and how the system elements function in the intended environments.

a. System Objective #1: Safely Transport Humans to Mars. This system objective has three system elements aligned and each of these elements will primarily operate in the space environment. Element #1: the launcher, is required to conduct several launch missions to take payloads into Earth orbit and then on to Mars. The launch missions include the rovers, communications system, the cargo missions (i.e., living units, life support units and supplies), and finally, the astronauts. Should any of these launches fail, the entire program is at risk for failure. Element #2: the transit vehicle, is defined as a "compact space station" which will carry the astronauts from Earth orbit to Mars. The transit vehicle is "comprised of four parts which are docked in Earth orbit: two propellant stages, a transit habitat and a lander. The propellant states are used to propel the transit vehicle from Earth orbit to Mars. The transit habitat is the home for the astronauts during the seven month journey [and] in it they sleep, train and prepare for their arrival and landing." (Mars One) The transit habitat and propellant stages never leave orbit, it is only Element #3: the lander that will take the astronauts onto Mars to establish the settlement, and as such, it is the system element that functionally links system objective one to system objective two.

In essence, the measure of effectiveness (MOEs) for objective one, Safely Transport Humans to Mars, includes the successful launch and placement of the Mars transit vehicle into earth orbit; followed by the completion of the seven month flight to Mars with all astronauts surviving; and the landing of the astronauts onto Mars in the lander. These MOEs are further elaborated in Table 3, which I've created from information provided in the Mars One Roadmap and technology pages.

b. System Objective #2: Establish Human Settlement on Mars. This system objective has four system elements aligned. Prior to the astronauts' arrival on Mars, several launch missions will have occurred inserting four of the remaining system elements required to establish the settlement. These system elements will primarily operate on the Martian planetary surface. Element #4: the rovers, will have significant autonomous capabilities. One rover is an intelligent rover and the other, a trailer rover, will require substantial haul capability; together the rovers have the ability to assemble and set-up the settlement area. These rovers are also tasked with pinpointing the settlement location. Upon identifying the location, the rovers then act as a signal beacon for the remaining items to land precisely at the settlement location. Once identified, the rovers also prepare the surface for arrival of the cargo missions; clearing large areas for the solar panels and settlement items (Mars One). Element #5: the supply unit, will launch and hone in on the rover beacon. This unit contains food, solar panels, spare parts and other components which are essential for the establishment of the settlement until the astronauts fully develop their capability to grow food and create supplies. Element #6: the life support units, and the living units, hereafter referred to as the life support system (LSS), arrive next and the rovers start at the task of establishing the settlement. "The rover picks up all the cargo units and then deploys the thin film Solar Panel of the life support units and the Inflatable sections of the living units. The life support units are connected to the living units by a hose that can transport water, air and electricity. The LSS is now activated. The rover feeds Martian soil into the LSS and water is extracted from the Martian soil by evaporating the subsurface ice particles in an oven. The evaporated water is condensed back to its liquid state and stored. Part of the water is used for producing Oxygen. Nitrogen and Argon, filtered from the Martian atmosphere make up the other components of the breathable air inside the habitat. Before the first crew starts their journey, the life support system has produced a breathable atmosphere of 0.7 bar pressure, 3000 liters of water and 120 kg of Oxygen that is in storage. The rover also deposits Martian soil on top of the inflatable sections of the habitat for radiation shielding." (Mars One) Element #7: the Marssuits, arrive last and are utilized when the astronauts step foot onto Mars and are required any time they must leave the living units. The suits are intended to protect astronauts from exposure to the Martian atmosphere with temperatures ranging 1 – 161 °F, non-breathable air, and exposure to radiation and Mars dust.

The measures of effectiveness for objective two, Establish a Human Settlement on Mars, includes: the completion of all launch missions, that is all items (i.e., rovers, cargo, supplies) arrived in-tact on Mars; the selection of the settlement area by the rovers; set-up of the outpost living units and life support units by the rovers; and the astronauts ability to navigate Mars in the Marssuits to move into the settlement outpost. At the time of writing, the Mars One team had not defined timeframes for the settlement upon establishment. However, the NASA Human Exploration of Mars Design Architecture, which contains a study to identify the objectives for the missions to Mars, defines the scope of initial three human missions to Mars as "…demonstrat[ing] the transportation of humans from the surface of Earth to the surface of Mars. Missions one through three will also have Mars surface-stay times of at least 30 days and potentially greater than 450 days." (Drake, 2009, p. 33). Table 2 outlines the MOEs in further detail and the contents of the table are derived from the Mars One roadmap and technology pages.

c. **System Objective #3: Establish Communications between Earth and Mars.** This system objective has two system elements aligned and will primarily operate in the space environment, specifically, planetary orbits. Element #8: Earth satellites and network and Element #9: Mars satellite and network, are two omnipresent system elements. Having been launched prior to the human launch, these system elements ensure that the astronauts can communicate back with Earth as well as allows for navigation toward Mars and is an aspect required for tracking the well-being of the human settlement.

The measures of effectiveness for objective three, Establish Communications between Earth and Mars, include: the launch of satellites into planetary orbits and the successful establishment of live communications networks; this includes the data bandwidth that supports the relay of images, video and other data to and from the Mars surface; communications are maintained 24 hours a day seven days a week. Table 4 outlines the MOEs in further detail and the contents of the table are derived from the Mars One roadmap and technology pages.

d. Mars One Program Boundaries and Interfaces. The nine system elements outlined above are expressly within the boundary of the Mars One program. However, the system will need to interface external to the system boundary. External interfaces include, but are not limited to:

- Transmission of satellite communications and remote instruction to/from the Earth (Hoffman & Kaplan, 1997, pp. 1-33 to 1-35)
- Interactions and construction in reduced gravity (Hoffman & Kaplan, 1997, pp. 1-33 to 1-35)
- Navigation and construction in/on the Martian terrain and atmosphere (Petrov, 2004, pp. 15-17)
- Excavation / mining of Mars surface (Drake, 2009, p. 319)
- Leveraging Solar Power (Hoffman & Kaplan, 1997, pp. 1-33 to 1-35)

As I continue to define / refine the specific system requirements and conduct a functional analysis of the above external interfaces with respect to the system elements, I will be better able to properly allocate, align and establish traceability for future validation and verification of the system and its requirements and determine the measures of performance related to the measures of effectiveness.

III. Requirements Identification and Attribute Analysis.

a. Systems Requirements Documents (SRDs). To date, the Mars One Program requirements documentation is not available for public release. The system requirements utilized for the requirements identification, definition, discussion and analysis in this paper were derived and compiled from a multitude of sources for similar technologies and systems as outlined below.

- Launcher Requirements (SRD #1): A 2011 Space Launch System NASA Research Announcement for Advanced Booster Engineering Demonstration and/or Risk Reduction
- Lander (SRD #2): A 2009 Preliminary Study on Lander System and Scientific Investigation for the Next Mars Exploration
- Life Support System – Living Unit (SRD #3): A 2005 Paper on In Situ Resource-Based Lunar and Martian Habitat Structures Development at NASA/MSFC
- Life Support System – Life Support Unit (SRD #4): A 1998 NASA Technical Manual on the Design and Operation of the Life Support Systems on the International Space Station
- Communications System – Earth Satellite and Network & Mars Satellite and Network (SRD #5): A 2004 NASA Technical Manual on Developing Architectures and Technologies for an Evolvable NASA Space Communication Infrastructure

b. Requirements Identification, Definition and Traceability. Since a comprehensive requirements document was not readily available, only select requirements are populated on the Requirements Traceability Matrix at Table 4. There is a minimum of one requirement traceable per system objective.

1) System Objective #1: Safely Transport Humans to Mars. This objective includes the successful launch and placement of the Mars transit vehicle into earth orbit; followed by the completion of the seven month flight to Mars with all astronauts surviving; landing of the astronauts onto Mars in the lander; and establishment of communications with Earth. There are three system elements and subsequent requirements aligned to this objective: the launcher, the transit vehicle and the lander; however, for the purpose of this case study, requirements are only aligned to the launcher and lander (see Table 6). There are a total of seven requirements for these two system elements (Crumbly & Craig, 2011) and the lander (Kubota, et al., 2009, pp. 2, 4 - 5).

2) System Objective #2 : Establish Human Settlement on Mars. This objective includes the completion of all launch missions, that is all items (rovers, cargo, supplies) arrived in-tact on Mars; the

selection of the settlement area by the rovers; set-up of the outpost living units and life support units by the rovers; and the astronauts ability to navigate Mars in the Marssuits to move into the settlement outpost. At the time of writing, the Mars One team had not defined timeframes for the settlement upon establishment. There are four system elements and subsequent requirements aligned to this objective: the rovers, the supply units, the life support system and the marssuits; however for the purpose of this case study, requirements are only aligned to the life support system (see Table 7). There are a total of two requirements and twenty sub-requirements for this one system element (Bodiford, Fisket, McGregor, & Pope, 2005, pp. 2 - 4) (Wieland, 1998, p. 62).

3) System Objective #3: Establish Communications between Earth and Mars. This system objective ensures the astronauts can communicate back with Earth and also allows for navigation toward Mars via signal beacons; accomplishment of this objective is required for tracking the well-being of the human settlement. The communications system will consist of two communications satellites and Earth-ground stations enabling 24/7 communication between the two planets to include relay of images, videos and other data from the Mars surface. There are two system elements and subsequent requirements aligned to this objective: the Earth satellite and network and the Mars satellite and network; there are requirements aligned to each of the system elements (see Table 8). There are a total of seven requirements for these two system elements (Bhasin & Hayden, 2004, p. 8).

c. Requirements Quality Attribute Analysis. The requirements for this case study were acquired from five separate sources that I classify as Systems Requirement Documents (SRDs). The respective SRDs and correlating system objectives are outlined in paragraph III. a. (above) and are also aligned with the respective requirements in Tables 6-8. In the aforementioned tables, you will find the requirements as derived from the SRD. I also conducted a requirements quality analysis using Davis' Quality Factors of: correct, unambiguous, verifiable, understandable, traced, design independent, annotated, and concise – for individual requirements. Davis also presents factors of: complete, consistent, modifiable, traceable, and organized for assessing SRDs overall (Grenn, Requirements Analysis Processes, 2013, pp. 16 - 22). Using these quality attributes, I have assessed that none of these SRDs earned a 100% quality score. This is primarily because the documents are not actual SRDs, but proxies, therefore some of the areas were virtually impossible to meet considering the documents original intended use. For discussion purposes, I have selected one quality factor, per system objective, to elaborate and explain why the item either meets or does not meet the criteria. Additionally, I will provide a rating for the SRD overall and also select a quality factor for elaboration. Full details about the quality attribute assessment are included in the aforementioned tables.

1) System Objective #1: Safely Transport Humans to Mars (Table 8).

A requirement is considered **correct** "…if, and only if, every requirement stated therein represents something required of the system to be built (Grenn, Requirements Analysis Processes, 2013, p. 17)." The requirements provided for the launcher were considered correct because each item listed specifically tied to a specification for the launcher which is an integral part of the Mars One System.

SRD #1. The document utilized for the launcher received only a 60% rating because it was neither modifiable nor traceable. **Traceable** pertains to if an SRD is "…written in a manner that facilitates the referencing of each individual requirement stated therein (Grenn, Requirements Analysis Processes, 2013, p. 21)." Since the original purpose of this SRD is a source selection briefing to familiarize potential bidders with the top-level requirements for rocket boosters, traceability was not a priority and is evident in this document, which contains only bullet points and not a numbering hierarchy.

Meanwhile, **unambiguous** is defined as "…if, and only if, every requirement stated therein has only one interpretation (Grenn, Requirements Analysis Processes, 2013, p. 17)." However, the requirements listed for the lander (Table 6) were the opposite of unambiguous. For example: the requirements for the entry module were "heat shield, aero-assist technology and parachute technology"

(Kubota, et al., 2009, p. 2) with no additional information about what temperatures the shield must withstand or the braking that must be provided by the aero-assist and parachute.

SRD #2 received a 20% rating for **organization**, which is occurs when the "…requirements contained therein are easy to locate (Grenn, Requirements Analysis Processes, 2013, p. 22)." This document was intended to be a preliminary study on lander technology; as such the document was well laid out sequentially for the lander functions, making it easy to identify the specific requirements for the lander.

2) System Objective #2 : Establish Human Settlement on Mars (Table 10).

Requirements are considered **verifiable** if they can be tested, demonstrated, analyzed or inspected, within reasonable cost (Grenn, Requirements Analysis Processes, 2013, p. 18). Although some of the living unit requirements, such as survivability, could potentially be demonstrated or tested with simulations, others like the construction hazards were not as well-defined to lend to verification.

SRD #3 received a 40% assessment rating and SRD #4 received an 80% rating. One differentiator between the documents was completeness. SRD #3 was not **complete**, that is "[e]verything that the system is supposed to do is captured in the SRD (Grenn, Requirements Analysis Processes, 2013, p. 18)." The document used for the SRD was originally intended as an analysis and comparison of several habitat formats; as a result, it focused more on composition, criteria and evaluation of options that singling out specific requirements. Whereas SRD #4 was originally intended for use as a NASA Technical Manual on the Design and Operation of the Life Support Systems on the International Space Station. As a result, it included copious details and technical specifications about the life support units.

3) System Objective #3: Establish Communications between Earth and Mars (Table 10).

Concise requirements are short, yet to the point and are preferred over longer requirements statements. **Traced** requirements are considered to be so if "…the origin of each of its requirements is clear," specifically if rationale is provided for the requirement (Grenn, Requirements Analysis Processes, 2013, p. 20)." The requirements for the satellites networks are quite concise, as each is simply a statement of the required data download or upload speed. Additionally, the SRD for this document is a NASA technical memorandum on evolving NASA's space communications infrastructure, which inherently includes an abundance of background information linked to the requirements.

The final SRD, #5 tied for the highest score of 80%, it was the most **consistent** of the SRDs utilized. An SRD is consistent "…if and only if (1) no requirement stated therein is in conflict with other preceding documents, (2) no subset of requirements therein conflict (Grenn, Requirements Analysis Processes, 2013, p. 19)." Since the communications system has the least direct interface with the other system requirements, it was the one least likely to have requirement conflicts.

Utilizing various SRDs proved to be most beneficial in understanding how the quality factors can be applied and also skewed by the purpose of focus of the authoring group. Overall, I would send this team back to the drawing board given the overall analysis of these requirements. Since requirements are the most important part of systems engineering process, we would need to redefine, disambiguate, complete and ensure that all the requirements, based upon these SRDs, are appropriate and ready for the next iteration of this project and for overall project success.

IV. Technology Readiness Levels and Technical Risk.

a. Maturity of Key Technology Enablers. The feasibility of the Mars One Program is based upon the premise that "[t]he science and technology required to place humans on Mars exists today" (Mars One). Furthermore the program claims that "[n]o new major developments or inventions are needed to make the mission plan a reality. Each stage of Mars One mission plan employs existing, validated and available technology" (Mars One). However, while conducting the technology readiness assessment, I've found that four technologies are at TRL 9, two are at TRL 7 and there are one each at TRLs 6 and 3. While it may seem positive that there are seven of nine technologies at such high technology readiness levels, I should note that only two of those are considered to be in the "off-the-shelf" risk profile (Table 12). In total, there are four technologies under the "increased complexity" risk profile, including the two at TRLs 3 and 6 (Figure 4).

b. System Element 1: Safe Transport of Humans (Table 13).

1) TRLs. The three technologies required for safe transport of the astronauts to Mars have two system elements at TRL 9 and one at TRL 7. The launcher is the only element ready off-the-shelf, and even so, the launcher is an upgraded version of the Falcon 9. The Falcon 9 has completed ten launches, successfully transporting items to the International Space Station (ISS), but the Falcon Heavy has yet to undergo real-world launches or test launches. However, the manufacturer has test launches scheduled for 2014 (SpaceX, 2013). Meanwhile, the transit vehicle and landers are at TRL 9. The transit vehicle is technically ready off-the-shelf, as the Dragon Capsule is reusable; however, I determined that there is increased complexity, as the module has yet to travel outside of Earth Orbit. The lander is the most ready of the three elements, as it is Mars-worthy, but may still require some minor redesign for each of the components to be attached for landing.

2) Risk. The overall risk for this system element is high due to the weighting applied to the increased complexity required to modify the transit vehicle for an interplanetary flight vs. geosynchronous Earth Orbit (GEO). Meanwhile, the launcher and lander both have medium risks applied. The selected risk mitigation technique is to control the risk for the launcher and the transit vehicle. Since the Mars One team plans to conduct a demonstration launch six years before the first human launch and will have successive launches for supplies and the rovers in the interim, these test and demonstration launches will provide valuable lessons learned about the selected launcher and transit vehicle technologies. In all, there will have been eight real-world launches prior to the first human crew launch (Mars One). The risks for the landing vehicles will be assumed, as there is no way to physically test land a lander on Mars, except to do it. However, the numerous successful Mars Rover landing missions dating back to 2004 are the baseline for success.

c. System Element 2: Establish Settlement on Mars (Table 14).

1) TRLs. There are four technologies required for the establishment of a human settlement on Mars and these technologies vary widely across the TRLs. The supply units are at TRL 9 as they have been utilized for several Mars missions; these are effectively off-the shelf elements. The Marssuits are presumed to be at TRL 6. With little information available, we know that the Mars One Program signed a contract with Paragon to develop the Marssuits (Wall, 2013). Paragon is the same company tasked by NASA to design the space suits for return to the Moon. The moon is a harsher planetary-like surface, as there is no atmosphere on the moon. In addition to the moon suit developments, there is another company which recently conducted testing on a prototype of a Marssuit in the badlands of North Dakota (Malik, 2006), further justifying the TRL 6 designation. The life support system is at TRL 7 with the 2006 and 2007 launches of the Bigelow Genesis I and II inflatable systems (Howell, 2013) and the Rovers are assumed to be at TRL 3. At the time of writing I have been unable to determine if there is a Rover contract signed for this program.

2) Risk**.** The overall risk for this system element is high due to the weight applied to the Marssuits and their linkage to human survival when compared to the schedule and cost implications of

development from TRL 6 to TRL 9. The TRL 3 for the Rovers is not rated high risk because of the implications for human life. As the rovers are developed, and later, launched there exists ample time to abort the aspects of the missions with human involvement.

d. System Element 3: Establish Communications (Table 15).

1) TRLs**.** There are two technologies required for the establishment of communications between Earth and Mars. At the time of writing, I have been unable to discern if there is a contract or plans for the development of separate Earth and Mars satellites or networks. As a result, I've made the assumption, based upon the program's earlier assertions of "available technology" (Mars One), that existing satellites and communications networks will be leveraged. As such, TRL 9 has been assigned, given the robust satellite network orbiting Earth and the use of the Mars Reconnaissance Orbiter currently transmitting data and information for the Rover program.

2) Risk**.** The overall risk for this system element is medium. Although the satellites exist, there may be some minor redesign or software upgrades required for use for the Mars One Program.

e. Technical Risk. Using the risk profiles, that is, the probability of achieving performance vs. technology options (Grenn, 2013, p 29) I assessed the Mars One program to have an overall risk of .6 probability of not achieving program performance success. This was assessed using the risk profile of performance probability versus the technology option and adding weight of 2 to any technologies with a .6 (or higher) probability of not achieving required performance.

1) Comparison of Risk Methods. Although I utilized risk profiles and the more objective matrix approach for risk assessment (Grenn, 2013, p 27), I wanted to compare the results of the risk assessment if a more subjective risk assessment approach was utilized (Figure 5). The results were not surprising, as there were zero items identified as "high" risk using the subjective method. However, once actual and unalterable figures were assigned to the technology performance probability and aligned to the technology options, it was much easier to assign a related risk level. Overall, the arbitrary method led to a lower, and most likely, less realistic risk assessment.

V. Lessons Learned.

This case study yielded four lessons learned that can be applied to acquisition agents, users, developers and program managers (PMs) and/or systems engineers (SEs). I built a table to take a look at the lessons learned during each iteration (i.e., Problem Statement, CONOPs, Requirements and Technical Risk), compared to the applicable audience (Figure 6). Interestingly, I found that the requirements iteration lessons learned is applicable to ALL audience, reinforcing the importance requirements. Additionally, the all four lessons learned were applicable to the PMs and SEs (Figure 7).

a. Capability gaps and technology readiness are closely interrelated (Figure 8). During this case study, the technology capability gaps identified in the problem definition stage were later linked to low TRLs and/or the high probability of not achieving performance success. Conducting a TRL assessment is imperative when determining the feasibility of system development within certain time and cost parameters. Since the Mars One program relies heavily on "existing technologies", it is particularly important that acquisition agents understand the technology readiness level and any additional design changes or modifications required of the technologies prior to procurement. PMs and SEs should also have a general knowledge of this concept and ensure the right questions are asked and the time or cost factored into the plan.

b. Visualization of the system elements, through a CONOPs overview diagram can facilitate clearer interrelation of system elements and allow for further refinement of the system – i.e., a picture is worth a thousand words (Figure 9). The initial system definition yielded only two system objectives. During development of the CONOPs, the “Safely Transport Humans to Mars” system objective included the communications system element. However, when depicted in the System Overview Diagram, it became readily apparent that the interface and boundaries for the communications element were not limited to the system objective to which it was aligned. Additionally, the communications system element did not fit neatly into the “Establish Human Settlement” system objective. In light of this observation, a third system objective emerged: “Establish Communications between Earth and Mars”. PMs and SEs should pay particular attention to this lesson learned, as the CONOPs is typically developed from the user’s perspective. This should then be conveyed to the development team, as understanding the interfaces, boundaries and system element relationships early and iterating often will ensure that details are not missed which could prove critical for requirements generation.

c. Reliance on 'existing technology' does not alleviate the need to develop detailed, quality requirements documentation. Although technologies may exist that were used for "similar" missions, it is extremely important to develop requirements documentation independent of the established technologies used. The (verified) requirements documentation for the existing technology is useful in verifying the requirements of the current system, but specific requirements for the new system must be drafted and the repurposed technology verified and validated. This is significant for all audiences of the program or project to understand. If acquisitions agents assume that ‘existing technologies’ is the same as requirements met, then there exists a risk of not allocating enough funding in the event that the technology is not appropriate or redesign or modifications are required. Additionally for PMs and SEs, the potential for wasting valuable time and/or the assumption of unnecessary technical risk exist. Finally, developers need not make assumptions and should plan for verification and/or validation of the ‘existing technologies’.

d. Although it goes without saying, objective risk assessment models should be utilized, particularly when assessing technical risk. When I started the technical risk assessment assignment, I completed a subjective risk assessment, utilizing my knowledge of the capability gaps and TRL issues. Then I utilized the matrix approach, which assigns a numerical value to technology options available. I found that the existence of an in-fungible aspect in the assessment made it easier for to assign a risk level and ultimately led to a more consistent application of risk. Upon comparison of the two methods, zero items were identified as “high” risk using the subjective method, yet the objective method yielded two “high” risk identifications (Figure 5). This is significant for PMs and SEs to understand, as the risk can negatively impact project completion and adherence to cost and schedule goals.

Supporting Figures and Diagrams

Figure 2: System Objectives and System Elements

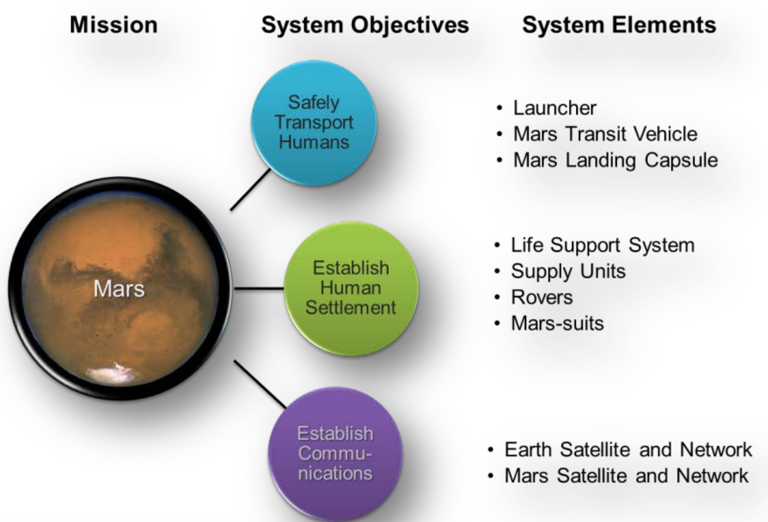


Image from www.nasa.gov Image of the Day Gallery

Figure 1: System Elements without Proven Use Cases

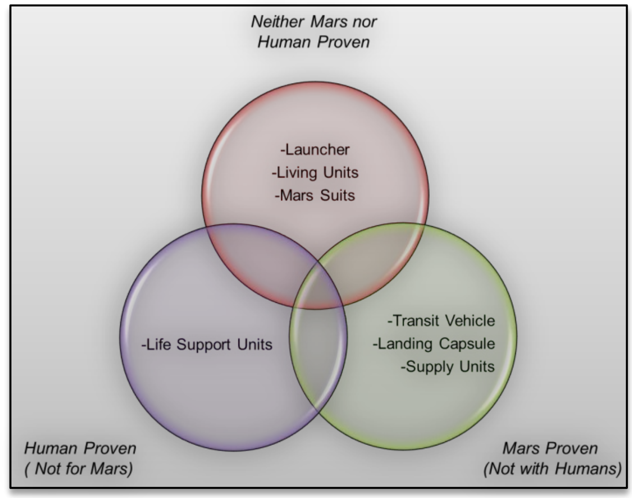


Table 1: Preliminary Gap Analysis

Capability	System Objectives: Transport	System Objectives: Settle	Requirement	Gaps	Y/N
Launcher	✓		• Multiple rocket launches to take payloads into Earth orbit and then on to Mars	• Selected launcher only used for cargo • Launchers prev. used for humans, not selected and haven't traveled Mars distance • Launchers used for Mar, not used for humans	Y
Mars Transit Vehicle	✓		• Human crew will travel through space for around seven months. • The transit vehicle will consist of two propellant stages-- a landing module and transit habitat.	• Proven for Mars Distance • Not utilized for humans, Rovers only	Y
Mars Landing Capsule	✓	✓	• Landers will be equipped to perform different functions to include carrying Life Support Units, Supply Units, Living Units, Humans and Rovers	• Proven for Mars Distance • Not utilized for humans, Rovers only	Y
Communications System	✓		• Two communications satellites and Earth ground stations. It will transmit data from Mars to Earth and back • One placed in Earth stationary orbit • One placed into a Mars stationary orbit. - Can relay images, videos and other data from the Mars surface. - Data bandwidth ~4 x NASA Mars Reconnaissance Orbiter. • Enables 24/7 communication between the two planets.	• Proven for Mars Distance with current Rover data transmit	N
Life Support Units		✓	• Has extra technologies to capitalize on the natural resources available on Mars. • Electrical energy is generated through solar panels • Potable water will be created through the heating of water ice in the local ground soil. • A portion of the water is stored while a portion is used to produce oxygen. • Nitrogen and argon gas are extracted from the Mars atmosphere and injected into the habitable space as inert gases	• Similar to those units which are fully functional on-board the ISS • Solar panel technology tested and successful • Never employed before in a planetary env.; not Mars tested	Y
Living Units		✓	• Has a unique, inflatable living section and an airlock • Filled with breathable air by the Life Support Unit prior to the arrival of the astronauts. • Contains construction materials for the astronauts to construct rooms, floors and install electrical outlets. • Contains the 'wet areas', such as the shower and kitchen	• The inflatable Living Unit will be built around Space Inflatables and landing airbags on the three Mars rovers prior to Curiosity. • NASA changed rom the landing airbags for Curiosity; decision to use airbags or further test Curiosity technology	Y
Supply Units		✓	• Unit with food, solar panels, spare parts and other components.	• Proven for Mars Distance • Not utilized for food transport	Y
Rovers		✓	• Two Rovers to set up the outpost before the humans arrive. • One intelligent rover which determines the most suitable settlement location and is a transporter of large hardware components and then conducts general assembly. • One trailer rover used for transporting the landing capsules. • Beacon signal to guide remaining transports in for landing	• Several very recent successes with Rover technology	N
Mars-suits		✓	• Protects astronauts from exposure to the Mars atmosphere. • The Mars Suit must be flexible enough to allow the astronauts to work and at the same time keep them safe from the harsh atmosphere. • Temps from −17.2 °C (1.0 °F) to −107 °C (−161 °F).	• Utility of design and some temperature functionality can be tested on Earth • Last space suits utilized or surface activity were Apollo in 1970s • No suits established for the Mars environment or tested	Y

Figure 3: CONOPS System Overview Diagram

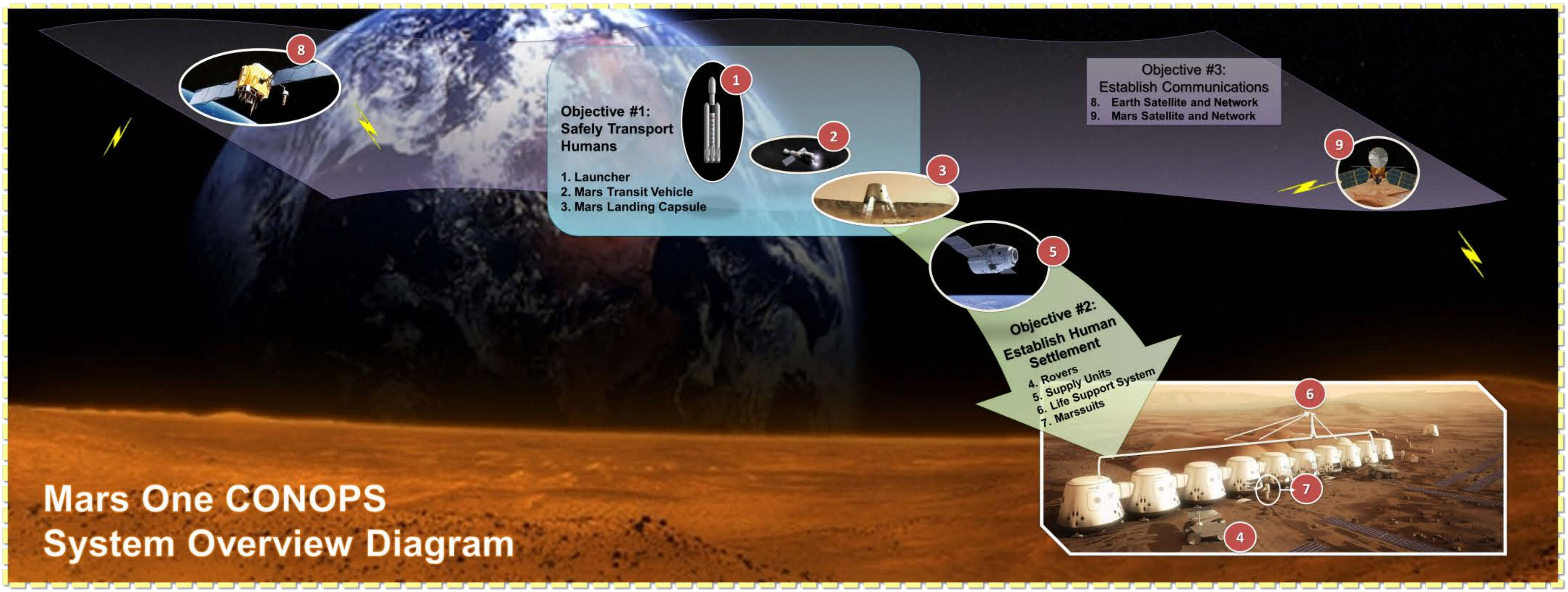


Table 3: Measures of Effectiveness - System Objective #1

Measures of Effectiveness	
System Objective #1: Safely Transport Humans to Mars	
Launch and placement of the Mars transit vehicle into earth orbit	• Components of the Mars Transit Vehicle are launched to Earth orbit on receiving the green light on the status of the systems on Mars. • Transit Habitat and a Mars Lander with an assembly crew on-board are launched into an orbit around the Earth. The assembly crew docks the Mars Lander to the Transit Habitat. Two propellant stages are launched a month later and are also connected. • The first Mars crew, now fully trained, is launched into the same Earth orbit. In orbit the Mars One crew switches places with the Assembly Crew, who descend back to Earth. • Final check of systems on Mars and of the Transit Vehicle, engines of the Propellant Stages are fired and the Transit Vehicle is launched on a Mars Transit Trajectory. • This is the point of no return; the crew is now bound to a 210-day flight to Mars. The Cargo for the second crew is launched to Mars in the same month.
Completion of the seven month flight to Mars with all astronauts surviving	• Showering with water will not be an option; wet towelettes (wet wipes) as used by astronauts on the International Space Station. • Freeze dried and canned food is the only option. • Constant noise from the ventilators, computer and life support systems • Regimented routine of 3 hours daily exercise in order to maintain muscle mass. • If hit by a solar storm, they must take refuge in the even smaller, sheltered area of the rocket which provides the best protection, for up to several days. • The journey will be arduous, pressing each of them to the very limits of their training and personal capacity.
Landing of the astronauts onto Mars	• 24 hours before landing, the crew move from the Transit Habitat into the landing module, bringing supplies from the Transit Habitat. • Landing module detaches from the Transit habitat, which is too large to land on Mars. • The Transit habitat is discarded and stays in orbit around the sun.

Table 2: Measures of Effectiveness - System Objective #2

Measures of Effectiveness (Mars One)	
System Objective #2: Establish Human Settlement on Mars	
Completion of all launch missions with all items (rovers, cargo, supplies) arriving in-tact on Mars	• The six Cargo units land on Mars, up to 10 km away from the outpost.
Rover selection of the settlement location	• Ideal location for the settlement is far enough North for the soil to contain enough water, • Equatorial enough for maximum solar power • Flat enough to facilitate construction of the settlement.
Set-up of the outpost living units and life support units by the rovers	• Rover picks up life support units using the trailer rover. • Places the life support unit in the right place and deploys the thin film Solar Panel of the Life Support unit. • Rover can connect to the Life Support unit to recharge its batteries much faster than using only its own panels, allowing it to do much more work. • Deploys the inflatable sections of the living units. Life Support unit is connected to the Living Units by a hose that can transport water, air and electricity - The Life Support System (LSS) is now activated. • Rover feeds Martian soil into the LSS. Water is extracted from the Martian soil by evaporating the subsurface ice particles in an oven. • Evaporated water is condensed back to its liquid state and stored. Part of the water is used for producing Oxygen. Nitrogen and Argon, filtered from the Martian atmosphere make up the other components of the breathable air inside the habitat.
Astronauts able to navigate Mars in the Marssuits and move into the settlement outpost	• Before the first crew starts their journey, the life support system has produced a breathable atmosphere of 0.7 bar pressure, 3000 liters of water and 120 kg of Oxygen that is in storage. • The Rover also deposits Martian soil on top of the inflatable sections of the habitat for Radiation Shielding. • Upon landing, the crew takes up to 48 hours to recover from experiencing gravity again after spending a long time in space. • In their Marssuits they leave the Lander and picked up by the Rover. • Enter the settlement and commence acclimatization period • Deploy the rest of the Solar Panels. They install the hallways between the Landers and set up Food Production units. • The Cargo for the second crew lands within a few weeks after the first crew lands; it is picked up and installed, adding to the redundancy in the settlement.

Table 5: Measures of Effectiveness - System Objective #3

Measures of Effectiveness (Mars One)	
System Objective #3: Establish Communications Between Earth and Mars	
Establishment of communications via Earth satellite / network and Mars satellite / network	• Earth - Communications Satellite in orbit around the Sun • Trails Earth at 60 degrees in L5 Lagrangian point of the Sun-Earth system. • Mars - Communication Satellite is also launched into Mars stationary orbit. • Can relay images, videos and other data from the Mars surface. • Data bandwidth of the ComSat is about 4 times that of the NASA Mars Reconnaissance Orbiter. • Enables 24/7 communication with Mars, even when the sun is in between the two planets.

Table 4: Requirements Traceability Matrix

Requirement Identifier	
1	**System Objective #1: Safely Transport Humans to Mars**
1.1	Launcher
1.1.1	*Booster-Core Interface*
1.1.2	*Booster-Ground Interface*
1.1.3	*Load Path*
1.1.4	*Height*
1.1.5	*Vehicle Width*
1.2	Transit Vehicle
1.3	Lander
1.3.1	*Entry*
1.3.2	*Descent and landing*
2	**System Objective #2 : Establish Human Settlement on Mars**
2.1	Rovers
2.2	Supply Unit
2.3	Life Support System (LSS)
2.3.1	*Living Unit*
2.3.1.1	Construction Hazards
2.3.1.2	Pressurized Environment
2.3.1.3	Survivability
2.3.1.4	Fabrication
2.3.1.5	Scalability
2.3.1.6	Compatibility
2.3.2	*Life Support Unit*
2.3.2.1	Metabolic Design Requirements
2.3.2.2	Oxygen Concentration
2.3.2.3	Oxygen Supply
2.3.2.4	CO2 Partial Pressure
2.3.2.5	Humidity Removal
2.3.2.6	Operating Pressure
2.3.2.7	Crew Accommodation
2.3.2.8	EVA Atmosphere
2.3.2.9	EVA Suits
2.3.2.10	Shower Water Usage
2.3.2.11	Food Supply
2.3.2.12	Potable Water
2.3.2.13	Hardware Location
2.3.2.14	Hardware Maintenance
2.4	Marssuits
3	**System Objective #3: Establish Communications between Earth and Mars**
3.1	Earth Satellite and Network
3.2.1	*Low Earth Orbit Spacecraft (Direct Link)*
3.2.2.	*Geosynchronous Earth Orbit Spacecraft (Direct Link)*
3.2.3	*Shuttle Transportation System*
3.2.4	*International Space Station*
3.3	Mars Satellite and Network
3.3.1	*Mars Science*
3.3.2	*Mars Exploration*
3.3.3	*Mars Proximity Link*

Table 6: Requirements – System Objective #1

	1.0	System Objective #1: Safely Transport Humans to Mars	Requirement	MOP	System Function Info
SRD #1	1.1	Launcher		1. Mass to Orbit - 130 metric tons (286,601 lbm) to LEO 2. Vehicle Dynamic Pressure < 800 psf 3. Vehicle Acceleration < 4.0 g's	-Conduct several launch missions to take payloads into Earth orbit and then on to Mars. -The launch missions include the rovers, communications system, the cargo missions (i.e., living units, life support units and supplies), and finally, the Astronauts. -Should any of the launches fail, the entire program is at risk for failure.
	1.1.1	*Booster-Core Interface*	*-Forward and aft mechanical attach points similar to Space Shuttle*		
	1.1.2	*Booster-Ground Interface*	*-Vehicle mates to 8 mechanical liftoff posts on Mobile Launcher (ML) similar to Space Shuttle* *-Vehicle fits to plume hole on ML*		
	1.1.3	*Load Path*	*-Boosters support vehicle mass / loads (on ML) during assembly, rollout, prep, and tanking* *-Boosters carry bulk of liftoff and ascent loads through forward attach points to the Core*		
	1.1.4	*Height*	*-Booster element max height limited to 235 ft based on Kennedy Space Center's Vehicle Assembly Building (VAB) lift constraint*		
	1.1.5	*Vehicle Width*	*-Vehicle width (core + boosters) limited to 67.5 ft due to VAB constraint*		
	1.2	Transit Vehicle			
SRD #2	1.3	Lander			-Take the astronauts on to Mars to establish the settlement -System element that functionally links system objective one to system objective two.
	1.3.1	*Entry*	*-Heat shield* *-Aero-assist technology* *-Parachute technology*	*--The entry will be performed at the altitude 120[km] at the velocity 4.6[km/s].* *--The peak of heat flux will occur at the altitude 48[km].* *--At the altitude 10km, the velocity will be 200[m/s].* *--The parachute will be deployed to reduce the velocity at the altitude 10[km].* *--At the altitude 200[m], the velocity will be reduced to about 24[m/s] and then the parachute will be jettisoned.* *--The powered descent will be performed by using main thruster.* *--The velocity will be smaller than 1[m/s] at the touch down to the Martian surface.*	
	1.3.2	*Descent and landing*	*-Pin-point soft landing* *-Navigation and guidance* *-Navigation sensors, Landers*	*--The leg system of the lander will reduce the shock at the landing.* *--Radar Type: Pulse radar* *--Function: Altimeter; Velocity meter* *--Frequency: 4.3 GHz* *--Range 10m-3.5km* *--Accuracy: 5%* *--Pulse Width: 15ns for short range; 50ns for middle and long range*	

Table 7: Requirements – System Objective #2

	2.0	**System Objective #2 : Establish Human Settlement on Mars**			
	2.1	Rovers			
	2.2	Supply Unit			
	2.3	Life Support System (LSS)			
SRD #3	*2.3.1*	*Living Unit*		*--Rectangular Configuration:* *20' long x 20' wide x 10' high* *Floor Area (ft): 400'* *Volume (ft): 4,000'* *Wall/Ceiling/Roof Area (ft): 2,000'* *--Hemispherical Configuration* *34.6' diameter, 17.3' high at center* *Floor Area (ft): 942.4'* *Volume (ft): 10,882'* *Wall/Ceiling/Roof Area (ft): 3,770'*	
	2.3.1.1	Construction Hazards	Minimal hazards posed to a manned crew in close proximity as a function of habitat configuration construction hazards.		
	2.3.1.2	Pressurized Environment	Support a pressurized (shirtsleeve) environment for the crew		
	2.3.1.3	Survivability	--Protect the crew from a worst case radiation (galactic cosmic radiation (GCR) & solar particle events (SPE)) exposure --Protect the crew from micrometeorites and exhaust plumes		
	2.3.1.4	Fabrication	Initially, be able to be fabricated in advance of a manned crew so as to provide immediate protection (semi-autonomous construction)		
	2.3.1.5	Scalability	Development should be evolutionary and scalable		
	2.3.1.6	Compatibility	Present a psychologically, ergonomically compatible living environment for the crew		
SRD #4	*2.3.2*	*Life Support Unit*		*-Limit atmospheric leakage for each module to a maximum of 0.23 kg/day at 101.3 kPa (0.5 lb/day at 14.7 psia) with a goal of considerably less leakage (an overall rate of no more than 0.68 kg/day (1.5 lb/day)).*	Life Support Units, and Element #8, the living units, arrive next and the rovers start at the task of establishing the settlement. "The rover picks up all the cargo units and then deploys the thin film Solar Panel of the life support units and the Inflatable sections of the living units. The life support units are connected to the living units by a hose that can transport water, air and electricity. The is now activated. The rover feeds Martian soil into the LSS. Water is extracted from the Martian soil by evaporating the subsurface ice particles in an oven. The evaporated water is condensed back to its liquid state and stored. Part of the water is used for producing Oxygen. Nitrogen and Argon, filtered from the Martian atmosphere make up the other components of the breathable air inside the habitat. Before the first crew starts their journey, the life support system has produced a breathable atmosphere of 0.7 bar pressure, 3000 liters of water and 120 kg of Oxygen that is in storage. The rover also deposits Martian soil on top of the inflatable sections of the habitat for radiation shielding." (Mars One) The final system element,
	2.3.2.1	Metabolic Design Requirements	O^2 Consumption: 0.84 kg/day/person (1.84 lb/day/person) CO^2 Production: 1.00 kg/day/person (2.20 lb/day/person)		
	2.3.2.2	Oxygen Concentration	Materials must be compatible with 24.1% ppO^2 (except for the AL, where the maximum is 30% ppO^2).		
	2.3.2.3	Oxygen Supply	Initial Operation: Supplied by RS or shuttle After the Hab OGA is Operating: 100% is generated by electrolysis. (O^2 for EVA's is resupplied from the space shuttle in tanks.)		
	2.3.2.4	CO2 Partial Pressure	See figure 93. (Note: During crew exchange, the specifications allow 7.6 mmHg with peaks to 9.9 mmHg.)		
	2.3.2.5	Humidity Removal	Moisture is removed from the atmosphere continuously. Temperature control and humidity removal are performed by the same device.		
	2.3.2.6	Operating Pressure	97.9 to 102.7 kPa (14.2 to 14.9 psia) 95.8 kPa (13.9 psia) normal minimum.		
	2.3.2.7	Crew Accommodation	After the Hab is activated, six people normally, and TBD during crew exchange (includes space shuttle and JEM/APM).		
	2.3.2.8	EVA Atmosphere	Recovery of atmosphere in the AL prior to EVA.		
	2.3.2.9	EVA Suits	29.66 kPa (4.3 psia).		
	2.3.2.10	Shower Water Usage	5.5 L (0.19 ft^3, 12 lb) shower every 2 days per person.		
	2.3.2.11	Food Supply	Diet includes moist food, which provides a source of water to the system.		
	2.3.2.12	Potable Water	No additives to the potable water.		
	2.3.2.13	Hardware Location	When possible, hardware items performing related or connected functions are located in the same module, however, fluids are plumbed between modules.		
	2.3.2.14	Hardware Maintenance	Components are replaced after failure or, for limited life items, on a scheduled basis.		
	2.4	Marssuits			

Table 9: Requirements – System Objective #3

	3.0	**System Objective #3: Establish Communications between Earth and Mars**	*A. NASA Enterprises Needs NASA's communications infrastructure must support all varieties of science and human exploration in the future. The science to be supported ranges from observation of the Earth, Moon, Mars, and the outer planet systems to the universe. The science also includes that which is obtained during human exploration and inhabitation of space, the Moon, Mars, and outer planet moons. Most of the NASA science missions that are under study require high* *'B. Emerging Needs for the Space Exploration Initiative Future robotic missions will need to operate autonomously by sensing the area around them so they can make decisions about where to go, what samples to measure, what data to report, and how to request and connect to the space communication network. Other robotic entities must be intimately connected to human operators via wireless systems that enable real time video and control for close coordination such as in assembling large space structures. The goal of the new infrastructure design is to become a space Internet that is as autonomous as possible in operation and one in which connections are made and broken as needed by the requesting entity. This kind of communications infrastructure is needed to enable access on the demand of any mission entity, including spacecraft, surface robot, in those activities*		
SRD #5	3.1	Earth Satellite and Network			
	3.2.1	*Low Earth Orbit Spacecraft (Direct Link)*	*>1 Gbps gateway, 1 Gbps D/L (2010); 10 Gbps (2020 +)* *>1 Gbps (2010); 10 Gbps (2020 +)*		
	3.2.2.	*Geosynchronous Earth Orbit Spacecraft (Direct Link)*	*>1 Gbps gateway, 1 Gbps D/L (2010); 10 Gbps (2020 +)* *>1 Gbps (2010); 10 Gbps (2020 +)*		
	3.2.3	*Shuttle Transportation System*	*50 Mbps(2010); 50 Mbps (2020+)*		
	3.2.4	*International Space Station*	*150 Mbps(2010); 300 Mbps (2020+)*		
	3.3	Mars Satellite and Network			
	3.3.1	*Mars Science*	*5 Mbps (2010); 20 up / 100 down Mbps (2020+)*		
	3.3.2	*Mars Exploration*	*10 Mbps (2010); 20 up / 100 down Mbps (2020+)*		
	3.3.3	*Mars Proximity Link*	*1-100 Mbps(2020+)*		

Table 8: Requirements Quality Assessment – System Objective #1

Requirement Identifier		Correct	Unambiguous	Verifiable	Understandable (by customer)	Traced (rationale)	Design Independent	Annotated (priority & relative stability)	Concise
1	**System Objective #1: Safely Transport Humans to Mars**								
1.1	Launcher	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**Y**
1.1.1	*Booster-Core Interface*	Y	Y	Y	Y	Y	Y	N	Y
1.1.2	*Booster-Ground Interface*	Y	Y	Y	Y	Y	Y	N	Y
1.1.3	*Load Path*	Y	Y	Y	Y	Y	Y	N	Y
1.1.4	*Height*	Y	Y	Y	Y	Y	Y	N	Y
1.1.5	*Vehicle Width*	Y	Y	Y	Y	Y	Y	N	Y
1.2	Transit Vehicle								
1.3	Lander	**N**	**N**	**Y**	**Y**	**N**	**Y**	**N**	**Y**
1.3.1	*Entry*	N	N	Y	Y	Y	Y	N	Y
1.3.2	*Descent and landing*	N	N	Y	Y	N	Y	N	Y

SRD1 ASSESSMENT (60%)	
Complete	Y
Consistent	Y
Modifiable	N
Traceable	N
Organized	Y

SRD2 ASSESSMENT (20%)	
Complete	N
Consistent	N
Modifiable	N
Traceable	N
Organized	Y

Table 11: Requirements Quality Assessment - System Objective #2

2	System Objective #2 : Establish Human Settlement on Mars								
2.1	Rovers								
2.2	Supply Unit								
2.3	Life Support System (LSS)	**N**	**N**	**N**	**N**	**N**	**Y**	**N**	**N**
2.3.1	*Living Unit*	N	N	N	Y	Y	Y	N	N
2.3.1.1	Construction Hazards	N	N	N	Y	Y	Y	N	N
2.3.1.2	Pressurized Environment	N	Y	Y	Y	Y	Y	N	Y
2.3.1.3	Survivability	N	Y	Y	Y	Y	Y	N	Y
2.3.1.4	Fabrication	N	Y	Y	Y	Y	Y	N	N
2.3.1.5	Scalability	N	N	N	Y	Y	Y	N	Y
2.3.1.6	Compatibility	N	N	Y	Y	Y	Y	N	Y
2.3.2	*Life Support Unit*	N	N	N	N	N	Y	N	N
2.3.2.1	Metabolic Design Requirements	Y	Y	Y	N	N	Y	N	Y
2.3.2.2	Oxygen Concentration	Y	Y	Y	N	N	Y	N	Y
2.3.2.3	Oxygen Supply	Y	Y	Y	N	N	Y	N	N
2.3.2.4	CO2 Partial Pressure	Y	Y	Y	N	N	Y	N	Y
2.3.2.5	Humidity Removal	Y	Y	Y	Y	N	Y	N	Y
2.3.2.6	Operating Pressure	Y	Y	Y	N	N	Y	N	Y
2.3.2.7	Crew Accommodation	N	N	N	Y	N	Y	N	N
2.3.2.8	EVA Atmosphere	N	N	Y	Y	N	Y	N	Y
2.3.2.9	EVA Suits	N	N	Y	N	N	Y	N	Y
2.3.2.10	Shower Water Usage	Y	Y	Y	N	N	Y	N	Y
2.3.2.11	Food Supply	N	N	N	Y	N	Y	N	Y
2.3.2.12	Potable Water	Y	Y	Y	Y	N	Y	N	Y
2.3.2.13	Hardware Location	N	N	N	Y	N	Y	N	N
2.3.2.14	Hardware Maintenance	Y	Y	Y	Y	N	Y	N	N
2.4	Marssuits								

SRD3 ASSESSMENT (40%)	
Complete	N
Consistent	N
Modifiable	Y
Traceable	N
Organized	Y

SRD4 ASSESSMENT (80%)	
Complete	Y
Consistent	Y
Modifiable	N
Traceable	Y
Organized	Y

Table 10: Requirements Quality Assessment - System Objective #3

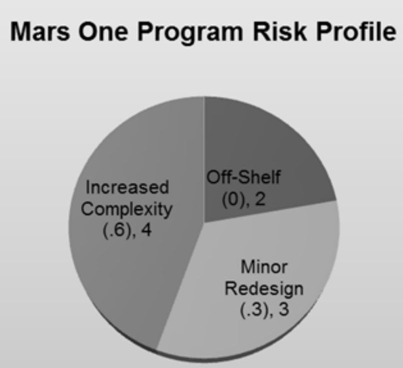
3	System Objective #3: Establish Communications between Earth and Mars								
3.1	Earth Satellite and Network	**N**	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**Y**
3.2.1	*Low Earth Orbit Spacecraft (Direct Link)*	N	Y	Y	Y	Y	Y	N	Y
3.2.2.	*Geosynchronous Earth Orbit Spacecraft (Direct Link)*	N	Y	Y	Y	Y	Y	N	Y
3.2.3	*Shuttle Transportation System*	N	Y	Y	Y	Y	Y	N	Y
3.2.4	*International Space Station*		Y	Y	Y	Y	Y	N	Y
3.3	Mars Satellite and Network	**N**	**Y**	**Y**	**Y**	**Y**	**Y**	**N**	**Y**
3.3.1	*Mars Science*	N	Y	Y	Y	Y	Y	N	Y
3.3.2	*Mars Exploration*	N	Y	Y	Y	Y	Y	N	Y
3.3.3	*Mars Proximity Link*	N	Y	Y	Y	Y	Y	N	Y

SRD5 ASSESSMENT (80%)	
Complete	Y
Consistent	Y
Modifiable	N
Traceable	Y
Organized	Y

Table 12: Technology Readiness Levels (TRLs) vs. Technology Options / Risk Profiles

TRL Level		Off-Shelf	Minor Redesign	Increased Complexity
TRL 3	1			1
TRL 6	1			1
TRL 7	2	1		1
TRL 9	5	1	3	1

Figure 4: Mars One Program Risk Profile



	Key Technologies	Readiness Assessment	Risk (L, M, H)	Risk Profile
1	Launcher - Falcon Heavy	• TRL 7	M	• Off-the-Shelf (0)
2	Transit Vehicle - Dragon*	• TRL 9	H	• Moderate / Significant Complexity Increase (.6)
3	Landing Capsule	• TRL 9	M	• Minor Redesign (.3)
4	Life Support System*	• TRL 7 (Life Support Unit)	M	• *Minor Redesign (.3)*
		• TRL 7 (Living Unit)	M	• Moderate / Significant Complexity Increase (.6)
5	Supply Units	• TRL 9	L	• Off-the-Shelf (0)
6	Rovers*	• TRL 3	M	• Moderate / Significant Complexity Increase (.6)
7	Marssuits*	• TRL 6	H	• Moderate / Significant Complexity Increase (.6)
8	Earth Satellite & Network	• TRL 9	M	• Minor Redesign (.3)
9	Mars Satellite & Network	• TRL 9	M	• Minor Redesign (.3)

**Weight of 2 applied due to potential and significant cost & schedule impacts of technology development*

Table 13: TRLs and Risk Assessment – System Objective #1

	Key Technologies	Readiness Assessment	Risk (L, M, H)	Risk Profile	Description	Consequence	Mitigation
1	**Launcher - Falcon Heavy**	• TRL 7	M	• Off-the-Shelf (0)	• Not completed real launches to date (is upgrade from previously successful model) • Not utilized for human launch	**Loss of Resources:** • Launch missions include: rovers, communications system, the cargo missions (i.e., living units, life support units and supplies), and astronauts. **Loss of Human Life:** • Launcher failure could result in loss of human life	**Control:** • Demonstration launch set for six years before the first human launch. • Test and demonstration launches to provide valuable lessons learned about the selected launcher technology • Launcher will have eight real-world launches prior to conducting human crew launch • Substitute the Falcon Heavy with the Falcon 9, which is at TRL 9
2	**Transit Vehicle - Dragon**	• TRL 9	H	• Moderate / Significant Complexity Increase (.6)	• Proven for Mars Distance; only used for International Space Station (ISS) • Not utilized for humans, cargo only • Similar technology has launched Rovers to Mars; not the selected system • 10 Launches already completed: included x4 demonstrations; x2 resupply missions to ISS • Atlhough resuable, may require development of additional versions due to distance and ability to return to Mars	**Loss of Human Life:** • Transit vehicle failure could result in loss of human life	**Control:** • Ensure demonstration launches utilize Dragon capsule; if so, eight more uses in addition to 10 prior • No true test for human uses until actual mission launch
3	**Landing Capsule**	• TRL 9	M	• Minor Redesign (.3)	• Proven for Mars Distance • Not utilized for humans, Rovers only	**Loss of Human Life:** • Transit vehicle failure could result in loss of human life	**Assumption:** • No true test for human uses until actual mission launch

Table 14: TRLs and Risk Assessment – System Objective #2

	Key Technologies	Readiness Assessment	Risk (L, M, H)	Risk Profile	Description	Consequence	Mitigation
4	**Life Support System**	• TRL 7 (Life Support Unit)	M	*• Minor Redesign (.3)*	• Units are fully functional on-board ISS • Solar panel technology tested and successful • Not yet utilized in planetary environment	**Loss of Human Life:** • Transit vehicle failure could result in loss of human life	**Assumption:** • Employ in analagous environments on Earth during eight-year training period • Provide the astronauts with drills and skills to address potential failures or malfunctions of the technologies
		• TRL 7 (Living Unit)	M	• Moderate / Significant Complexity Increase (.6)	• Launch completed into space in 2006 and 2007; still in orbit • Not yet utilized in planetary environment	**Cost Overruns:** • Potential for cost overruns exist depending on the adjustments that must be made to this technology **Loss of Human Life:** • Liing unit failure could result in loss of human life	**Control:** • Collate data from the 2006 & 2007 versions • Test launch set for 2015, where the inflatable will be attached to the ISS for two years of suitability testing. • Gather lessons learned from the inflatable habitat launches and compre 2006/7 data to 2015 data to reduce the risk • Testing period will end five years prior to the human launch, but only three years prior to the cargo launch – which is when the living units are expected to be Mars-worthy. • Employ in analagous environments on Earth during eight-year training period • Provide the astronauts with drills and skills to address potential failures or malfunctions of the technologies
5	**Supply Units**	• TRL 9	L	• Off-the-Shelf (0)	• Units utilized for previous Mars missions	**Loss of Resources:** • Supplies include: food, solar panels, spare parts and other components; launched and arrives prior to human launch	**Accept:** • Low risk technology
6	**Rovers**	• TRL 3	M	• Moderate / Significant Complexity Increase (.6)	• Several very recent successes with Rover technology • Unable to find indications of specific Rover technology for Mars One program	**Cost Overruns:** • Potential for cost overruns exist depending on the level of development required for the Rover technologies	**Assumption:** • Mars One indicates that the proposed budget includes a large safety margin to take into account significant mission failures as well as smaller but costly failures of components on Mars. • Initiate multiple development efforts, backups, early prototyping, test- analyze-fix, demonstration events, mockups, simulation/modeling
7	**Marssuits**	• TRL 6	H	• Moderate / Significant Complexity Increase (.6)	• Prototype being tested in North Dakota Badlands • Company contracted has been working the NASA Constellation Space Suit for mankind's return to the moon	**Cost Overruns:** • Potential for cost overruns exist depending on the level of development required for the Rover technologies	**Assumption:** • Mars One indicates that the proposed budget includes a large safety margin to take into account significant mission failures as well as smaller but costly failures of components on Mars. • Initiate multiple development efforts, backups, early prototyping, test- analyze-fix, demonstration events, mockups, simulation/modeling

Table 15: TRLs and Risk Assessment – System Objective #3

Key Technologies		Readiness Assessment	Risk (L, M, H)	Risk Profile	Description	Consequence	Mitigation
8	**Earth Satellite & Network**	• TRL 9	M	• Minor Redesign (.3)	• Unable to find indications of specific Rover technology for Mars One program • Assume use of exisiting satellite capability	N/A	N/A
9	**Mars Satellite & Network**	• TRL 9	M	• Minor Redesign (.3)	• Unable to find indications of specific Rover technology for Mars One program • Assume use of exisiting satellite capability	N/A	N/A

Figure 5: Comparison of Risk Assessment Methods

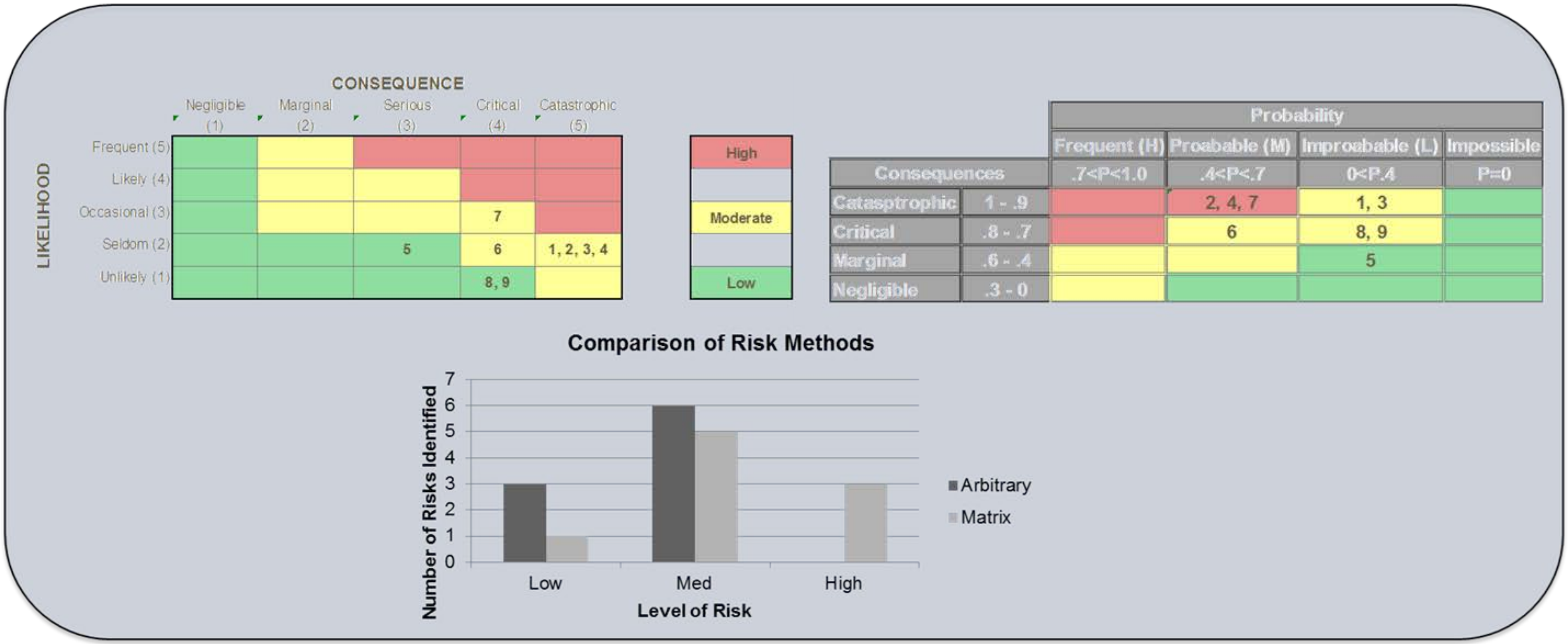


Figure 6: Lessons Learned vs. Iteration vs. Audience

AUDIENCE \ ITERATION:	Problem Statement	CONOPs	Requirements	Technical Assessment & Risk
AA	●		●	
DEV		●	●	
PM	●	●	●	●
SE	●	●	●	●

Lesson 1:	Capability gaps and technology readiness are closely interrelated
Lesson 2:	A (CONOPs) picture is worth a thousand words
Lesson 3:	Reliance on 'existing technology' does not alleviate the need to develop requirements
Lesson 4:	Objective risk assessment models should be utilized

Figure 7: Lessons Learned Distribution

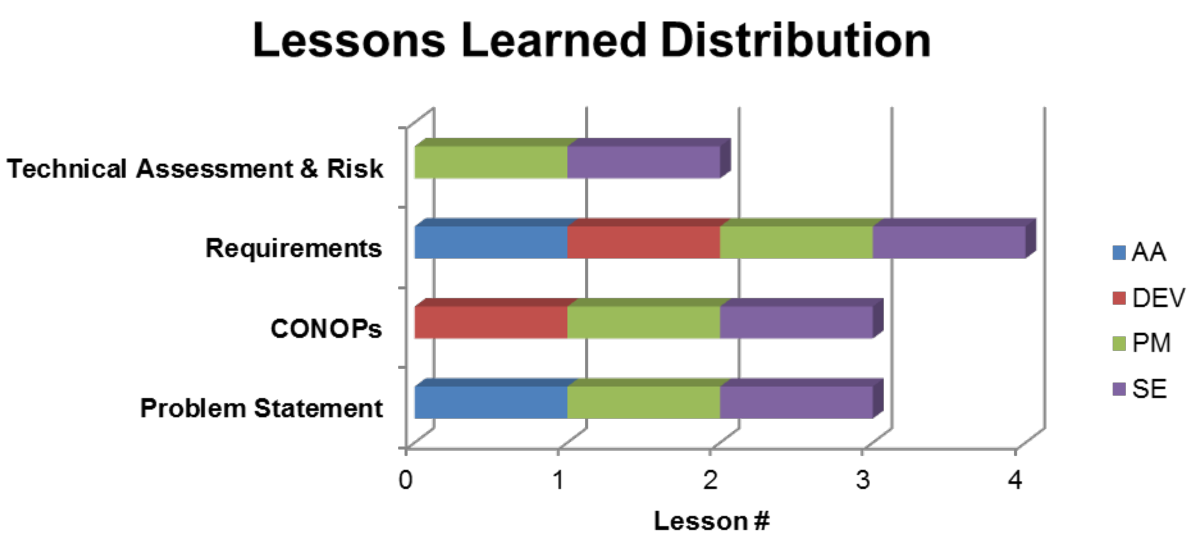


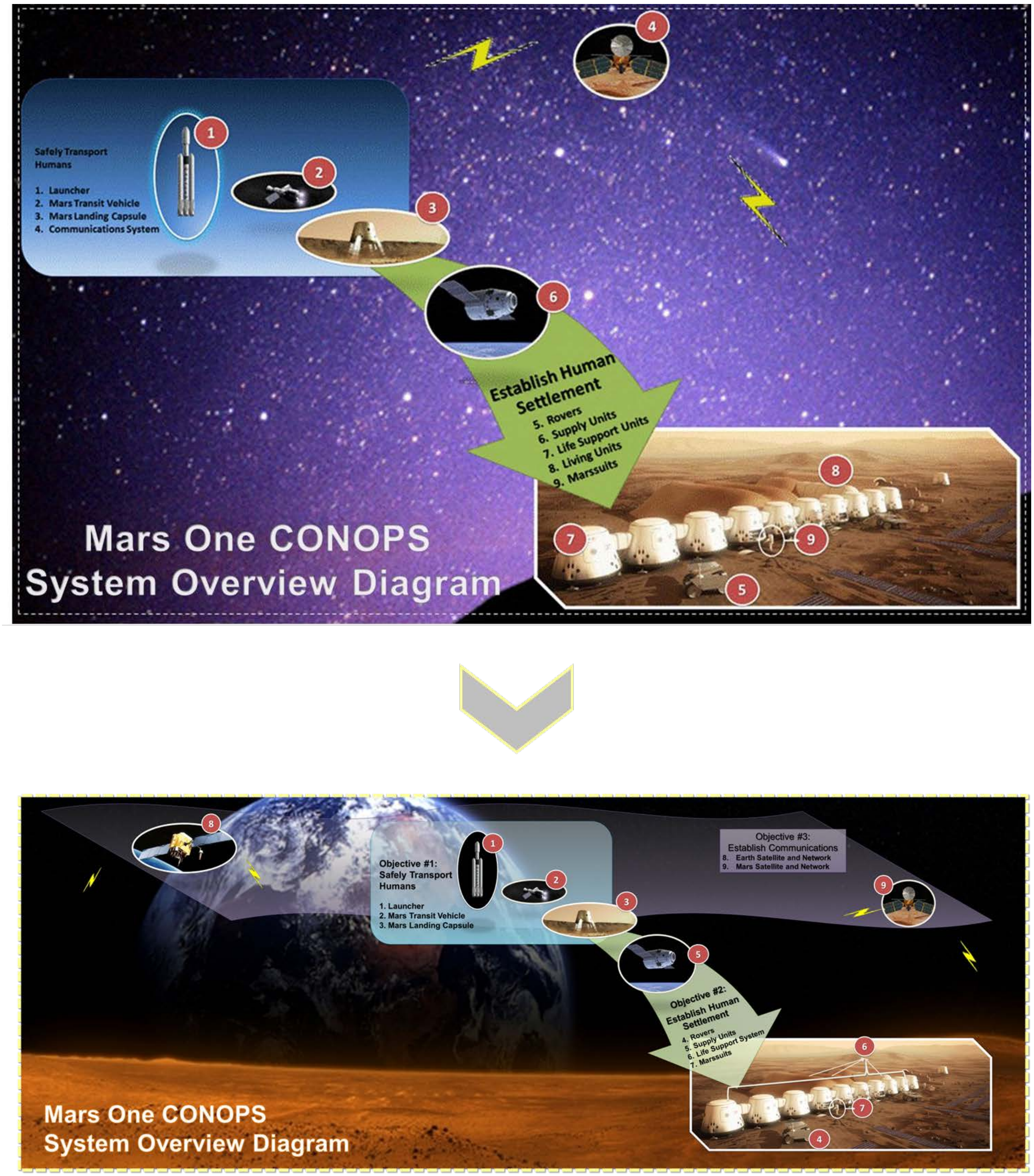
Figure 8: Relationship of Capability Gaps & TRL Risk Profiles

Capability	System Objectives: Transport	System Objectives: Settle	System Objectives: Comms	Requirement	Gaps	Y/N
Launcher	✓			• Multiple rocket launches to take payloads into Earth orbit and then on to Mars	• Selected launcher, not proven for Mars Distance, only ISS • Not completed real launches to date (is upgrade form previously successful model) • Not utilized for human launch	Y
Mars Transit Vehicle	✓			• Human crew will travel through space for around seven months • The transit vehicle will consist of two propellant stages– a landing module and transit habitat	• Proven for Mars Distance • Not utilized for humans, Rovers only	Y
Mars Landing Capsule	✓			• Landers will be equipped to perform different functions to include carrying Life Support Units, Supply Units, Living Units, Humans and Rovers	• Proven for Mars Distance • Not utilized for humans, Rovers only	Y
Life Support System		✓		Life Support Unit • Has extra technologies to capitalize on the natural resources available on Mars • Electrical energy is generated through solar panels • Potable water will be created through the heating of water ice in the local ground soil • A portion of the water is stored while a portion is used to produce oxygen • Nitrogen and argon gas are extracted from the Mars atmosphere and injected into the habitable space as inert gases Living Units • Has a unique, inflatable living section and an airlock • Filled with breathable air by the Life Support Unit prior to the arrival of the astronauts • Contains construction materials for the astronauts to construct rooms, floors and install electrical outlets • Contains the "wet areas", such as the shower and kitchen	• Very similar to those units which are fully functional on-board the International Space Station • Solar panel technology tested and successful • very similar to those units which are fully functional on-board the International Space Station • The inflatable Living Unit will be built around existing technologies in and orbiting since 2006 / 2007 • None currently utilized for human use • None utilized in a planetary environment	Y
Supply Units		✓		• Unit with food, solar panels, spare parts and other components		N
Rovers		✓		• Two Rovers to set up the outpost before the humans arrive • One intelligent rover which determines the most suitable settlement location and is a transporter of large hardware components and then conducts general assembly • One trailer rover used for transporting the landing capsules • Beacon signal to guide remaining transports in for landing	• Several very recent successes with Rover technology and landings • Not a scientific Rover	N
Mars-suits		✓		• Protects astronauts from exposure to the Mars atmosphere • The Mars Suit must be flexible enough to allow the astronauts to work and at the same time keep them safe from the harsh atmosphere • Temps from −17.2 °C (1.0 °F) to −107 °C (−161 °F)	• Utility of design and some temperature functionality can be tested on Earth • Last space suits utilized or surface activity were Apollo in 1970s • No suits established for the Mars environment or tested	Y
Communications System			✓	Earth Satellite & network / Mars Satellite & network • Two communications satellites and Earth ground stations. It will transmit data from Mars to Earth and back • One placed in Earth stationary orbit • One placed into a Mars stationary orbit - Can relay images, videos and other data from the Mars surface - Data bandwidth ~4 x NASA Mars Reconnaissance Orbiter • Enables 24/7 communication between the two planets	• Proven for Mars Distance with current Rover data transmit • Internet and other streaming communications requirements may not operate as intended – not yet tested/proven	N

	Key Technologies	Readiness Assessment	Risk (L, M, H)	Risk Profile
1	Launcher - Falcon Heavy	• TRL 7	M	• Off-the-Shelf (0)
2	Transit Vehicle - Dragon*	• TRL 9	H	• Moderate / Significant Complexity Increase (.6)
3	Landing Capsule	• TRL 9	M	• Minor Redesign (.3)
4	Life Support System*	• TRL 7 (Life Support Unit)	M	• *Minor Redesign (.3)*
		• TRL 7 (Living Unit)	M	• Moderate / Significant Complexity Increase (.6)
5	Supply Units	• TRL 9	L	• Off-the-Shelf (0)
6	Rovers*	• TRL 3	M	• Moderate / Significant Complexity Increase (.6)
7	Marssuits*	• TRL 6	H	• Moderate / Significant Complexity Increase (.6)
8	Earth Satellite & Network	• TRL 9	M	• Minor Redesign (.3)
9	Mars Satellite & Network	• TRL 9	M	• Minor Redesign (.3)

Technology	Capability Gap?	Low Tech. or Perf. Level?
Launcher	Y	N
Transit Vehicle	Y	Y
Lander	Y	N
Life Support	Y	Y
Supply Units	N	N
Rovers	N	Y
Mars-suits	Y	Y
Communications	N	N

Figure 9: Iterative Development of CONOPs Diagram



Works Cited

Bhasin, K., & Hayden, J. (2004, July). Developing Architectures and Technologies for an Evolvable NASA Space Communication Infrastructure. Cleveland, Ohio, USA. Retrieved September 20, 2013, from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.106.1795&rep=rep1&type=pdf

Bodiford, M. P., Fisket, M. R., McGregor, W., & Pope, R. D. (2005, February). In Situ Resource-Based Lunar and Martian Habitat Structures Development at NASA/MSFC. Huntsville, Alabama, USA. Retrieved September 20, 2013, from http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20050111573_2005093325.pdf

Crumbly, C. M., & Craig, K. D. (2011, December 15). Space Launch System NASA Research Announcement Advanced Booster Engineering Demonstration and/or Risk Reduction. Retrieved September 20, 2013, from http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120003042_2012002617.pdf

Drake, B. G. (Ed.). (2009, July). *Mars Architecture Steering Group.* Retrieved August 31, 2013, from NASA: http://www.nasa.gov/pdf/373667main_NASA-SP-2009-566-ADD.pdf

Edgecombe, J., dela Fuente, H., & Valle, G. (2009, April 16). *NASA Technical Reports Server.* Retrieved August 30, 2013, from http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090014832_2009014374.pdf

Grenn, M. (2013, August). *Requirements Analysis Processes (Lecture Slides)*. Arlington, VA, USA.

Grenn, M. (2013). *SE Process Outputs and Risk Management Overview (Lecture Slides).* Arlington, VA, USA.

Haskins, C. (Ed.). (2011). *Systems Engineering Handbook: A Guide For System Life Cycle Processes and Activities v. 3.2.2.* San Diego, CA, USA: INCOSE.

Hoffman, S. J., & Kaplan, D. I. (Eds.). (1997, July). Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team. *NASA Special Publication 6107*. Houston, Texas, USA. Retrieved August 25, 2013, from http://2004.isdc.nss.org/settlement/mars/1997-NASA-HumanExplorationOfMarsReferenceMission.pdf

Howell, E. (2013, January 17). Bigelow Aerospace: Inflatable Modules for ISS. *Space.com*.

Kubota, T., Ogawa, N., Okada, T., Miyamoto, H., Morimoto, M. Y., Fujita, K., et al. (2009). Preliminary Study on Lander System and Scientific Investigation for Next Mars Exploration . Japan. Retrieved September 20, 2013, from http://flab.eng.isas.jaxa.jp/member/oyama/papers/ists2009-k-21.pdf

Malik, T. (2006, May 5). Mars Spacesuit Prototype Trials Underway in North Dakota. *Space.com*.

Mars One. (n.d.). About Mars One. Retrieved August 25, 2013, from http://www.mars-one.com/en/about-mars-one/about-mars-one

Mars One. (n.d.). Mars One Astronaut Training Program. Retrieved August 29, 2013, from http://www.mars-one.com/en/faq-en/21-faq-selection/203-how-are-the-astronauts-prepared

Mars One. (n.d.). Mars Transit Vehicle. Retrieved September 5, 2013, from http://www.mars-one.com/en/mars-transit-vehicle

Mars One. (n.d.). Road Map 2016 - Demosntration and ComSat Mission. Retrieved August 25, 2013, from http://www.mars-one.com/en/roadmap2016

Mars One. (n.d.). Roadmap. Retrieved September 5, 2013, from http://www.mars-one.com/en/mission/summary-of-the-plan

Mars One. (n.d.). *Roadmap 2018 - Rover Mission Launch.*

Mars One. (n.d.). The Technology. Retrieved August 25, 2013, from http://www.mars-one.com/en/mission/technology

Mars One. (n.d.). Why Should We Go To Mars. Retrieved August 29, 2013, from http://www.mars-one.com/en/faq-en/22-faq-mission-features/200-why-should-we-go-to-mars

Petrov, G. I. (2004, February 24). *Massachusetts.* Retrieved August 28, 2013, from DSpace@MIT: http://hdl.handle.net/1721.1/27373

SpaceX. (2013). Falcon Heavy Specifications. Hawthorne, CA, USA. Retrieved August 25, 2013, from http://www.spacex.com/falcon-heavy

Wall, M. (2013, March 13). Mars Colony Project Signs Deal to Study Spacesuits. *Space.com*.

Wieland, P. (Ed.). (1998, January). Living Together in Space: The Design and Operation of the Life Support Systems on the International Space Station. *1*. Huntsville, Alabama, USA. Retrieved September 20, 2013, from http://spaceflightsystems.grc.nasa.gov/repository/NRA/tm206956v1%20living%20together%20%20in%20space.pdf