Blue Dragon

An Affordable and Achievable Humans-to-Mars Mission Architecture and Program to Create an International Mars Research Station

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Abstract

This document outlines a program of three near-term, affordable and achievable missions to send international crews of six people to Mars and return them safely to Earth. Developed as an evolution of the NASA Design Reference Architecture 5.0 (Mars Architecture Steering Group, 2009), it incorporates a number of innovations designed to reduce costs and to improve safety and the probability of success.

The fundamental difference from the Design Reference Architecture (DRA) is to focus on a single location rather than several, enabling reuse of hardware elements across multiple missions. The reduces the cost of the program, compared with the DRA, and makes more sense strategically. Rather than visit three distinct locations, the purpose of the program is to create the International Mars Research Station (IMRS), a research facility on Mars for use by multiple Earth space agencies and potentially also companies.

Another key strategy for lowering costs is to use commercial off-the-shelf hardware components such as capsules, rockets, engines, spacesuits and inflatable spacecraft modules. ISRU (In Situ Resource Utilisation) technology is leveraged for manufacturing propellant, water and breathable air, thus reducing launch mass and mission cost.

The mission also achieves improved safety by using capsules to ferry crews between the surfaces and orbits of both Earth and Mars, and by pre-deploying the majority of station hardware, including the Mars Ascent Vehicle, habitat, surface vehicles (rovers), power systems and ISRU equipment. Habitat volume may be significantly expanded through the use of inflatable extensions.

Blue Dragon is designed as a first step in a broader process of settlement rather than a self-contained Apollo-style program of science and/or exploration. This affects the destination of the mission, as well as surface activities. The reasoning is that science and exploration can proceed more readily and at a much greater scale once a permanent human presence has been established. Successive missions targeted to a single location will progressively build up infrastructure, establishing a permanent base of operations quickly, beyond which further science and exploration can proceed. Research activities during surface stay are oriented around science, exploration and engineering, primarily in the context of supporting habitation of Mars and settlement.

Blue Dragon is not designed to serve the interests of any one nation, but humanity as a whole. For this reason, and because of the cost and scale of the mission, the intention is that it will be executed by an international partnership in a similar fashion to the International Space Station (ISS). This is considered necessary, not only for financial, but also political, ethical and philosophical reasons.

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Introduction

Many H2M (Humans-to-Mars) architectures have been proposed over the years, with each new iteration incorporating innovations and technologies, filling gaps and solving problems, and bringing us step-by-step closer to the goal of sending people to the red planet. It is now widely believed within the Mars community that there remain few, if any, genuine technological barriers to sending humans to Mars, and almost all elements required for a successful mission are now available either from commercial suppliers, or could be, or are being, developed by government space agencies. Although some crucial mission elements still need to be developed, the primary challenges are now financial rather than technological.

Perhaps the most important and disruptive architecture presented in recent years is Mars Direct (Zubrin *et al.*, 1991), principally because it introduced the idea of ISPP (In Situ Propellant Production) as a method for drastically reducing the mass transported to Mars and therefore the investment required for a successful H2M mission. This represented a quantum leap forward in H2M mission concepts, reducing the estimated total cost by approximately a factor of eight.

In 1995 NASA began developing a new Mars mission architecture, known as the *NASA Design Reference Mission*, which incorporated elements of Mars Direct, including ISPP. This architecture has evolved to version 5.0, and is now called the *Design Reference Architecture* (DRA). The DRA has been in development for at least 12 years, involving many experts and departments within NASA, and arguably represents one of the best H2M architectures currently available.

Nonetheless, a variety of modifications to the DRA have since been proposed, suggesting further opportunities for improving the architecture:

- Adopting a base-first approach rather than a series of missions to disparate locations (Gage, 2010).
- The use of biconic spacecraft to improve EDL (Entry, Descent and Landing) performance and to more efficiently optimise spacecraft and habitat geometry (Willson and Clarke, 2005).
- The use of MLLV (Medium Lift Launch Vehicles) or EELV (Evolved Expendable Launch Vehicles) to eliminate the significant investment required to develop a suitable HLLV (Heavy Lift Launch Vehicle) (Bonin, 2006).
- The use of inflatable modules to significantly expand habitat volume (Kozicki, 2011).
- The use of capsules to safely deliver cargo and crew (Wielders *et al.*, 2013).

The Blue Dragon architecture is largely based on the DRA, but incorporates a number of changes based on innovations such as those listed above, plus more. Importantly, Blue Dragon takes advantage of a number of COTS (Commercial Off The Shelf) hardware components that have recently become or will soon become available, thus drastically reducing the estimated cost of sending people to Mars. The result is an affordable and achievable architecture that offers increased safety and reliability, and improved outcomes.

The mission is named “Blue Dragon” because it makes use of several (at least five) Dragon capsules from Space Exploration Technologies Corporation (SpaceX) for transporting crew and cargo to Mars. It’s “blue” because the blue planet is reaching out to the red planet.

Two related concepts for precursor missions currently in development are “Green Dragon” and “Gold Dragon”, both designed to test mission-critical elements of the Blue Dragon architecture. These missions are described briefly towards the end of this document, and in more detail separately.

Aside from architectural changes, there are two other important differences from the DRA, related to the intention of the mission.

1. Blue Dragon is intended as the beginning of a process of settlement. The focus is less on “flags and footprints”, or scientific exploration for its own sake. The primary emphasis is laying the foundations for a permanent human presence: making use of local resources, building up technological infrastructure, studying effects on human physiology and psychology, and generally learning how to live on Mars. The fundamental philosophy here is to develop a permanent presence first, then we can do as much science as we want, much more easily, cheaply, efficiently and conveniently.

2. The intention is that Blue Dragon be implemented as an international collaborative effort. If Mars is to be a future home for humanity, it must be for all humanity, and not any single Earthian nation. To become multiplanetary, we must leave nationalistic ideas behind and approach Mars as a united people.

Background

Dragon capsules

The current version of Dragon capsules, including the one that historically became the first commercial spacecraft to dock with the ISS, are designed to splash down in water, like those used in NASA's Mercury, Gemini and Apollo programs and like NASA's new Orion capsule.

The next generation of Dragon capsules are designed to land on solid ground. Currently in development at SpaceX, they are fitted with eight "SuperDraco" engines, which are a powerful new variation of the Draco engines used by the Dragon RCS (Reaction Control System). Like the Dracos, they use non-cryogenic propellant: monomethyl hydrazine fuel and nitrogen tetroxide oxidiser. However, they're much more powerful, each capable of delivering about 67 kilonewtons of axial thrust, for a total of about 534kN. These engines will enable the Dragon to land propulsively on solid ground, usually back at the original launchpad, thereby saving the time and expense of water recovery and opening up the possibility for Dragon capsules to land on the Moon, Mars and other worlds with solid surfaces. This is in alignment with SpaceX CEO Elon Musk's stated purpose of establishing settlements on Mars.

SpaceX Dragon capsule landing on Mars

DragonRider

SpaceX offer two basic configurations for the Dragon capsules: cargo and crew. The crewed version is known as a “DragonRider”, and can accommodate up to seven astronauts. These may be used for transporting crew between Earth and the ISS in the near future.

In the Blue Dragon architecture, which is designed for a crew of six, the seventh seat is removed and the volume that it (and a seventh person) would normally occupy is reserved for cargo. This may be last minute personal items from Earth, or samples from Mars. All three DragonRiders in the architecture will be modified to accommodate six people plus storage.

DragonRider capsule with 7 crew

Red Dragon

“Red Dragon” is a proposed variant of the SpaceX Dragon capsule currently being investigated by NASA as a low cost alternative for delivering payloads to Mars (Karcz *et al.*, 2012).

Red Dragon will presumably be similarly configured with SuperDraco engines. Alternatively, they may utilise new methane-fuelled “Raptor” engines being developed at SpaceX, which would have the advantage that they could be refuelled on Mars. In addition, Red Dragon will incorporate several modifications necessary for EDL on Mars, including:

- Removal of systems unique to LEO missions, such as berthing hardware.
- Addition of deep space communications.
- Modifications to SuperDraco (or Raptor) engines to suit the Martian atmosphere.
- Reduction of heat shield thickness, since the atmosphere is far less dense.

- Algorithms and avionics for pinpoint landing on Mars.

The gravity on Mars is lower, which reduces the acceleration of the capsule towards Mars; however, in the case of direct entry the capsule will be approaching from interplanetary space at a much higher velocity than if it were descending from orbit. Also, Mars' atmosphere is much thinner (less than 1%) than Earth's, so it will play less of a role in reducing spacecraft velocity during EDL. However, for the same reason, there is less heating due to atmospheric friction, and therefore less or, perhaps, different heat shield material may be used. The different conditions will affect the forces experienced by the spacecraft, which may require changes to thrusters, heat shield, avionics and other aspects.

NASA have calculated that a Red Dragon capsule will be capable of delivering payloads of up to 1.9 metric tonnes to the surface of Mars. This delivery mechanism has been receiving increasing attention from NASA, being considerably simpler and cheaper than, for example, the sky crane method used to deliver *Curiosity*. Not only will it be cheaper per kilogram of payload mass, but much cheaper overall.

Another clear advantage is that a landed capsule can be repurposed as a storage unit, shelter or habitat.

Once the Red Dragon technology has been proven as a reliable mechanism for delivery of cargo, this approach may be used to deliver up to seven crew members to Mars surface, simply by using a DragonRider modified in the same way.

Red Dragon represents a near term technology that can enable comparatively inexpensive and functional Mars missions. It's a fundamental element of the Blue Dragon architecture (hence the name), being utilised for delivery of both crew and cargo to Mars surface.

The Dragon capsules are being designed to land with a high degree of accuracy. From the SpaceX website:

> *"SuperDraco engines will power a revolutionary launch escape system that will make Dragon the safest spacecraft in history and enable it to land propulsively on Earth or another planet with pinpoint accuracy."*

This ability to land "with pinpoint accuracy" is supported by the Dragon's GNC (Guidance, Navigation and Control) system. Due to the lack of GPS (Global Positioning System) on Mars, high-accuracy landings must be achieved using alternate methods. However, this problem has effectively been solved. For example, ESA (European Space Agency) have been developing a system known as "LION" (Landing with Inertial and Optical Navigation) that will enable pinpoint landing on the Moon, Mars and asteroids using image recognition of major landmarks (Delaune *et al.*, 2012). Another important development is the Fuel Optimal Large Divert Guidance (G-FOLD) algorithm (Acikmese *et al.*, 2012), able to autonomously calculate landing trajectories in real-time. This was recently tested successfully with Masten Space System's Xombie VTOL experimental rocket, with the vehicle making a 750 metre course correction in real time. Considering these developments it's reasonably safe to assume that the Red Dragon will be capable of pinpoint landings on Mars by the time we begin sending them. Because the position of landed base components can be known with precision, a neat, safe and optimised layout of the base can be designed beforehand.

Red Dragon potentially represents a mechanism for delivering cargo or crew to the surface of Mars that is not only repeatable, but affordable. SpaceX currently charge $135M for a Falcon Heavy launch including the Dragon capsule. Making use of COTS and other pre-developed hardware it may be possible to develop and deliver a payload to Mars for under $250M. This is a mere one tenth of the $2.5B *Curiosity* rover.

Once SpaceX have developed their RLS (Reusable Launch System) for the Falcon Heavy - a goal likely to be achieved within a few years, considering the recent Grasshopper tests, and thus well before the first H2M mission - this price will come down even further.

Red Dragon II

Dragon capsules have a diameter of 3.7 metres. However, the architecture for the Mars One mission, which proposes to send 24-40 astronauts on a one-way mission to Mars, relies on a larger, 5-metre-diameter Dragon capsule for habitat modules. Although these are yet be to be built or demonstrated, their plan is to land the first two of these on Mars in 2020; only seven years from the time of writing.

Therefore, it could be inferred that plans exist at SpaceX to have these larger Dragon capsules operational and available within seven years. This is well within the timeline of Blue Dragon.

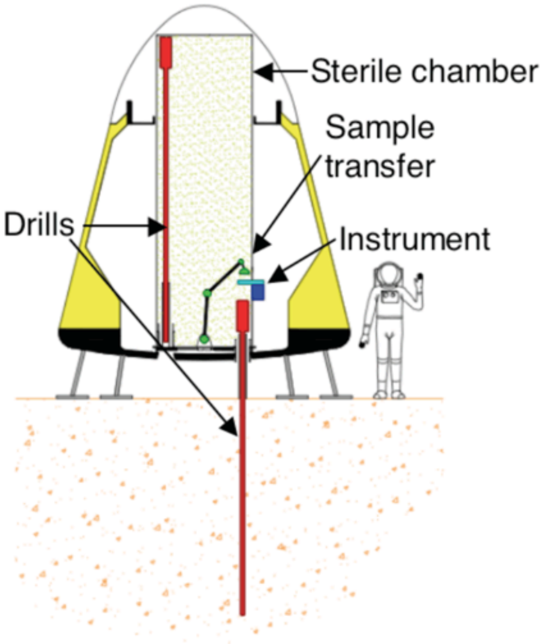
As no information about these larger capsules is currently available, Blue Dragon does not presently utilise them; however, this may change as more information becomes available.

Ice Dragon

NASA have commenced studies of a mission to Mars based on the Red Dragon landing system, which may be flown as early as 2018. Known as “Ice Dragon” (Stoker *et al.*, 2012), it’s being developed in collaboration with SpaceX, and will deliver a science package to Mars including a drill that will penetrate up to two metres into the permafrost to investigate environmental conditions suitable for past or extant life.

There are six objectives currently envisaged for Ice Dragon:

1. Determine if life ever arose on Mars.
2. Assess subsurface habitability.
3. Establish the origin, vertical distribution and composition of ground ice.
4. Assess potential human hazards in dust, regolith and ground ice, and cosmic radiation.
5. Demonstrate ISRU for propellant production on Mars.
6. Conduct human relevant EDL demonstration.



Ice Dragon showing drills. (Human figure shown for scale only)

Besides the scientific outcomes of the mission, which will certainly be of tremendous value to human missions, one of the most important contributions of Ice Dragon will be demonstration of the EDL capabilities of the Red Dragon capsule.

Architectural Overview

Friendly names

To mitigate acronym overload, the primary elements of the mission have been given “friendly” names.

1. The MTV (Mars Transfer Vehicle) is named “*Adeona*”, which is the name of the Roman goddess of safe return. It comes from the Latin verb *adeo*, “to approach or visit” as well as “to take possession of one's inheritance”. Mars is our inheritance and we hope for a safe return for the crew.

2. The MAV (Mars Ascent Vehicle) is named “*Success*”.

3. The DragonRider capsules that carry the crew between the surfaces and orbits of Earth and Mars are named “*Pern-1*”, “*Pern-2*” and “*Pern-3*”. These names comes from the novel “Dragonriders of Pern” by Anne McCaffrey. *Pern-2* forms the uppermost stage of *Success*.

4. The Mars Surface Habitat is known more simply as “the Hab”.

5. The Mars Exploration Vehicle is known more simply as “the Rover”.

The names *Adeona*, *Success*, *Pern-1*, *Pern-2* and *Pern-3* are italicised, following the convention for ship names.

The first crew to go to the IMRS is called “Alpha Crew”, the second is named “Bravo Crew”, the third is named “Charlie Crew”, and so on, following the international phonetic alphabet for aviation. This pattern has been adopted to support clear radio communications between different Mars exploration crews and Earth, which will become more important when multiple crew are operating on Mars at the same time.

Primary Hardware Components

Type	Component	Acronym	Friendly name	Description
Rockets	SpaceX Falcon 9			Rocket for launching *Pern-1* and *Pern-3*, lighter sections of *Adeona*, fit-out crews, etc.
	SpaceX Falcon Heavy			Rocket for launching cargo capsules, Hab and Rover to Mars, and *Adeona* cruise stage to LEO.
	SpaceX Falcon X			Rocket for launching MAV to Mars.
	Atlas V Heavy			Rocket for launching BA 330 to LEO.
	Mars Cargo Module		Cargo Dragon	Red Dragon capsule used to deliver cargo to the Martian surface.

Capsules	Mars Crew Module		*Pern-1, -2*, etc.	DragonRiders that carry the crew between *Adeona*, Mars and Earth.
Satellites	L5 Commsat			Heliocentric satellite for communications, navigation and observation, positioned at Earth L5.
	IMRS Commsat			Areosynchronous satellite for communications, navigation and observation, positioned above IMRS.
Main Custom Components	Mars Ascent Vehicle	MAV	*Success*	Rocket to carry the crew from Mars surface to Mars orbit. Includes descent stage, ISPP system, ascent stage and *Pern-2*.
	Mars Transfer Vehicle	MTV	*Adeona*	Spaceship that carries the crew to Mars and back.
	Mars Surface Habitat	MSH	Hab	Habitat where the crew live and work while on the surface of Mars. Contains ISAP and ECLSS.
Surface Vehicles	Mars Exploration Vehicle	MEV	Rover	A pressurised rover for exploring Mars.
	All Terrain Vehicle	ATV	Quad bike	Unpressurised 4-wheeled vehicle.

Phase 1: Prepare (2014-2029)

1. Develop the Red Dragon EDL system.
2. Select location for the IMRS.
3. Select and train Alpha Crew.
4. Develop and construct *Adeona*, *Success*, the Hab, Rover and Commsats, and other major hardware components.
5. Fit-out and training missions to *Adeona*.
6. Green Dragon mission to test ISRU technology. Gold Dragon mission to test the Mars Ascent Vehicle.

Phase 2: Pre-deploy (2029-2031)

1. Pack and launch Cargo Dragons, send to the IMRS.
2. Launch the the L5 Commsat and place in heliocentric orbit at Earth L5.
3. Launch the the IMRS Commsat and place in areosynchronous orbit above IMRS.

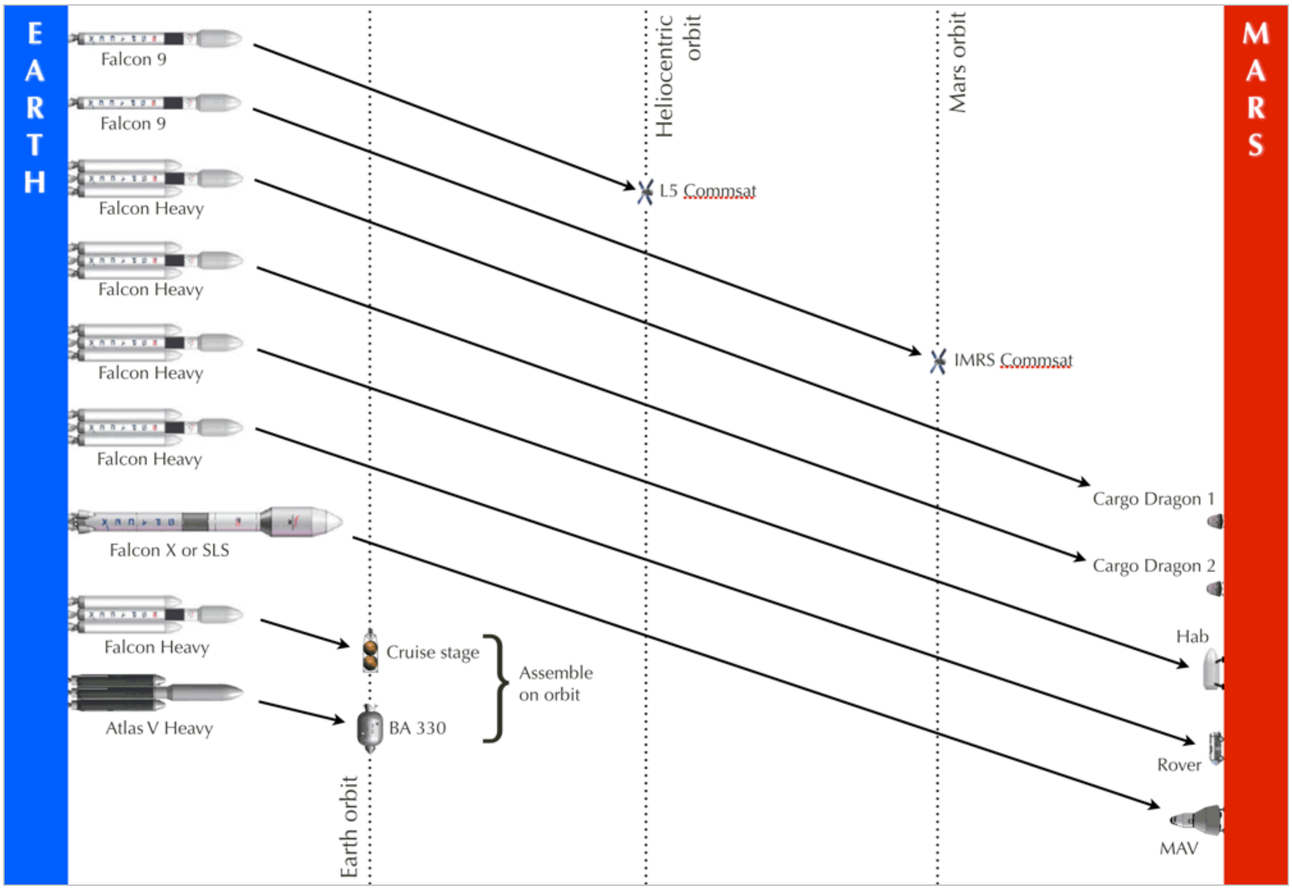
4. Launch the Rover, land it safely at IMRS, remotely activate and test.

5. Launch *Success*, land it safely at IMRS, remotely activate and test.

6. Launch the Hab, land it safely at IMRS, remotely activate and test.

7. Launch BA 330 and cruise stage(s) of *Adeona* separately, and assemble on orbit.

8. Use the Rover to explore the surrounding terrain and find a suitable LZ (Landing Zone) for *Pern-1*.



Bat chart - Pre-deployment phase

Phase 3: Crew Outbound (2033)

1. Launch crew in *Pern-1* by Falcon 9. Perform EOR (Earth Orbit Rendezvous) and dock with *Adeona*. *Pern-1* remains docked to *Adeona* en route to Mars.

2. *Adeona* performs TMI (Trans Mars Injection) and flies to Mars on a minimum-energy Hohmann transfer orbit for ~6 months.

3. On approach to Mars, *Adeona*'s RCS rotates the vehicle 180° so the engine is facing Mars.

4. *Adeona* performs MOI (Mars Orbit Insertion) and parks in Mars orbit.

5. Crew transfers from *Adeona* back into *Pern-1*, wearing marssuits.

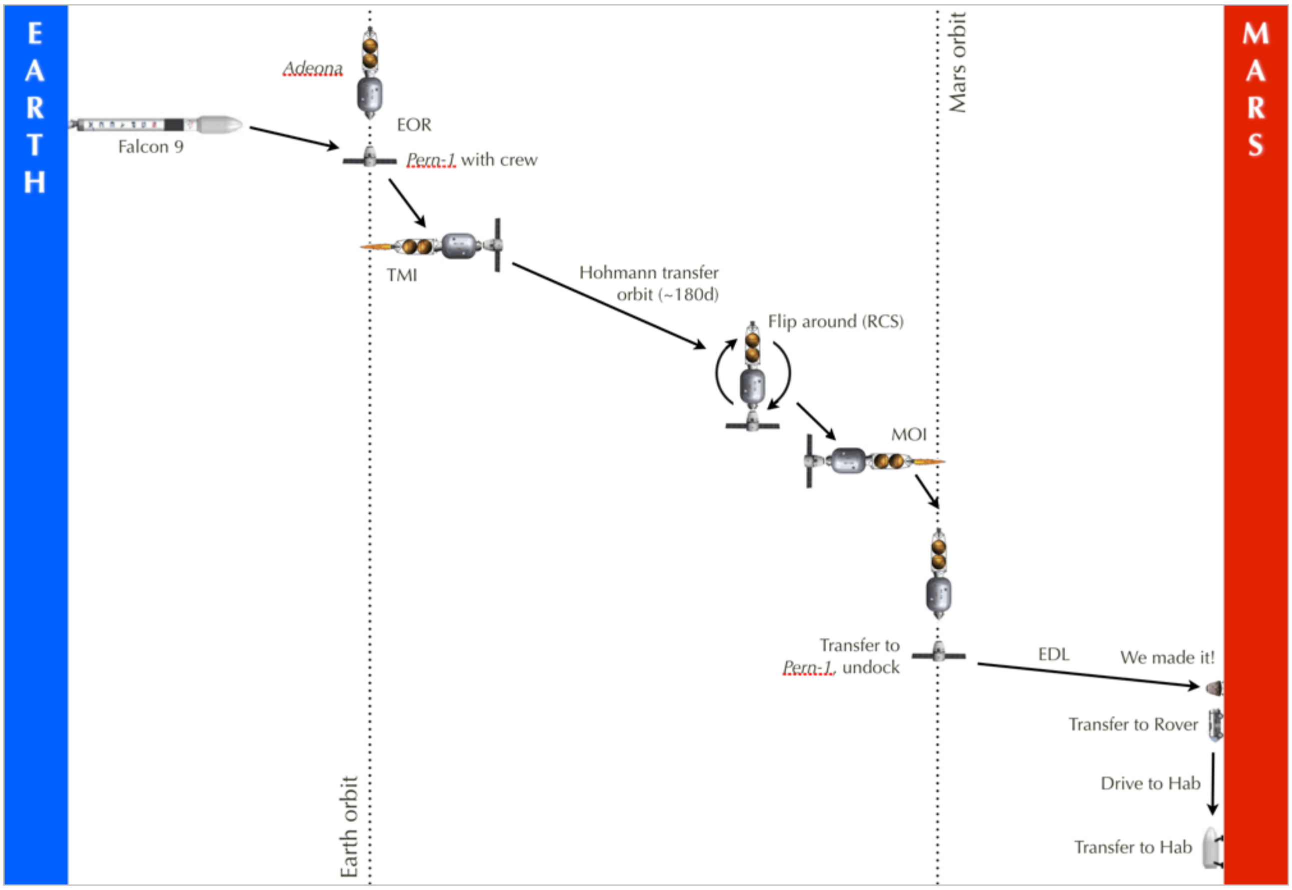
6. Crew descends to the surface of Mars in *Pern-1.*

7. The Rover drives from the Hab to the LZ of *Pern-1*.

8. Crew transfer from *Pern-1* to the Rover.

9. Crew drive the Rover to the Hab.

10. Crew transfer from the Rover to the Hab through airlocks.



Bat chart - Outbound phase

Phase 4: Surface Mission

1. The crew spend 1-2 weeks in the Hab, setting up their living space and adapting to Mars gravity.

2. Surface mission for ~18 months.

3. On Earth, prepare for second mission. Select and train Bravo Crew. Construct new propulsion stages for *Adeona*.

Phase 5: Crew Return (2035)

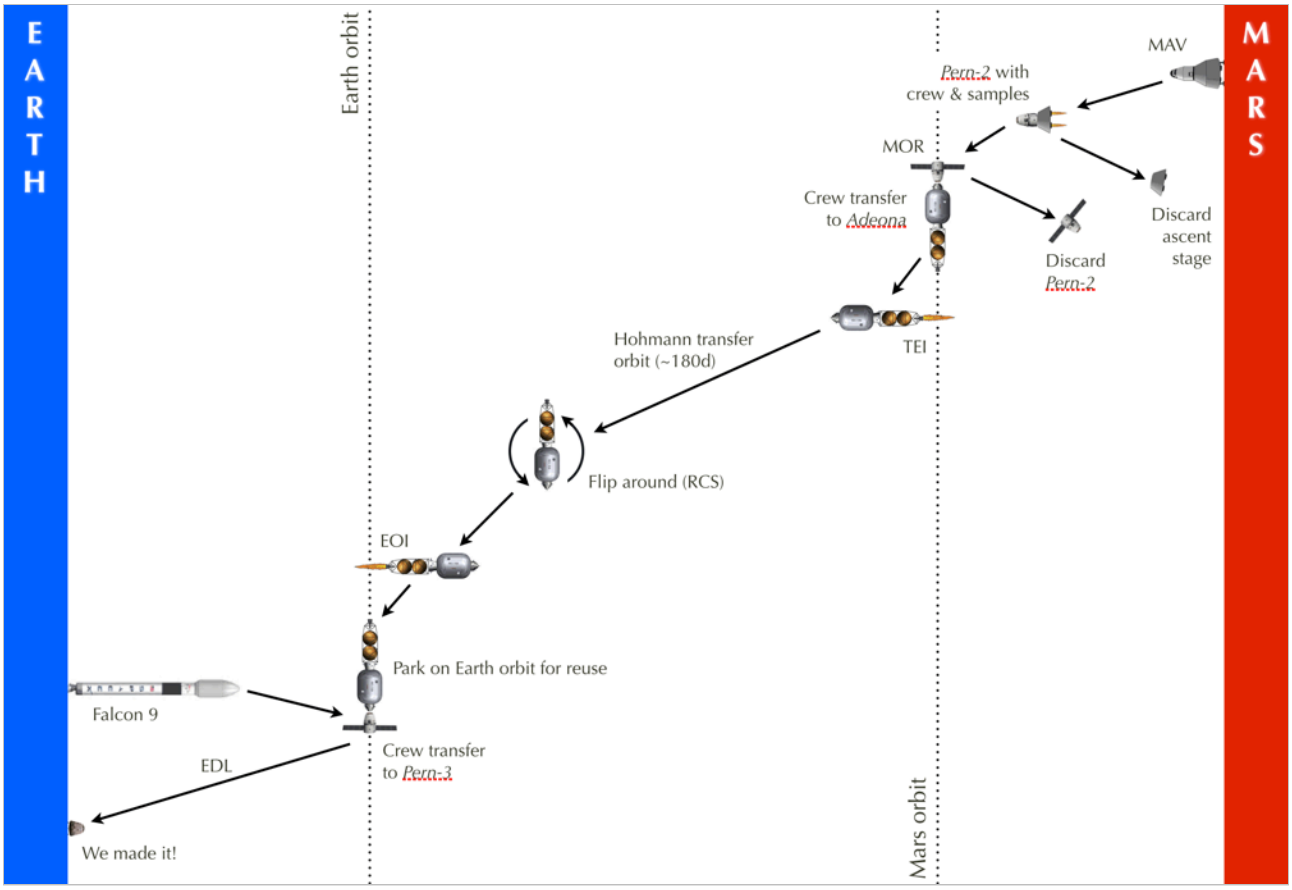
1. About 1-2 months before departure, commence systems checks of *Success* and *Adeona*.
2. On departure, Hab is placed in standby/ISRU mode, in preparation for arrival of the next crew in ~8 months.
3. Crew transfer to the Rover in marssuits, along with their boxes of samples for bringing back to Earth (or these may have been delivered to *Success* previously).
4. The crew drives the Rover to *Success*.
5. Crew transfer, with samples, to *Success*.
6. The upper two stages of *Success* (ascent stage and *Pern-2*) launch from Mars surface, leaving behind the descent stage and ISPP hardware.
7. On reaching space, *Pern-2* separates from the ascent stage, which is discarded on Mars.
8. *Pern-2* performs MOR (Mars Orbit Rendezvous) and docks with *Adeona*.
9. Crew transfer, with samples, from *Pern-2* to *Adeona*.
10. *Pern-2* is undocked and discarded on Mars, rather than remaining docked and used for EDL at Earth. Although this is more expensive (costs an additional Falcon 9 + DragonRider), this is done for three reasons:
    1. Planetary protection. *Pern-2* has been sitting on Mars for 44 months, so we shouldn't bring it to Earth.
    2. Reduces mass of *Pern-2*, as no heat shield is required for Earth EDL, which therefore reduces difficulty of launching from Mars.
    3. Reduces mass for TEI (Trans Earth Injection).
11. *Adeona* performs TEI and flies back to Earth on a minimum-energy Hohmann transfer orbit for ~6 months.
12. On approach to Earth, *Adeona*'s RCS rotates the vehicle 180° so the engine is facing Earth.
13. *Adeona* performs EOI (Earth Orbit Insertion) and parks on Earth orbit.

14. Falcon 9 with *Pern-3* launched from Earth.

15. *Pern-3* performs EOR with *Adeona*.

16. Crew transfer themselves and samples from *Adeona* to *Pern-3.*

17. *Pern-3* undocks from *Adeona* and performs EDL to Earth surface.



Bat chart - Return phase

Phase 6: Recover/Prepare

1. Mars samples quarantined, contained and securely relocated.

2. Alpha Crew commence physical rehabilitation to restore fitness.

3. Alpha Crew extensively debriefed.

4. Send more power hardware etc. to the IMRS.

5. Missions to connect new propulsion stages and refurbish *Adeona*.

6. Bravo Crew commence on-orbit training missions in *Adeona* (unless they've already left - see *Compressed Schedule*).

Discussion

Blue Dragon is a proposed evolution of the *NASA Human Exploration of Mars - Design Reference Architecture (DRA) 5.0* (Mars Architecture Steering Group, 2009). Refinements to the DRA described in this document are intended to improve safety, reduce cost, and to achieve a much better overall result. DRA is likely to be the most mature Mars mission architecture currently available, having been iteratively developed by hundreds of qualified people since 1995. Nonetheless, like anything, it has the potential to be further improved on the basis of new science, technology and ideas.

Three missions

The DRA specifies a program of three missions for these reasons:

- A more substantial overall return on the necessary investment in hardware development, human resources and intellectual capital can be achieved if the mission architecture is implemented a minimum of three times.
- To complete the DRA three times, using successive launch opportunities, will take a total of approximately one decade. During this period of time new technology will become available, the space industry will have evolved, and it will probably be appropriate timing to develop a more efficient or practical architecture.

These reasons apply equally well to Blue Dragon. Although all missions in Blue Dragon go to the same location, the same arguments apply. In addition, once three missions have been conducted, an important milestone of establishing “PHP-M” - a permanent human presence on Mars - will have been achieved, or be very close.

After each run-through of the architecture, opportunities to make improvements will present themselves and it’s likely that each mission will be slightly more efficient, faster, cheaper, safer, or otherwise an incremental improvement on the previous. However, these would likely be minor revisions, and major changes would be postponed until after three Blue Dragon missions have been completed. In this way, the bulk of the expenditure is constrained to the period leading up to the first mission, after which expenditure drops as the architecture and associated designs and assets are re-used.

Re-use of the architecture several times produces an even greater value benefit in Blue Dragon than it does in DRA, because the missions are all targeted at the same location; therefore, much of the hardware delivered in the initial pre-deployment can be re-used by each successive mission. If an ongoing financial commitment can be secured from each space agency in the partnership, this would enable the subsequent development of an updated architecture based on new technology and scientific information, and further exploration and development of Mars could continue.

Focus on settlement

The Blue Dragon architecture does not have precisely the same goals as the DRA, although they are very similar.

The DRA proposes a series of three more-or-less identical missions to Mars, each to different, scientifically interesting locations, and at these locations to perform exploration of, and scientific research about, Mars; for example, analysing rocks, dust, subsurface ice and the Martian atmosphere, searching for past or extant life, etc.

This is effectively the same approach as the Apollo program, in which crews were sent to different regions of the Moon. Although the scientific research performed at the Apollo sites has been useful for investigation into future settlement of the Moon, none of the Apollo sites were intended as sites for future settlements because settlement was not the primary objective. The mandate for Apollo was supremacy in space for political reasons. Although the world was amazed with the achievements of Apollo, only a relatively small number of hopefuls anticipated lunar settlement.

In contrast, a clear desire in the global community for settlement of Mars has emerged. This is manifest in recently proposed private missions such as Inspiration Mars and Mars One, and in the stated plans of companies like SpaceX (Space Exploration Technologies) and Virgin Galactic. The number of people interested in settlement of Mars clearly far outweighs those interested in settlement of the Moon or Earth orbit. Because of Mars' similarities with Earth, such as an approximately 24-hour day, seasons, weather, a transparent atmosphere, a coloured sky, and familiar-looking terrain highly reminiscent of Earthian deserts, settlement of Mars is far more amenable to the human imagination and therefore has far stronger appeal. In addition, its relative abundance of all the elements necessary for life and technological civilisation, including a variety of options for energy production (solar, wind, areothermal and nuclear), make it a more attractive and affordable settlement target than any reasonable alternatives.

As our technical capability develops, interest in human settlement of Mars grows steadily. The facts that over 200,000 people have applied for a one-way trip to Mars as part of the Mars One initiative, plus the consistent turnout to international Mars conferences, are strong indicators of this trend.

Inspiration Mars and Mars One represent the first two of what is likely to be a series of private enterprise missions to Mars. These missions have developed from a growing interest in settlement of Mars, and have stimulated yet more interest. More public, private or public-private combined missions are likely to follow, especially as new possibilities are enabled by the development of new COTS space hardware.

The International Mars Research Station

If settlement of Mars is our primary goal rather than purely “flags and footprints” exploration, scientific research or political oneupmanship, then conducting a series of distinct missions to disparate locations on Mars makes less sense. If we’re going to Mars to stay, a superior strategy is to build up infrastructure in one location and establish PHP-M as quickly as possible. This is referred to as a “base-first” strategy (Gage, 2010).

Once a Mars base is established we’ll be better positioned to conduct whatever further science and exploration is desired, as expeditions can be launched from the base rather than from Earth. This will be more efficient, cheaper, and much more convenient.

For this reason, Blue Dragon is designed as a series of missions to one particular location on Mars. The intention is to progressively build up infrastructure and technological capability at this location, establishing a base that can support multiple missions and be developed to a point where it can support a human presence more-or-less indefinitely. This is the *International Mars Research Station* (IMRS).

As the name suggests, the IMRS draws on the legacy of both the International Space Station (ISS) and the Mars Analog Research Station (MARS) program.

The International Space Station

The ISS is a triumph of space engineering and international collaboration, and is one of the greatest success stories in the history of space development. It is the most expensive artefact ever constructed, with an estimated total cost of US$150 billion. This high cost is one of the reasons why an international partnership has been helpful, as it spreads the cost across multiple governments.

It has also been profoundly important for encouraging and developing international cooperation in space. Cooperation in space is especially important because it involves cutting-edge technologies that may have military applications. Therefore, cooperation between nations participating in the ISS indicates a high level of trust between nations.

The ISS continues to benefit people all over the world, and not only the participating nations. It is a beacon of inspiration and achievement at the forefront of human expansion into space. Because the Blue Dragon program is designed to be international, for the reasons discussed, it makes sense to continue building on the collaboration framework already developed for the ISS.

Mars Analog Research Station

For some years the Mars Society has conducted a program to build and operate several MARS’s (Mars Analog Research Stations). To date, two operational MARS’s have been constructed and are in active use:

1. FMARS (Flashline Mars Arctic Research Station), located at Haughton Crater on Devon Island in the Canadian arctic.

2. MDRS (Mars Desert Research Station), located near Hanksville in Utah, USA.

A third station, MARS-OZ (Australian Mars Analog Research Station) is planned for the Lake Frome Plains east of Arkaroola in South Australia, possibly to be constructed within the next 1-2 years.

The MARS program has been enormously successful. To date, 14 simulated missions have been operated at FMARS and more than 100 at MDRS. Mission durations range from weeks to months. The season during which FMARS operates is much shorter than that for MDRS, being located in a far more extreme and less accessible environment.

An ambitious 365-day simulated mission to FMARS, called MA365 (Mars Arctic 365), has begun. Phase 1 of MA365, a refurbishment mission, has already been completed. Phase 2 and the full 365-day simulation will commence in July 2014.

Through the MARS program, research has been conducted by the Mars Society as well as various space agencies, universities and independent researchers into almost every aspect of the surface element of H2M missions. This includes EHA (Extra-Habitat Activity); geological and biological research; marssuit and airlock design; habitat layout and operation; recycling and resource management; psychology and human factors; art; construction and building materials; food preparation and production; command, control and communications; surface mobility and robotics; navigation; scheduling and rostering; and much more.

Crews who have been involved in simulations at FMARS and MDRS invariably speak highly of the experience. One of the more interesting factors is the reuse of a habitat that contains the imprints of previous crews - signatures and inspirational quotes, photographs, furniture, musical instruments, cooking equipment, and the countless iterative tweaks and refinements to improve the interior environment and make it progressively safer and more agreeable as a living space. This is also a desirable feature for the IMRS.

To highlight the advantage of the base-first strategy, as well as landing crews in capsules rather than in habitats, consider how much the MARS program would have cost if a new habitat was constructed and delivered to a different site for every single mission. Once the IMRS has been built, numerous missions and considerable research can be conducted to the same location at comparatively low cost.

Benefits of a single location

The DRA is designed as a precursor to settlement in the sense that it will provide data and knowledge to assist with settlement; however, the material assets delivered to Mars during the DRA missions are not included as part of an overall vision for establishing PHP-M. It proposes three identical or very similar missions to different locations on Mars.

In Blue Dragon, the assets delivered to Mars during the three missions form the seed of a settlement. Components are intended and designed to last a long time (at least a decade), and be re-used across multiple missions.

This strategy enables infrastructure to be accumulated at that location, which each successive mission will benefit from. Roads will be built. Transponders will be installed around the base to provide an accurate LPS (Local Positioning System) for use by vehicles and robots. Habitats, greenhouses, rovers, power plants and other base components may be re-used, improved, developed, expanded, and integrated with each other and the surrounding landscape until the base can be permanently inhabited. Structures may be built from regolith. A communications, observation and navigation satellite will be positioned above the base in an areosynchronous orbit.

It is therefore crucial that an especially good location be selected, as will be discussed.

A build-up of power-production resources in one location is of particular importance, and serves to demonstrate the real advantage of this approach. Energy is critical for heating, lighting, communications, computing, ECLSS, ISRU and more. Instead of sending, say, shipments of solar cells and batteries to three different locations on the planet, money can be saved by sending two shipments to the same location, to provide a reliable abundance of power at that location. The result is significantly improved energy security *and* reduced cost. With each mission, more hardware can be sent to the IMRS until a very reliable, robust and abundant energy subsystem is installed at the location. This is crucial for long-term survival on Mars, and the same rationale applies to subsystems for water, food, air, propellant, rovers, etc.

By sending hardware to three separate locations on Mars, perhaps we would learn more about Mars in the short term. However, each mission would be almost equally risky and costly, and subsequent missions would be less likely. By sending hardware to one location, however, multiple redundant backups of key components (habitats, greenhouses, rovers, power plants, etc.) can be emplaced, reducing risk with each successive mission. PHP-M can be established much quicker, and missions can be conducted from the settlement to anywhere on Mars. The long-term result will be that *more* of Mars is explored, and a new world will be opened up for human habitation. This goal is essential for the long-term success of our species.

Pre-deploy the Hab and land on Mars in a DragonRider

In contrast to the DRA, the Hab does not wait in Mars orbit, but, like the MAV, is pre-deployed to Mars surface, activated, and its systems checked out remotely. There are three main reasons for this:

1. It's far safer to land the crew in a proven EDL system such as a 6 tonne capsule, rather than a 30 tonne habitat (or a similar-sized descent/ascent vehicle).

2. Pre-deployment of the Hab enables testing of its systems, including ISRU and power, providing peace of mind before the crew leave Earth.

3. With a base-first strategy the architecture doesn't require a new Hab for each mission, which saves money.

One of the innovations in Mars Direct is that the ERV (Earth Return Vehicle) is landed on Mars one launch opportunity (~26 months) prior to arrival of the crew. Once at Mars, the ERV's power system and propellant plant are activated and the LOX/LCH4 bipropellant is manufactured quickly to minimise hydrogen boil-off. In this way, the crew and mission planners know that there's a fully fuelled vehicle at the base ready to bring them back, before the crew leave Earth. This idea became incorporated into the DRA, and is also part of Blue Dragon.

It this is a good idea for the MAV then it applies equally well to the Hab, which is equally mission critical. The crew spend minutes in the MAV, but 1.5 years in the Hab. If the Hab is known to be fully operational before the crew leave Earth it will greatly improve the confidence of mission directors and the crew.

In Mars Direct, the crew travel to Mars and land in the habitat. In the DRA, the habitat waits on orbit for arrival of the crew in the Mars Transfer Vehicle, then they transfer to the habitat and land in the habitat. Both architectures have the same two problems:

1. The crew would not have the peace of mind of knowing there's a fully functional habitat ready for them on the surface of Mars.

2. Landing a 20-40 tonne Hab may involve a new EDL system that has never been properly tested before.

It will be much safer to land the crew in a SpaceX DragonRider capsule. It's likely that Dragon and DragonRider capsules will have been used multiple times for carrying crew and/or cargo between Earth orbit and surface, and the Red Dragon landing system may similarly have been used several times to deliver cargo and experiments to Mars.

The Hab is likely to be heavier than anything else ever landed on Mars before, other than the Mars Ascent Vehicle. It will probably not be possible to thoroughly test EDL of the Hab prior to the actual deployment. Naturally we will run computer simulations, but these are never perfect. It's unlikely we would attempt to test the Hab's EDL system on Earth because the atmosphere and gravity are completely different. It's therefore very difficult to be 100% certain that an EDL system developed for landing such a heavy piece of hardware on Mars will work, just as it was very difficult to be sure that the EDL system for Curiosity would work.

Rather than risk LOC (Loss Of Crew), it's much safer to use a proven EDL system for landing the crew on Mars, for example, the Red Dragon, if this has indeed been utilised for one or more robotic science missions or cargo deliveries. Even if Ice Dragon or other Red Dragon-based missions are not executed, the Red Dragon EDL system can be utilised two or more times within the Blue Dragon architecture to pre-deploy cargo.

A crewed version of the Red Dragon will provide the exact same, proven method for landing on Mars. On arrival at Mars surface in a DragonRider, wearing suits, the crew will transfer to the Rover and drive to the Hab.

In the unlikely event that the Hab crashes on Mars we can improve the design, build another one and send that, and keep doing so until we succeed, without ever risking LOC. We will only send the crew when there's a MAV, Hab, Rover, power system, supplies, and everything else already in place on Mars to ensure a successful surface mission. This approach may seem to take pre-deployment to an extreme, but it makes sense when running several missions back-to-back at the same location. It allows the architecture to be much cheaper, safer and more repeatable. Everything will be ready for the crew on Mars before they even leave Earth.

Getting to the Hab

Because the crew land in a DragonRider rather than in a habitat, a method for safely transferring to the Hab is necessary.

The capsule will not be able to land too close to the Hab (or any other part of the base), because dust and debris thrown up by the engines during the landing may cause damage. They may have to land several hundred metres or perhaps a kilometre away. After spending six months in μg, it would be impractical to expect the crew to walk that far, in suits, immediately after landing on Mars, as they would have become weakened by the time spent in space.

Therefore, they'll be picked up by the Rover. After the dust has settled post-landing, the Rover is remotely driven from the Hab to the DragonRider's LZ. As a backup, both the crew and MCC (Mission Control Centre) will have the ability to remote-control the Rover.

The path the Rover will take between Hab and the crew's landing point will have been driven along several times, and will be clear of hazards. The LZ will have been decided during the previous ~20 months by exploring the surrounding terrain with the Rover via remote-control, and finding a smooth, flat, clear and safe path between the Hab and the LZ. As the Rover has a dirt-moving attachment (a front-end loader bucket), it may be used to make the path yet smoother, clearer and safer during the 20 month window, thus making absolutely certain that the crew will reach the Hab safely. This strategy relies on the ability to land the DragonRider accurately.

Note: The Blue Dragon architecture does not incorporate suitports, but rather, MCP (Mechanical Counter-Pressure) marssuits. Although suits with suitports offer advantages with regard to dust migration and contamination prevention, they are large, bulky, and have the mobility issues generally associated with gas pressurised space suits. A DragonRider capsule may not be able to accommodate a crew of six wearing gas-pressurised suits with suitports, and in addition, a Rover with six suitports (which would be necessary with this architecture) may be impractical. Instead, the crew are wearing MCP marssuits during EDL, and will enter and exit the Rover and the Hab through their airlocks.

Only one vehicle for outbound and return legs

In Mars Direct the crew fly out in the Hab, and return in the Earth Return Vehicle. However, in the DRA and in Blue Dragon, the crew fly out and back in the same vehicle.

It makes much more sense to use the same vehicle. During the 6-month outbound trip, the crew will make *Adeona* their home. They'll humanise the space. They will put up posters and sticky notes, hooks and loops, photos and knick-knacks, with each person making little tweaks to the environment to suit their individual behaviours. They'll develop routines that work with the spacecraft, and learn each other's habits and develop protocols for co-habitation in the relatively confined volume. They will find a whole range of optimisations, and learn the various quirks of the vehicle. The vehicle's server will have all their favourite music, movies, books, games and websites already downloaded. They will fix and improve things - an improvised washing line here, a pencil-holder there.

Spacecraft are designed by engineers, and decorations and personal touches are usually a distant consideration to the primary function of the hardware, namely to keep people alive and carry them safely to their destination. It would be foolish to imagine that engineers will think of everything six individuals need or want in order to create a comfortable living and working space for one year. By using the same ship for the inbound trip, there will be a sense of familiarity, almost home-coming, when they re-enter *Adeona* for the inbound journey. Everything will already be prepared, by each crew member, for themselves. This will surely have a positive effect on morale, and be important for safety. This will mitigate post-Mars depression (as likely as postnatal or post-festival depression), and will eliminate the time cost of setting up a return vehicle in much the same way as the outbound vehicle.

In the event that any members of the crew are coming back from Mars sick or injured, having a familiar environment will be important.

The reason for using the same vehicle for the outbound and return trips goes beyond comfort, however. The MTV will be designed specifically for a micro-gravity environment. If the crew fly out to Mars in a Hab, however, it would need to be designed for both gravity and μg environments (assuming no AG), which would naturally require compromises. Furthermore, using a single vehicle for in-space travel simply saves money. The intention is that *Adeona* can be re-used over and over, refurbished or upgraded each time it arrives back at Earth.

There is one important difference between DRA and Blue Dragon, however. In DRA, the crew capsule performs direct entry on arrival at Earth, and the MTV is discarded. In Blue Dragon, *Adeona* performs EOI at the end of the mission, and is parked on orbit. There are two main reasons for this change:

1. It means the crew will be descending to Earth from orbit, which involves much lower g-forces than direct entry, and is therefore safer, more comfortable and less risky.

2. *Adeona* can be refurbished on orbit, be refitted with new propulsion stages, and reused by subsequent crews, thus saving money and taking advantage of the homely tweaks made by previous crews - just like in FMARS and MDRS.

The cost of this change is that additional fuel is required for EOI - fuel that must be transported to Mars and back. This will necessitate larger propulsion stages, which will incur a non-trivial cost (perhaps even a greater cost than a replacement BA 330 habitat module). Note that this additional fuel requirement is mitigated by the fact that, in Blue Dragon, *Adeona* does not have a capsule attached during the return trip, hence the fuel required for TEI is correspondingly lower.

Cost Management

Cost is a major factor in any space venture, and in light of shrinking space agency budgets and an increasing need to allocate public money to more pressing issues, it has become an even more important consideration. NASA's nominal benchmark for implementing the DRA is up to $100 billion for the full program lifecycle, including all development costs and three missions. However, with the following considerations it should be possible to achieve a total cost well below this:

1. The mission architecture is largely assembled from commercially-available (COTS) hardware components, which are cheaper to purchase than it is to develop custom-designed components.

2. All three missions are to the same location, therefore major components such as the MTV, Hab, Rover, greenhouse and ATV's can be reused by multiple crews. The architecture is specifically organised for component reuse across multiple missions (at least 3).

3. As an international mission, some of the engineering, development and other work will be done by countries where costs of labour, rent and other overheads are considerably lower than in the US, such as China and India.

Our goal should not be to do the cheapest possible H2M mission, as overly aggressive cost-cutting measures compromise safety and results. Our goal should be to do the smartest one, with the appropriate balance of cost, safety and ROI (Return On Investment). However, whatever else the architecture may be, it must be affordable. As was observed with the *90-Day Report*, with its bottom line of $450 billion, an excessively high price tag simply makes the program nonviable.

By assembling a mission from primarily commercially available products and services, combined with successful management, logistics and financing, the goal of sending humans to Mars is within reach. Although further calculations still need to be done, with this architecture and an internationally collaborative approach it should be possible to implement a full program, including robotic precursor missions and three crewed surface missions, for well under $100 billion, and perhaps as low as $50 billion.

For the purpose of this exercise a ballpark figure of $72 billion is used, which, in theory, should be a maximum. This amounts to an average cost per crew slot of $4 billion, or an average of $200 million per crew slot, per year, for two decades (~2020-40). The hope is that this amount will be affordable for the top 10 space agencies.

Cost benefits of a single location

In the DRA, because the crew are landed in the habitat, and because each mission is to a different location, this obviously necessitates three habitats, three Mars Ascent Vehicles, and three sets of surface vehicles and ISRU equipment.

However, by constraining ourselves to a single location, we can spend less money and use the available resources more creatively in order to achieve a permanent human presence on Mars (PHP-M) more quickly. Since the crew arrive by DragonRider rather than landing in the Hab, only one Hab is needed, as subsequent missions can reuse the same one, just like with FMARS or MDRS. The same applies for the ground vehicles. This obviously represents a huge cost saving; not only the cost of the actual hardware elements, but the more substantial cost of sending them.

Once the Hab and Rover are at the IMRS, we only need to deliver another MAV, crew and supplies in order to run the mission again. However, if financial resources are available to send additional hardware on the second or third Blue Dragon mission, rather than waste this on identical hardware it will be possible to send an additional Hab or Rover, cargo modules, a greenhouse, inflatable modules, additional power production or ISRU hardware, equipment for excavation or experiments, or other useful items of hardware that develop the IMRS and bring us yet closer to PHP-M. This would be a better use of the money.

Commercial hardware

The most important goals of Blue Dragon are to reduce costs and increase safety and the likelihood of success compared with existing proposals. These goals are all arguably made more achievable through utilisation of primarily COTS hardware, such as Falcon rockets, Dragon capsules and Raptor engines from SpaceX, and inflatable space station modules from Bigelow Aerospace.

Rather than having a collection of one-off custom-built components that only a few specialist engineers understand, using COTS components gives several advantages:

- COTS components often have a greater operational maturity and a higher TRL (Technology Readiness Level) than custom-built hardware. They may have been used in multiple real-life applications, perhaps many times, enabling refinement and better understanding of the design. This drastically improves confidence in the technology and reduces the likelihood of design flaws. Although this may not currently apply to the Falcon Heavy or the BA 330, as these are new and developing products, it may well apply in the proposed timeline.

- COTS hardware is usually understood by a much larger number of people, including engineers, customers and others who've used or studied it, who may be numerous if the product is popular or has been in use for some time. This makes problem identification and resolution quicker, easier and more likely to be accurate.

- COTS hardware is usually cheaper than purpose-built hardware because with each successive production run optimisations are made in the product design, supply chain and manufacturing processes.

- Components produced in quantity, rather than one-off, are usually cheaper - sometimes orders of magnitude cheaper - due to the cost savings obtained by mass production.

It's always more expensive to build a prototype than a reproduction, because creating a prototype always involves an element of involves real-time interactive design. The development of a prototype involves numerous iterations, modifications and redesigns, and several usually need to be made before the final version is considered ready for reproduction. When using COTS hardware, this work has already been completed and paid for, saving both time and money.

The total lifecycle cost of any hardware component in a space mission may be calculated using the following formula:

$$C_{total} = C_{dev} + C_{man} + C_{trans} + C_{op} + C_{dec}$$

where

C_{total} = the total lifecycle cost of the item

C_{dev} = the cost of development

C_{man} = the cost of manufacture

C_{trans} = the cost of transportation and installation

C_{op} = the cost of operation

C_{dec} = the cost of decommissioning

The main benefit of using COTS hardware is that C_{dev}, which, in a traditional space mission, is a major expense (on the order of millions to billions of dollars depending on the item) is considerably lower *per item* because it's recovered across multiple sales, and shrinks towards zero over time. In addition, C_{man} is often lower due to the cost benefits of mass production. Even C_{trans}, which is the total transportation cost from the manufacturer to the final destination (e.g. Mars), may be lower if a transport system designed especially for the item is available, such as we have with the SpaceX Falcon rocket family and the Dragon capsule. C_{op} and C_{dec} may also have been optimised.

We are living in a different era to any in which a H2M mission has been developed before. The private space sector is experiencing a revolution, characterised by an exponential growth in the number of startups in the space sector, reminiscent of the IT sector during the past three decades. Numerous so-called "NewSpace" companies are developing commercial space hardware, and the available options are rapidly expanding. Private companies now exist for a wide range of services related to space, including launch services; space station and spacecraft components; satellites; space suits; ECLSS hardware; space electronics; robotics; and other miscellaneous space products and services. The cost of purchasing these items from commercial suppliers is typically much lower than developing them from scratch for one or even three missions.

By taking advantage of this proliferation of commercial products and services, the cost of transporting people and equipment to Mars can be significantly lower than previous estimates. As the design for the Blue Dragon mission evolves, the intention is to track new developments in COTS hardware and take advantage of these where possible, in order to further evolve and improve the architecture.

COTS hardware suppliers sometimes collaborate in ways that support the assembly of mission architectures. For example, SpaceX and Bigelow Aerospace have begun discussions about developing a common docking interface that will enable Dragon capsules to dock with Bigelow's inflatable space station modules for delivery of cargo and crew. This will be a valuable design feature that will save money in development costs.

Although a reasonably young company, SpaceX is favoured in the architecture as it currently stands, primarily because their hardware is comparatively very cheap and also very good. Focusing on a single technology for surface-to-space and space-to-surface crew transport, using fundamentally the same tech to deliver cargo to the surface of Mars, will significantly reduce mission complexity and cost and generally improves robustness.

Having said that, as an international mission, it's likely that the major players such as Russia and China will want their own hardware (e.g. rockets) to be represented. Solving this to all partners' satisfaction will require successfully balancing these desires with cost and safety. It will be important for all partners to understand that a decision to use hardware predominantly from one supplier would not be intended deliberately to favour that supplier's country, but to make the program affordable and viable.

Development

Components unavailable from commercial suppliers must still be developed, and this may require a substantial investment. However, current trends indicate this cost will decrease as more commercial space hardware suppliers and components become available, and as the space industry becomes increasingly confident in its own evolution and the expansion of the market. Considering the vast range of technical services now available in the space community, it should be possible to develop any remaining requirements within more modest time frames and budgets than have previously been considered. The development of any major component should begin with a comprehensive survey of products and services available from commercial suppliers.

Examples of technological components that still need to be developed include:

- A reliable EDL system for delivering loads to of 10-40 tonne payloads to Mars surface.
- A reliable method of transporting a crew from Mars surface to Mars orbit (i.e., a Mars Ascent Vehicle).
- A reliable and lightweight (< 50 kg) Mars Activity Suit.

- Proven technology for manufacturing propellant, breathable air and potable water from the local Martian environment.
- Effective techniques and technologies for dealing with Martian dust and radiation.

The expense of developing these components is not necessarily a sunk cost. Because there's a clear desire in the population for settlement of Mars, initiatives such as Mars One and Blue Dragon will be followed up by other human exploration and settlement programs, both public and private. As these technologies will be of value to *any* human mission, they could be licensed, sold, or developed into new COTS products, providing opportunities to recover the initial investment and potentially make a profit.

International partnership

The Blue Dragon program is made yet more viable by distributing the cost across a consortium of multiple space agencies, in a similar fashion the ISS.

As a very rough estimate, imagine an approximate total program cost of $72 billion. This is based on the nominal NASA budget of $100 billion for a total cost for implementing the DRA, and the total cost of the ISS of $150 billion, revised downwards by the cost-reduction strategies described. It is essentially a guess, but will do for this exercise. A full analysis needs to be done to determine a more accurate total cost estimate.

This $72 billion is for three missions ($24B each, on average) to send a crew of six to Mars and back, with a total program duration of approximately two decades: one to prepare and develop, one to execute. The overall program therefore offers a total of eighteen crew slots with an approximate average cost of $4 billion each, thus averaging $200M per year per crew slot.

In order to preserve the truly international nature of each crew, and to permit a larger international partnership with each agency represented by at least one astronaut, we set a restriction that any one space agency can "purchase" a maximum of one crew slot per mission.

The total investment by the US and Russia ("Level A" partners), with one astronaut on each mission, would therefore be approximately $12 billion each. The total investment by "Level B" partners (e.g. Europe, China, Japan, India) would be about $8 billion each, and the total investment by smaller "Level C" partners would be about $4 billion each.

Because the economies of the participating nations are quite different, and because $200M per year is comparable to, or larger than, many space agencies' entire budgets, it's possible that investment could be made partially or wholly "in kind" rather than "in cash". For example, a space agency may contribute an equivalent value in engineering, launch services, hardware or facilities.

Ideas for implementing the program as an international partnership is discussed further in the section titled "International Aspects".

International Aspects

It is the intention that the Blue Dragon program and the IMRS are developed as a true international collaboration, for the following reasons:

- To reduce the financial burden on any one nation.
- To open up Mars for all humanity, rather than only one nation (or only “western” or “eastern” ideologies).
- To improve international relations by further developing trust, communication and cooperation between the world’s major powers, thereby bringing about world peace.
- To gain greater leverage from the research, expertise, designs and philosophies of the most talented scientists, engineers and managers from all over Earth, thus advancing space technology further and more quickly, reducing costs, benefiting Earth and all humanity, and increasing the overall value of the project’s outcomes.

Expanding the international partnership of the ISS

The ISS partnership already formed provides an excellent starting point for the establishment of a similar, expanded partnership to develop the IMRS.

China

One of the most important goals for the IMRS is to include China. China have indicated they want to be part of the ISS partnership, and this has been supported by Europe; however, the US have expressed concerns, presumably over the transfer of technology with potentially military applications. To include China in the IMRS partnership it is therefore important to overcome this mistrust, which is certainly possible, as this has already been achieved between US and Russia prior to Russia’s inclusion in the ISS partnership. The cooperation between US and Russia has proved highly beneficial for both parties, particularly since the Soyuz has become essential for crew transport since the grounding of the Shuttle. The nations in the existing ISS group stands to benefit greatly from friendly cooperation with China, who are so talented and determined that they’re building their own space station (Tiangong). US-China relations are improving, at least with respect to space: NASA has recently lifted their ban on the participation of Chinese scientists at scientific conferences.

Iran

It would also be highly desirable to include the Iranian Space Agency, which is currently the best-funded space agency in the Middle East. Although at this time it may seem impossible to imagine a collaboration involving the US and Iran, the same could have been said about Russia 50 years ago or China 10 years ago.

The history of space development is one of making peace and cooperating on large-scale, interesting projects and cutting-edge research. In 10-20 years, it's certainly possible (and indeed probable, if we set the intention now) for Iran to be included in the IMRS. Then we will truly be on the road to world peace and the creation of a positive and space-faring future for humanity. It's a worthy and important goal and in line with the fundamental philosophy that Mars is for all humanity.

Others

Space agencies of individual European nations such as France, Germany, Italy and the UK would participate in the program via ESA, as they do with the ISS.

India and South Korea have also indicated that they would like to join the ISS program. Whether or not that eventuates, they will almost certainly also wish to be involved in the development of the IMRS, and should be. India have recently launched their first Mars mission, the Mars Orbiter Mission.

Brazil were initially involved in the ISS program, but were forced to leave due to cost issues. Ideally the financial elements of IMRS can be structured in such a way that they will be able to participate fully.

Ten partners

If this ambitious collaboration can be achieved - and it can, with determination, diplomacy, forgiveness and time - we would have the following 10 international partners (listed in order of current funding level):

<table>
<tr><td rowspan="2">Level A partners
3 crew slots each</td><td>USA</td><td>NASA</td></tr>
<tr><td>Russia</td><td>RKA</td></tr>
<tr><td rowspan="4">Level B partners
2 crew slots each</td><td>Europe</td><td>ESA</td></tr>
<tr><td>Japan</td><td>JAXA</td></tr>
<tr><td>India</td><td>ISRO</td></tr>
<tr><td>China</td><td>CNSA</td></tr>
<tr><td rowspan="4">Level C partners
1 crew slot each</td><td>Iran</td><td>ISA</td></tr>
<tr><td>Canada</td><td>CSA</td></tr>
<tr><td>Brazil</td><td>AEB</td></tr>
<tr><td>South Korea</td><td>KARI</td></tr>
</table>

Crew slots

All international partners will be represented by at least one astronaut. This will give each partner a greater stake in the program, a greater return on investment in terms of national pride and recognition, and first-hand experience of a deep space, interplanetary mission.

Here is a potential crew slot schedule for the three missions:

	Crew slot 1	**Crew slot 2**	**Crew slot 3**	**Crew slot 4**	**Crew slot 5**	**Crew slot 6**
Mission 1	US	Russia	Europe	Japan	China	Canada
Mission 2	US	Russia	Europe	South Korea	China	India
Mission 3	US	Russia	Brazil	Japan	Iran	India

Scheduling and Timing

Mission Profile

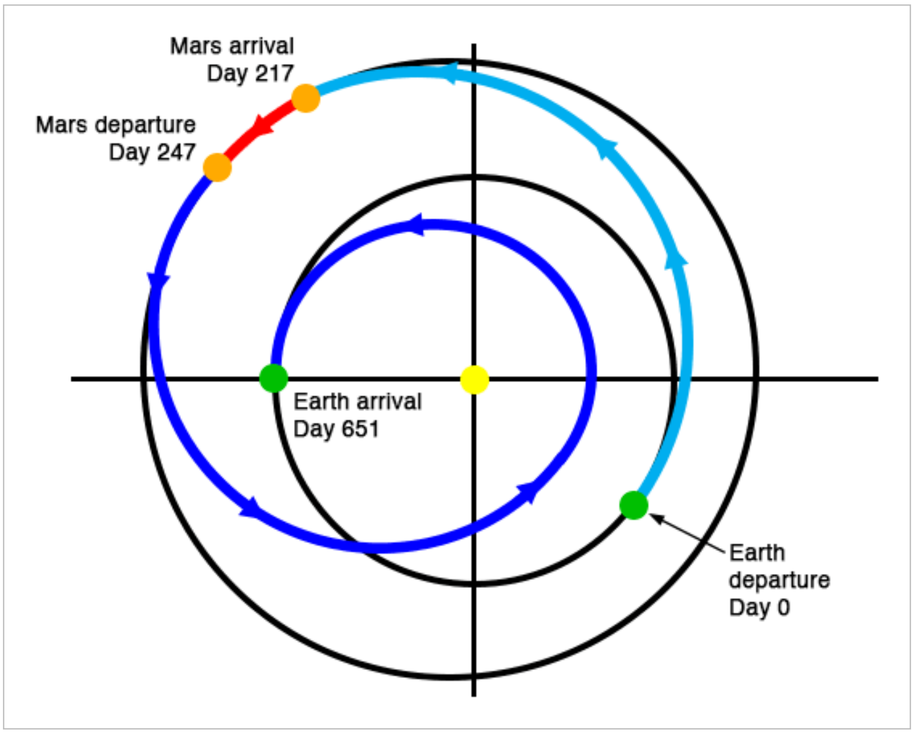
There are fundamentally two options for an H2M mission:

Opposition-class or “short stay” mission.

Conjunction-class or “long stay” mission.

Blue Dragon is a long stay mission, using the same rationale as Mars Direct, DRA and many other architectures. While the long stay option means a longer and more expensive mission, it greatly increases the amount of time spent on Mars and decreases the period spent in space.

Opposition-class or “short stay” mission



Approximate schedule for an opposition-class Mars mission.

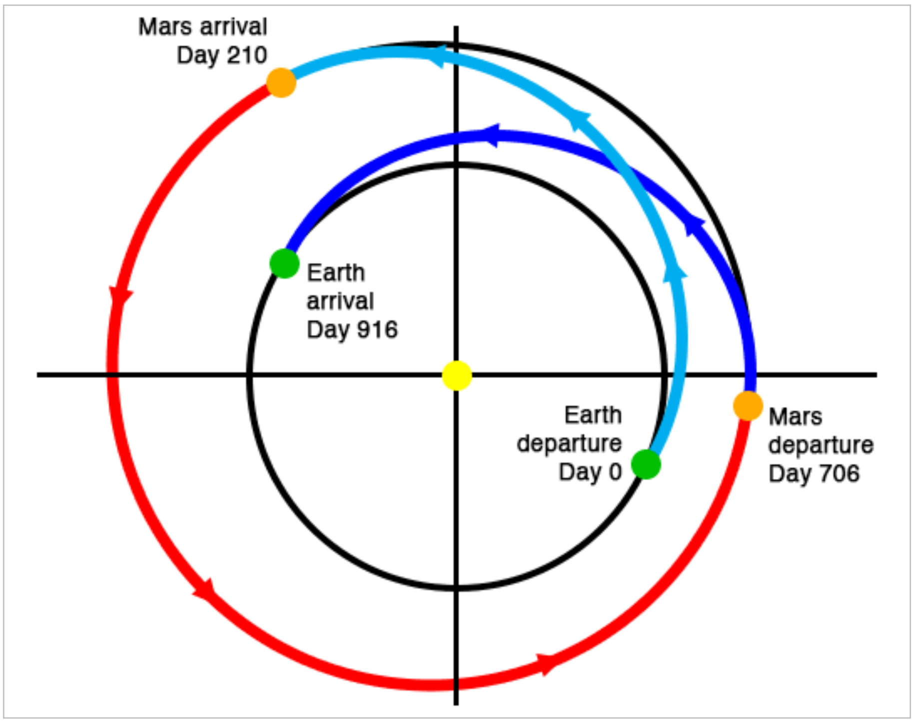
A short-stay mission involves a trip out to Mars (around 5-7 months), then spend, say, 14-30 days on the surface doing science and exploration, then launch and come home. However, after a few weeks Mars and Earth will have moved to new positions in their orbits, and will no longer be optimally aligned. Since we are constrained by fuel requirements, the return trip must necessarily be longer; in fact, more than one year.

Although numbers will vary depending on the timing of the launch, propulsion technology and available fuel, these approximate figures indicate of how time is apportioned during a short stay mission:

Outbound	217 d
Stay	30 d
Return	403 d
Total	**650 d**
% time on Mars	5%
% time in space	95%

A short stay mission may, at first glance, seem very safe and sensible. However, the crew will spend almost all that time in space, and only a very small fraction of the overall mission duration on Mars, which is the whole point of the mission. Furthermore, the space environment is more damaging to the crew's health in terms of exposure to microgravity and radiation than the Martian environment, therefore it's actually safer to be on Mars than in space.

Conjunction-class or "long stay" mission



Approximate schedule for a conjunction-class Mars mission.

A long stay mission begins by flying out to Mars when it's at closest approach, with a trip duration of approximately 5-7 months. The crew then remain on the surface while the two planets orbit the Sun along their respective paths until they're again coming up to closest approach approximately 1.5 years later. The crew then launch and return to Earth, again on a minimum duration trajectory of about 5-7 months.

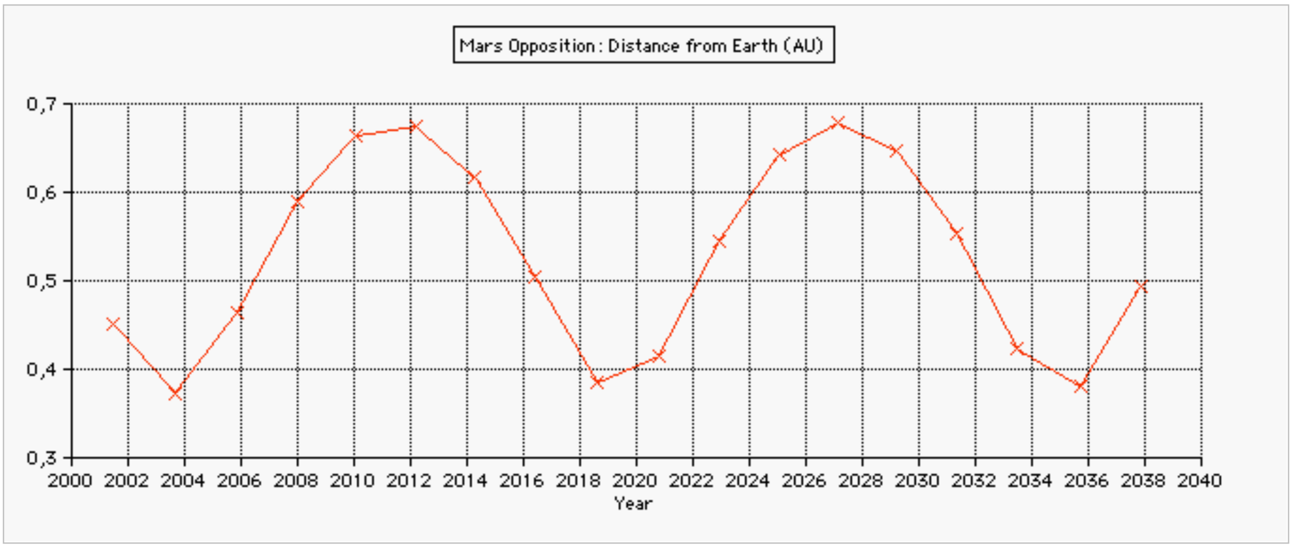
Outbound	210 d
Stay	496 d
Return	210 d
Total	**916 d**
% time on Mars	54%
% time in space	46%

Although the long stay option increases mission duration by 266 days or about 40%, the amount of time spent on Mars increases by a factor of almost 14 (over a year longer), and accounts for more than half the mission duration. The amount of time spent in space is reduced by one third. Most mission planners agree that this option delivers improved safety and a much greater ROI, although the challenge if keeping the crew alive on the surface of Mars is greater.

It may seem that a 2.5 year mission is a big risk. But then, so is an 1.8 year mission. If a short stay mission is possible then so is a long stay one, but the pay-off is much greater.

Schedule

The outbound and return journeys occur when Mars is at its closest approach to Earth, which occurs about every 26 months. We can minimise the trip time even further by traveling in the right years. Due to Mars' elliptical orbit, every 15-16 years the distance between Mars and Earth reaches a minimum.



Distance between Earth and Mars at solar opposition.

The next time Mars and Earth are at their closest approach will be in 2018, which is therefore a popular choice for a trip to Mars, especially since this also coincides with the solar minimum (a point in the 11-year solar cycle when solar activity is at a minimum, and therefore risk of a CME is correspondingly lower). It is for these reasons that the Inspiration Mars flyby mission is planned for 2018.

To minimise the amount of time spent in space and/or the amount of fuel required to get from Earth to Mars or vice-versa, we could fly the crew out in 2018 and bring them back in 2020. It doesn't matter how long it takes the uncrewed components such as the Hab to travel out there, so we could start launching those items in 2014 or 2016.

This is quite soon, therefore a preferred launch date for the Alpha Crew of Blue Dragon is in 2033, which is 20 years away at the time of writing, allowing plenty of time to build momentum in the space community for the mission, develop the international partnership, develop the hardware, and run precursor missions.

Of course, we aren't constrained to use these launch windows - they are simply the most advantageous. Bravo and Charlie Crews will each involve a longer space element (assuming the same propulsion systems). Naturally we want the Alpha mission to be optimised for safety, being the first, hence why we choose the shortest trip for that mission.

Compressed and Extended Schedules

There are two potential schedules for running the three missions, named here the "compressed" and "extended" schedules.

In the compressed schedule, each successive crew is sent out approximately four months *before* the previous crew returns, since there are 26 months between launch opportunities, but a total mission takes about 30 months. Therefore, a second MTV will be required, which (for the sake of the exercise) is simply called *Adeona II*. The disadvantage of this architecture is therefore the additional cost of constructing a second MTV. In theory only two are needed, as the MTV used for the Alpha mission can be refurbished for the Charlie mission.

In the extended schedule, crews are sent out on every other opportunity, so Alpha Crew would arrive back at Earth about 22 months before Bravo Crew leave. This means the same MTV (*Adeona*) can be used for each mission, lowering hardware costs. Another advantage would be that Alpha Crew will be able to spend some time with Bravo Crew before they leave, allowing them time to share stories, tips, ideas, warnings, etc. There will be more time to make changes to the architecture and hardware, or to send additional cargo and equipment to Mars, based on lessons learned from the previous mission.

The extended schedule requires an additional 52 months (about 4.3 years) to complete all three missions. This increases the overall cost of the mission, as hundreds of peoples' salaries plus rent and other overheads must be paid during that time. However, the long schedule does allow the total cost to be spread out over a longer period, which may make the program more affordable for some space agencies.

Although a full cost analysis still needs to be done the compressed schedule is probably preferred, for the following reasons:

- Lower total program cost.
- Maintains momentum throughout the program.
- Less risk of program cancellation due to changes in government(s).
- Reduces risk of hardware malfunction (the longer a piece of hardware is in operation, the more likely it is to fail).
- Advantage of having two Mars Transfer Vehicles, as one can function as a backup.

Bravo Crew can communicate with Alpha Crew during their time on Mars and in space, so there will still be plenty of opportunity for sharing stories and information.

Compressed schedule - overlapping missions.

	Alpha	Bravo	Charlie
2031	Launch MAV, cargo capsules, Hab, Rover, Commsats, power and ISRU systems. Construct Adeona on orbit.		
2033	Send crew.	Send MAV, cargo capsules, greenhouse. Construct Adeona II on orbit.	
2035	Bring crew back.	Send crew.	Send MAV, cargo capsules. Refurbish Adeona.
2037		Bring crew back.	Send crew.
2039			Bring crew back.

Extended schedule - no overlapping missions.

	Alpha	Bravo	Charlie
2031	Launch MAV, cargo capsules, Hab, Rover, Commsats, power and ISRU systems. Construct Adeona on orbit.		
2033	Send Alpha Crew.		

	Alpha	Bravo	Charlie
2035	Bring Alpha Crew back.	Send MAV, cargo capsules, greenhouse. Refurbish Adeona.	
2037		Send Bravo Crew.	
2039		Bring Bravo Crew back.	Send MAV, cargo capsules. Refurbish Adeona.
2041			Send Charlie Crew.
2043			Bring Charlie Crew back.

Location

Because we're sending three missions to a single location in order to establish the first permanent human settlement on Mars, it's especially important that the location choice be a good one. The intention in this section is not to identify one specific optimal location for the IMRS, which would require a more involved analysis, but to highlight the salient characteristics such a location would have, and to outline a general approach to analysis.

There are several drivers in selecting an optimal location, which must be balanced:

- **Availability of key resources.** This includes sunlight, heat and water and (secondarily) areothermal energy. Atmospheric resources such as carbon, oxygen, nitrogen and atmospheric water are not location-dependent. Other location-dependent resources that will become more important in the future include wind energy, certain minerals and metals, caves and lava tubes, tourist attractions, and infrastructure.

- **Terrain characteristics.** For safety in landing, and ease and safety of surface mobility both in marssuits and surface vehicles, we require a location that is reasonably flat, level, and not overly dusty. Low dust is indicated by high thermal inertia, which will also be advantageous for reducing energy storage requirements. In addition, we desire loose regolith to pile on the Hab for radiation and thermal protection.

- **Scientific interest.** Naturally the best location will be close to sites that can help to answer scientific questions about Mars. Most importantly, has Mars ever hosted, or does it currently host, life as we know it? Other questions relate to the presence of liquid water, Mars' geologic history, etc.

Previous Mars missions and the DRA have primarily favoured scientifically interesting locations, in line with their intent to continue exploiting the scientific goldmine that is Mars. However, the goal for Blue Dragon and the IMRS is to establish a permanent human presence on Mars as a base from where further and extensive scientific exploration of Mars can occur more cheaply and conveniently. With this in mind (and the general principle that *all* of Mars is scientifically interesting, especially to humans on the ground), selecting a site of maximum scientific value is considered less important than selecting a site with maximum potential for supporting habitation.

Solar energy

Our preference for a power system based on solar energy (discussed later) is our strongest driver for location selection. Generally speaking, as on Earth, the availability of sunlight reduces with increased latitude. However, due to the eccentricity of Mars' orbit northern latitudes receive more solar energy than southern, which is fortuitous as there are other reasons for favouring the northern hemisphere. It has been shown that the latitude of 31° north has the highest minimum solar incidence for a single sol over a Martian year (Cooper *et al.*, 2010). Because the minimum solar energy a site receives in a single sol determines the maximum required mass of the energy storage subsystem, this is a good reason for locating the base near this latitude. The ideal location might be within approximately 5-10° of this optimal latitude, as long as it also satisfies other conditions.

In addition, we must not select a location deep in a crater or chasm, as this would increase the amount of time the PV cells are in shadow each day. Rather, we must choose a location out in the open that receives as much sunlight as possible each day. This is harmonious with our need to land somewhere flat.

Heat

One of the primary energy requirements of a habitat on Mars is thermal control. The surface temperature on Mars varies between 130K and 308K, with an average of about 218K; temperatures that are, on average, comparable with Antarctica.

The desired temperature inside the Hab, however, is a comfortable 295K (22°C) ± ~5K. Therefore the ECLSS must maintain the interior temperature of the Hab around 80K warmer than the external environment, on average. This is a significant temperature gradient, and one that must be maintained all day, every day, throughout the entire 1.5-year surface stay.

The amount of energy necessary for heating is mitigated to some extent due to warming of the Hab's atmosphere by human metabolism and operation of electrical and electronic equipment. During warmer days the Hab will need cooling. Further analysis is required to determine the actual energy requirements for thermal control, however, the warmer the location, the lower they will be.

The amount of thermal energy available from the natural environment is partly a function of solar incidence. As we're already selecting for high solar incidence, this automatically selects for warmth as well.

Thermal inertia of the terrain is also important, as a higher thermal inertia will keep the base warmer for longer after nightfall, reducing energy storage needs. Selecting for higher thermal inertia means choosing a less dusty site. This is somewhat harmonious with our terrain requirements, as a less dusty site is preferable for surface mobility.

Seasonal advantages

For a long surface stay mission architecture (~540 days), the crew is be on Mars for approximately three-quarters of a Martian year (687 days), or three out of four seasons.

Mars seasons are aligned with the eccentricity of its orbit. At perihelion it's winter in the north and summer in the south. At aphelion it's summer in the north and winter in the south. The southern hemisphere therefore experiences a more extreme climate, with hotter summers and colder winters than the north.

When Alpha Crew departs for Mars in 2031, it will be close to perihelion, which is the reason we choose that particular year to travel. The distance to Mars will be at its minimum in the approximately 16-year cycle of perihelic oppositions. Therefore, it will be winter in the northern hemisphere at time of launch. The crew will arrive approximately at the end of the northern winter and spend the next three seasons on Mars, and leave at approximately the beginning of the next northern winter. Alpha Crew will therefore miss the northern winter, which is optimal for light and heat. This is fortunate, as there are several other reasons to locate the base in the north.

Bravo and Charlie Crews, however, will be at the IMRS during northern winter. The intention is to increase power production at the base by at least 100kW with each mission, thus compensating for degradation of PV cells, developing increasing energy security at the base, and ensuring ample power for surviving suboptimal conditions such as winter and dust storms. Because Alpha Crew will have the least infrastructure and experience, the intention is to make their mission as safe as possible.

Terrain Characteristics

Surface roughness

Choosing an especially flat area (low surface roughness) is important for:

- Safe landings.
- Mobility in marssuits and surface vehicles.

The Blue Dragon architecture requires safely landing the MAV, Hab, and at least two cargo capsules in approximately the same location. However, note that they will not be directly adjacent to each other, because landing any item will kick up a lost of dust and debris; therefore, each item must be landed some distance, perhaps about 100-1000 metres, from the others.

The Rover must be able to negotiate the terrain between these elements, and the surrounding area. In addition, the AWESOM (Autonomous Water Extraction from the Surface Of Mars) robot must be able to traverse the ground around the MAV.

As this is our first landing on Mars with a human crew, we must minimise the probability of landing on a large boulder or a slope, so the flatter and smoother the better. Fortunately this corresponds with our desire to find a location near a potential source of areothermal energy, because it’s the locations that have most recently been covered in lava (and therefore have few craters) that are most likely to still be areologically active.

The downside of choosing an especially flat area is that there may not be much of areological interest in the vicinity, which means more exploration will have to be performed using the Rover rather than simply in marssuits. However, safety is a priority. The goal will be to locate the base within, at most, a few hours drive away from areologically interesting regions.

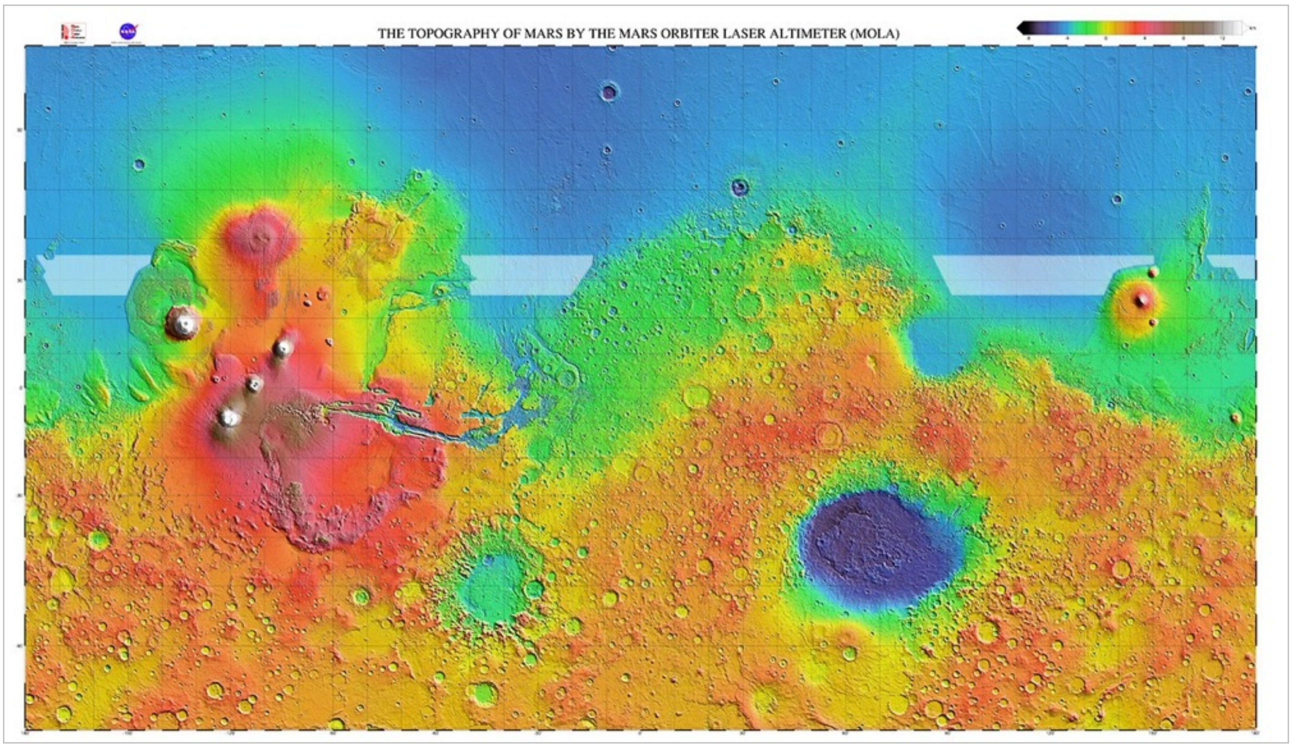
The flattest region of Mars is *Vastitas Borealis*, the vast low-lying northern region that may have once been the floor of a huge ocean (known as “Oceanus Borealis”).

The following map shows surface roughness, with smooth areas appearing dark and rough areas appearing light. Regions of low surface roughness between 26-36N are highlighted. Note that the region west of Olympus Mons is one of the smoothest on Mars:

Low elevation

The Martian atmosphere is warmest at lower elevations, as the atmosphere is thicker and functions as a thermal blanket.

Vastitas Borealis is at a much lower altitude than the southern highlands, which again leads us to favour this region. The following map shows the topography of Mars, based on data returned by the MOLA (Mars Orbiting Laser Altimeter). Low elevation regions between 26°N and 36°N are highlighted:



Because Martian air is warmer at lower elevations, some researchers have proposed Hellas Basin as a good location for a base. However, this choice would not exploit other advantages of the northern hemisphere, it is not very flat, and it's a dust trap. Hellas Basin is one of the regions from where dust storms frequently erupt.

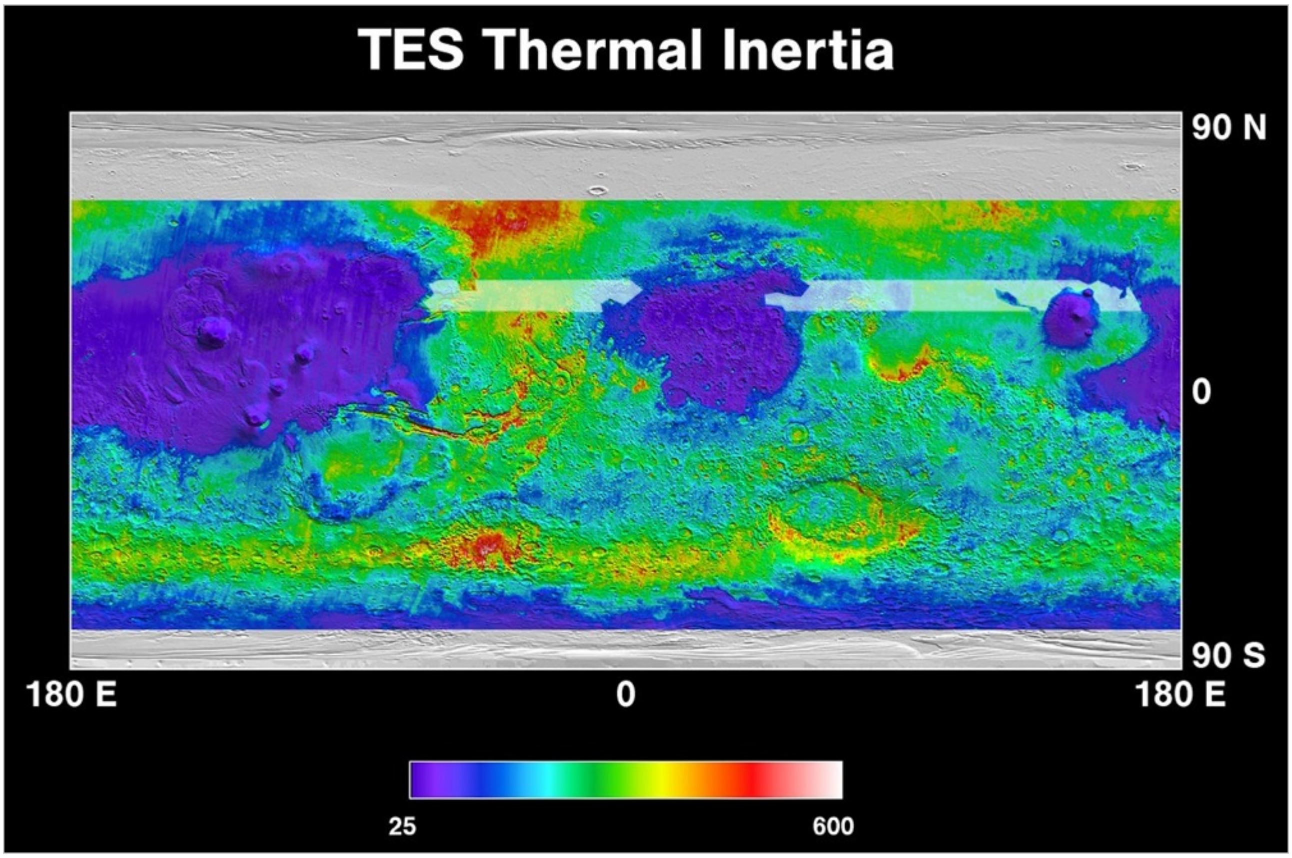
Thermal Inertia

Thermal inertia refers to the ability of the terrain to retain heat. Small particles, such as dust, have low thermal inertia, i.e. they lose heat rapidly. Boulders and exposed bedrock have high thermal inertia, i.e. they retain heat longer. (This is why people use polished concrete indoors, as a thermal mass to reduce heating costs.) Thermal inertia at the location is important for several reasons:

- A very low thermal inertia implies thick dust, which could impede mobility in marssuits and surface vehicles. Dust is also less useful for piling around and on the Hab for thermal and radiation protection.
- A high thermal inertia is advantageous as the ground will serve to keep the base warmer after sunset, reducing energy requirements.
- A very high thermal inertia would imply large boulders or large regions of exposed bedrock.
- A medium thermal inertia implies loose regolith, which we desire for piling around and on the Hab, both for insulation to maintain habitat temperature after nightfall, and for radiation protection.

In other words, when it comes to thermal inertia, it's a case of not too low and not too high.

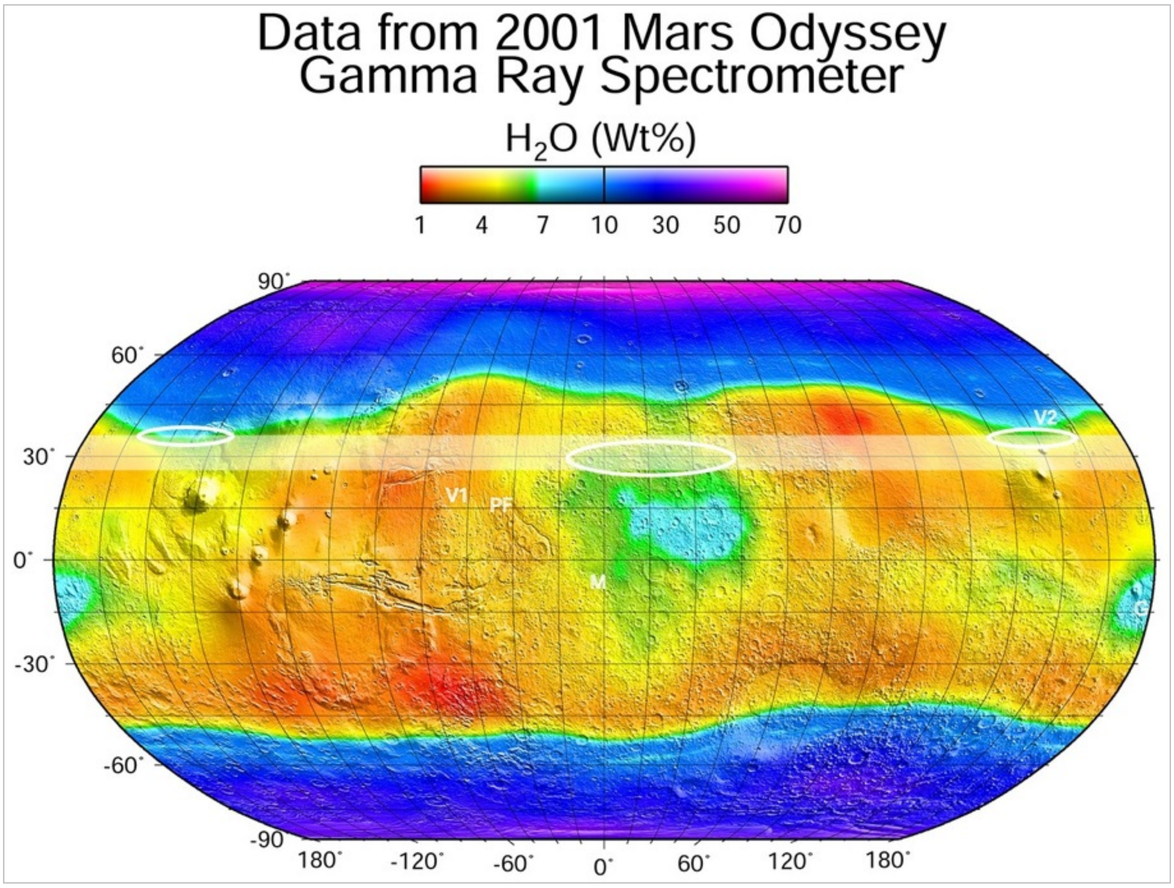
The following map shows thermal inertia, with areas of intermediate thermal inertia between 26°N and 36°N highlighted:



Water

One of the key goals of Blue Dragon is to make use of locally obtained water, in order to avoid transporting hydrogen from Earth.

The amount of water that could reasonably be obtained from the air would not provide enough hydrogen for ISPP. Therefore, we must look to ground-based sources. Fortunately there's plenty of water on Mars. The following map shows, circled, the wettest areas between 26°N and 36°N:



The ground on Mars is above 20-30% water beyond ~60° north and south, which is attractive. However, at these latitudes the solar incidence is somewhat low. if we seek to remain close to 31°N, we may select a location around 35-45°N as a compromise. The wettest locations in this zone may contain as much as 10% H_2O, which would be a useful quantity.

Areothermal energy

Areothermal energy may be available in some areas on Mars, most likely in regions that have been the most recently areologically active (i.e. the Upper Amazonian epoch). Although not a requirement for the first three missions, it is scientifically interesting and will be important to future settlements. If the IMRS is expanded into a larger-scale settlement, being close to areothermal energy will be a huge advantage.

A reliable source of areothermal energy on Mars will be of exceptional value, potentially superior to all other energy options currently under consideration. Areothermal energy could provide a continuous abundant supply of energy, without the environmental issues of fission or the need for energy storage subsystems as for solar or wind, and can be used directly for settlement heating, water supply, and electricity generation. If it is shown that areothermal energy is only available in a few places on Mars, these places may well be settled first, or may be more successful.

Areothermal energy combined with large ice deposits, such as we see in Arcadia ad Amazonis Planitias, could be indicative of liquid aquifers. Not only would this be a tremendously valuable resource for a settlement, but also a potential home for extant Martian life.

Regions on Mars that have been recently areologically active (Fogg, 1996) include:

- Cerberus Plains
- Hecates Tholus
- Medusae Fossae Formation
- Northwestern Tharsis
- Valles Marineris

Conclusion

The northern hemisphere of Mars is strongly preferred for a variety of reasons:

- More water, in the form of both ground ice and atmospheric water vapour.
- A higher minimum solar incidence.
- Less extreme climate.
- Lower elevation.
- Flatter, smoother terrain.
- Higher probability of areothermal energy sources and underground aquifers.
- More mineral ores, which are often formed by liquid water.
- More thorium, which may be important for LFTR’s (Liquid Fluoride Thorium Reactor).

Because solar energy is preferred (see *Power Systems*), the first base should be located close to the optimal latitude of 31°N in order to minimise the mass of the power system. However, by going a little further north more water can be accessed. Somewhere in Vastitas Borealis will be suitable, as this region is low, flat and reasonably smooth. The goal will be to find a location in this region that is not too dusty, and has loose regolith.

A higher-capacity energy storage subsystem would effectively eliminate the motivation to remain close to 31°N, which would therefore open up a wider range of options. However, there are a couple of good candidate locations near this latitude that should perhaps be investigated more closely:

Northern Amazonis Planitia, around 35°N 145°W

This may be the sweet spot in this region just northwest of Tharsis. There's abundant water at relatively low latitudes, with good solar incidence, and it's low and flat. This is one of the smoothest regions of Mars, and one of the most recently areologically active at only 100 million years old, making it likely to have areothermal energy. Arcadia Planitia is just to the north, which shows signs of near-surface ground water. From Wikipedia:

> *In a lot of the low areas of Arcadia, one finds grooves and sub-parallel ridges. These indicate movement of near surface materials and are similar to features on earth where near surface materials flow together very slowly as helped by the freezing and thawing of water located between ground layers.* ***This supports the proposition of ground ice in the near surface of Mars in this area.*** *This area represents an area of interest for scientists to investigate further.*

Areothermal energy in combination with underground ice could be indicative of aquifers, which would be tremendously valuable resource both materially and scientifically, as they may potentially harbour extant life. This location is close to Olympus Mons, one of the most famous and impressive features in the Solar System, which is both scientifically and aesthetically interesting. The thermal inertia is a bit low, which may make this region overly dusty; however, less dusty sites may be discovered on closer inspection.

Utopia Planitia, just north of Hecates Tholus, around ~40-45°N 150°E

This area may in fact be slightly superior due to a moderate level of thermal inertia. It's flat and smooth and has about 7-10% H_2O, good solar incidence, and low elevation. The area is areologically very young and considered a candidate for areothermal energy. It's also within striking distance of Phlegra Montes, where radar probing has indicated large volumes of water ice below the surface.

Crew Selection

Crew size

The Mars Semi-Direct and NASA DRA architectures specify crews of six, although the Mars Direct and MARS-OZ architectures require only four. Although it may be possible that a smaller crew could suffice, Blue Dragon is designed for six. There are a variety of reasons for this:

- It's about as large a crew as we can handle while keeping the mission achievable and affordable.
- A crew of six permits a dedicated crew member for the most crucial functions, while also allowing for a degree of redundancy in skill coverage.
- The DRA and other architectures have been designed for a crew of six, therefore we can leverage existing research.
- A single Bigelow Aerospace BA 330 module, the habitat section of *Adeona*, is designed to support six people.
- A SpaceX DragonRider capsule is designed for seven people. It should be large enough for six crew in spacesuits, with some additional space for samples.
- It permits a greater degree of flexibility with team configurations.

Since the BA 330 provides life support and ample volume for six people, to design the mission for less would be inefficient.

Why not five, or three, or seven? The Apollo crews had three members. There's one main advantage to having an odd number of people in the crew: it means that you never get a tied vote. However, it also means you can't use the buddy system. The "buddy system" is something kids learn in school, but is also a good idea for H2M missions. It simply means that everyone works in pairs. Your partner is your "buddy", and it's their job to keep you company, watch your back, and make sure you don't fall into a collapsed lava tube or anything like that. In turn, you do the same for them. This is important for safety as well as psychological health.

Naturally, the crew will not always be able to all work together. However, for safety and psychological reasons we may want to avoid any crew member being left alone; at least, they shouldn't work alone.

Six people can be organised as:

- Three teams of two
- Two teams of three
- A team of four and a team of two

This flexibility can be useful when organising shifts, EHAs, and chores, and it means no-one works alone and safety and happiness is optimised.

With a 3-person crew, either the three would always stay together, or people would often have to work alone. With a 4-person crew, if no-one is to work alone, the only team configuration available is two pairs of two. With a 5-person crew, there's also only one option: a team of two and a team of three.

While 3-5 people may be enough in terms of skills, we have capacity for six and a crew of six offers greater advantages.

Astronaut roles

Each crew member on this mission will need to be capable of fulfilling multiple roles, from coder to videographer to commander. All occupations are crucial to the mission and require redundant backups. Therefore each astronaut on the mission must be trained in multiple roles.

The crew is comprised of two teams: three engineers plus three scientists. The engineers ostensibly have different roles; however, they must all also be able to fix any of the mission hardware, and therefore, to a large degree, be able to do each other's jobs.

Engineering Team	**Flight/Mechanical**	Commander, handyman, pilot, rover operator
	Mechatronics/ Communications	Software, robotics, computers, electronics, antennas, commsats, multimedia
	Chemical/Electrical	ISRU, ECLSS, fuel and power systems
Science Team	**Planetary Scientist/ Astronomer**	Areology, planetology, navigation, site selection
	Astrobiologist/ Astrohorticulturist	Search for past/present life, bio-experiments, food production
	Medical/Safety	Health, fitness, nutrition, psychology, safety

Flight and Mechanical Engineer, and Commander

This role requires understanding, operating and maintaining all vehicles, including *Adeona*, *Success* and the Rover. This person is not only the mechanical engineer, but also the mechanic. As commander, they must liaise with Mission Operations on Earth, and make executive decisions.

Mechatronics and Communications Engineer

This role will include responsibility for all computers and mechatronic equipment, including flight computers, on-board computers in the rover, robotic systems, multimedia/web servers, personal computers, and more. They will also be responsible for all communications hardware used in space and on Mars.

Chemical and Electrical Engineer

This person is responsible for operating, maintaining and repairing all chemical engineering hardware in the habitat and various spacecraft, including fuel systems, ISRU systems, ECLSS, waste disposal systems and plumbing. They are also in charge of monitoring and maintaining all power and electrical systems.

Planetary Scientist and Astronomer

This role combines geology, planetary science, astronomy and cartography. On the surface of Mars they will study areology, areomorphology, areochemistry, areography, etc., and in space they will perform Earth, Mars and astronomical observation. They will be responsible for any telescopes used in space and on Mars, and producing maps of the IMRS site and surrounding area.

Astrobiologist and Astrohorticulturist

This role includes searching for and (if found) examining extant life on the surface of Mars, and conducting experiments with food production in *Adeona* and in a greenhouse or laboratory on Mars.

Medical and Safety Officer

This person is responsible for keeping the crew alive and healthy. This critical role combines ship's doctor, personal trainer, psychologist, and safety officer. It includes monitoring crew health and effects of microgravity and radiation, taking crew members through daily exercise routines, providing nutritional advice, administering medications and treatments, monitoring psychological health of the crew, monitoring solar flares and conducting safety drills, and developing and implementing safety protocols.

Journalist duties

If we could squeeze one more person into the mission it would be tempting to include a dedicated journalist and communicator, whose responsibility would be documentation and communications, including writing, photography, videography, blogging, interviews and other forms of reporting. This would be tremendously valuable to any space mission, as it would drastically increase engagement with the public (i.e. viewing audience) on Earth. This will generate a greater ROI across the board, helping to justify the cost of the mission, improve revenues (if that should be important), and generate a higher volume of feedback and good wishes for the crew, thus improving morale and decreasing feelings of isolation.

However, as ideal as it might be, it would be hard to justify. The alternative, which might in fact produce a better result, is to train all crew members in basic journalism and communications. Another approach would be to assign journalism duties to the Planetary Scientist and/or Biologist during the space travel stages of the mission, since they may not be able to do as much science during that time. The two scientists could share the responsibility once on the surface, or all the crew members could engage in daily or weekly reporting of their individual activities.

Alternatively, there may simply be one or two crew members who are naturally more extroverted, expressive, and better suited to journalist-style duties, and who may voluntarily take on much of that role. For example, a person like Carl Sagan or Neil deGrasse Tyson, who could take the the role of both scientist and science communicator.

Colour coding

Once the crew has been selected, they will each be assigned a unique, distinct colour, which is theirs until the end of the mission. These colours are used for everything that belongs to that astronaut - their bunk, spacesuit, treat meals, clothes packs, towels, everything. Everyone in the crew will learn everyone's colours.

Apart from the advantages of not mixing up your towel with someone else's, one of the primary advantages of having distinct spacesuit colours is that it will be easy to identify who's who during EVA, when it may be difficult to see each other's faces or bodies. Brown, orange and pink are excluded due to similarity with local colours on the Mars surface. Red should actually be ok, since, despite Mars being known as the "red planet", there's not a lot of actual red in the landscape.

White	Associated with purity and kindness, it belongs to the mission commander/flight engineer.
Blue	The colour associated with communications belongs to the mechatronics/communications engineer.
Purple	The colour of magic and alchemy belongs to the chemical/electrical engineer.
Red	As we're going to the red planet, this colour belongs to the planetary scientist.
Green	The colour of life and growth naturally belongs to the astrobiologist.
Yellow	The colour for happiness and safety belongs to the medical/safety officer.

Resource Requirements

In order to maintain the health of the crew for the full duration of the mission, we require specific life support consumables such as air, water and food. In addition, fuel is required for the trip to Mars and back.

The intention here is not to calculate exact amounts of resources required, as this has been done before in the DRA and elsewhere (Hanford, 2004). The intention here is merely to offer a number of ideas and strategies for obtaining and managing resources in a practical way.

Optimising resource usage

In space missions we are effectively separate from the environment of Earth where resources are comparatively far more abundant. Therefore, they must be strictly conserved. In addition, the high cost of launching mass from the surface of Earth to space dictates that the amount of consumables must be minimised as much as possible; without, of course, compromising crew health and safety.

There are three main strategies for minimising the amount of consumables that need to be launched from Earth:

1. Rationing and rules
2. Recycling
3. In Situ Resource Utilisation

Rationing and rules

Rationing and other consumable conservation rules must be followed by the crew in order to control resource consumption below certain limits.

Rationing applies primarily to food and water, and simply means that a daily ration of each is calculated for each function (eating, drinking, washing, etc.), and the crew are required to strictly consume an amount equal to or less than their ration. In this way, a limited quantity of food and water can be made to last for the full duration of the mission. Naturally, a buffer is built into the supplies to allow some flexibility here when required (for example, additional food and water is required for EVA's).

Rules can also be implemented to conserve energy consumption. For example, not using computers or communications equipment during the night, when power cannot be drawn directly from solar panels but must be drawn from less efficient sources such as batteries or fuel cells.

Recycling

This applies to water and air, and is the most effective strategy for reducing consumable requirements.

Almost all water consumed by the crew can be recovered from solid or liquid waste, and the habitat atmosphere. With modern spacecraft systems such as those found on the ISS, water can be recycled with an efficiency of 90% or greater; or in other words, the net loss of the consumable after recycling is effectively only about 10% or less of the amount consumed. This greatly reduces the amount of water required for the mission.

The efficiency with which air can be recycled depends largely on how CO_2 is handled. In space it may simply be purged. On Mars it may be purged, or it could be recycled back into the ISAP system, which obtains oxygen from CO_2.

In Situ Resource Utilisation

ISRU refers to making use of resources in space or at Mars rather than transporting them from Earth. Blue Dragon proposes producing bipropellant, water and breathable air from the local Martian environment.

Previous proposals for H2M architectures have been reasonably conservative in terms of inclusion of ISRU, either excluding it altogether, or including only ISPP. This is because provision and management of resources is in the critical path for the mission, and ISRU has not yet been demonstrated “in the field”, so to speak. However, because ISRU provides such a benefit in terms of reduction in launch mass and improved safety, it’s worth including if it can be shown to be reliable.

Although ISRU is yet to be demonstrated at Mars, this problem can be addressed by sending one or more missions to Mars to do just that. A concept mission called “Green Dragon”, which is a Red Dragon capsule containing an integrated ISRU system, would be a reasonably inexpensive method to achieve this. Although the cost of Green Dragon will be non-trivial, the benefits and ROI are substantial, as demonstration of, and experience with, Mars ISRU will be invaluable for future missions. Green Dragon is described briefly at the end of this document and will be discussed in more detail separately.

ISRU is valuable not only for reducing launch mass, but also for improving safety. To highlight this, consider a situation in which the crew is reliant on water transported from Earth:

1. What if the amount of water required is underestimated, and they run out?
2. What if the recycling equipment malfunctions and cannot be repaired?
3. What if something causes the water to be lost? (e.g. a micrometeorite puncturing a tank)
4. What happens if the crew miss the return launch window for some reason and must stay on Mars for a further 26 months until they can attempt another launch?

In all cases, if water can be manufactured from the local environment, the crew will be better off, at least in terms of that resource. There are other risks associated with ISRU, such as, what if it doesn’t work, or what if the equipment breaks down? However, once developed, tested and refined, ISRU technology ultimately results in a far more secure situation for the crew.

Propellant

Calculations of the exact quantities of propellant required by the MTV and the MAV are beyond the scope of this document. However, ISPP is discussed here because it relates to the architecture.

Propellant type

Earth surface to orbit

If the engines used by SpaceX and many other modern rockets do not change dramatically during the next two decades, then the propellant likely to be used to transport the crew and all other hardware to Earth orbit will be LOX/RP1.

Earth orbit to Mars orbit, and Mars orbit to Earth orbit

Many chemical propulsion systems designed for interplanetary transport use LOX/LH2 as propellant due to its high specific impulse. However, for *Adeona* this may be less than ideal, as it must carry the crew to Mars, and then back again after loitering in Mars orbit for 18 months. Hydrogen is notoriously difficult to store for long periods in space, especially in the vacuum of space, as it leaks away, or “boils off”. A typical boil-off rate for hydrogen in space is about 3.8% per month, therefore, if *Adeona* was to use LOX/LH2 propellant, a non-trivial additional quantity of hydrogen would be required to compensate for this. In spite of this, the chemical propulsion version of the transportation systems designed for NASA’s DRA currently specify RL10B-2 engines from Pratt and Whitney Rocketdyne for the MTV, which use LH2/LOX.

Because of the long period *Adeona* must wait on orbit it may be preferable to use a storable propellant such as mono-methyl hydrazine and nitrogen tetroxide, like the SuperDraco engines. However, it remains to be seen if this is practical. It may even use LOX/CH4. As mentioned, SpaceX are developing a LOX/CH4 engine called “Raptor”. It’s likely as settlement of Mars progresses that methane engines will become more common, as methane offers a range of advantages, including the fact that it can be manufactured on Mars and at other locations in the Solar System relatively cheaply and easily.

At this stage more exotic propulsion methods such as nuclear thermal rockets, ion propulsion, VASIMR, plasma thrusters, etc., are not under consideration for use in Blue Dragon. However, that may change if they can be shown to be superior in terms of cost, safety and performance. Chemical propulsion has a high TRL, is comparatively cheap, and more exotic or expensive propulsion systems are not required for human missions to Mars. The DRA includes two alternative designs for transportation systems, namely chemical propulsion and NTR’s (Nuclear Thermal Rockets). Although NTR’s may provide a thrust around twice that of any chemical propulsion system, they would be much more costly (unavailable as COTS products), take longer to develop, are arguably more dangerous, may be difficult to get approved, and would also require long-term cryogenic storage of liquid hydrogen.

Mars orbit to surface, and Earth orbit to surface

As mentioned, SpaceX Dragon and DragonRider capsules designed for ground landings on Earth will include eight SuperDraco engines, which use a hypergolic storable propellant (mono-methyl hydrazine as fuel and nitrogen tetroxide as oxidiser). It seems likely they would use the same engines for Mars.

As for the MAV and Hab, the DRA goes into some detail about how masses of this scale (30-100 tonnes) could be landed on Mars, with the following conclusion:

> *The reference EDL architecture that was ultimately selected for this study was a hypersonic aeroassist entry system, with a mid lift-to-drag ratio (L/D) aeroshell that was ejected at low supersonic Mach numbers. An LOX/LCH4-fueled propulsion system was used for deorbit delta-V maneuvers, RCS control during the entry phase, and final terminal descent to the surface.*

Therefore, LOX/LCH4 engines are proposed for all aspects of Mars EDL. To manage costs, ideally we will have access to a COTS engine for this purpose; however, at present there are no methane-fuelled engines that would be suitable, and it therefore may be necessary to develop a new engine. Alternatively, we may consider something like SpaceX SuperDraco engines.

Mars surface to orbit

The MAV's ascent stage carries the crew from Mars surface to orbit. These will use LOX/CH4 propellant produced from local Martian resources, as described below in the section on ISPP. One candidate engine may be the new Raptor engine currently in development by SpaceX, as this may well be reason for its development.

ISPP (In Situ Propellant Production)

It is for this reason that ISRU concepts were first developed for Mars. A fully-fuelled MAV weighs considerably more than a dry one (of the order of 100 tonnes), which would have required a far more elaborate and expensive EDL system. It has been shown that if the majority of the LOX/LCH4 propellant for Mars ascent is manufactured at Mars, the resulting mass saving could potentially reduce the cost of a human mission to Mars as much as a factor of eight (Zubrin *et al.*, 1991).

The ISPP process currently envisaged for the MAV closely parallels that described in the Mars Direct architecture. The difference between Blue Dragon and Mars Direct or the DRA is that all the propellant - both fuel and oxidiser - is obtained at Mars.

In the DRA, methane is brought from Earth and oxygen is manufactured at Mars. In Mars Direct, hydrogen (H_2), which represents the lightest fraction of the propellant yet also the most difficult to obtain from local Martian resources, is carried from Earth. This is reacted with carbon dioxide (CO_2) obtained from the Martian atmosphere in order to produce methane (CH_4) and oxygen (O_2), which are liquified and stored cryogenically.

Additional oxygen is obtained from carbon dioxide via RWGS, which produces water (H_2O) that is then electrolysed to hydrogen and oxygen.

In Blue Dragon hydrogen is obtained locally by mining water from the surrounding regolith and electrolysing it into hydrogen and oxygen. It has been shown that a significant fraction of the water frozen in the top layer of regolith can be liberated using microwave radiation (Ethridge and Kaukler, 2012).

The optimal stoichiometric ratio for LOX/LCH4 bipropellant is 3.5. The DRA specifies a fuel requirement of 21490kg of CH_4 (for two ascent stages), therefore the amount of LOX required is 75215kg. Although the MAV design in Blue Dragon is somewhat different than the one proposed in the DRA, i.e. it carries no propellant, but a more elaborate ISPP and ISWP (In Situ Water Production) system, and is topped with a DragonRider, these figures will do until after a more detailed analysis.

The process is as follows:

Step 1: On arrival at Mars, the AWESOM robot is deployed. It's first task is to unroll a solar blanket out of the descent stage of the MAV, providing power the ISPP system.

Step 2: Carbon dioxide is obtained from the Martian atmosphere by filtering out dust, removing water via zeolite adsorption, and freezing the CO_2 out of the remaining gas mix, enabling it to be separated from the remaining gases. The small amount of water captured by zeolite adsorption may be sent to the water tank.

Step 3: The AWESOM rover traverses back and forth across a patch of ground, microwaving the regolith below and collecting released water. At the end of each sol, the rover returns to the MAV to deliver its payload of water. The rover will require some form of LPS (Local Positioning System) so it knows what ground it has covered.

Step 4: Water is separated into hydrogen and oxygen gas via electrolysis:

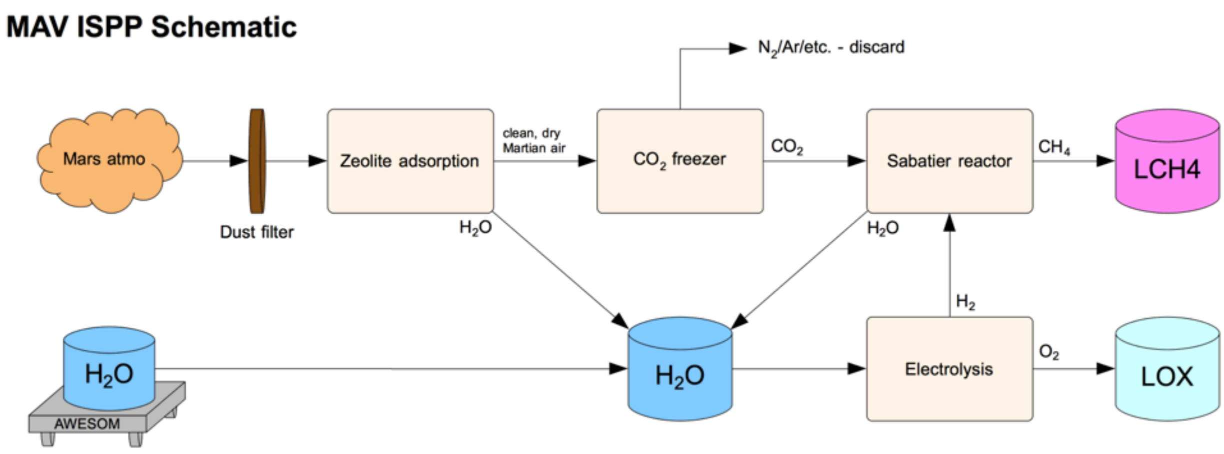
$$2\ H_2O(l) \rightarrow 2\ H_2(g) + O_2(g)$$

The oxygen is stored cryogenically as LOX.

Step 5: Methane is produced by reacting carbon dioxide (CO_2) obtained from the Martian atmosphere with hydrogen (H_2) produced in step 3, via the Sabatier reaction:

$$CO_2(g) + 4\ H_2(g) \rightarrow CH_4(g) + 2\ H_2O(v)$$

The Sabatier reaction occurs at high temperatures, optimally around 600K. Water produced by the reaction is stored in the water tank, and can therefore be used by the electrolysis unit to produce more hydrogen and oxygen.



Combining the reactions in step 3 and 4, the overall result is:

$$CO_2(g) + 2\ H_2O(g) \rightarrow CH_4(g) + 2\ O_2(g)$$

59.1 tonnes of carbon dioxide combined with 48.4 tonnes of water (a total of 107.5 tonnes) will produce 21.5 tonnes of methane and 86 tonnes of oxygen. This gives us a surplus of nearly 11 tonnes of oxygen that may be used to supplement air supplies for the Hab or the Rover.

The Martian atmosphere is approximately 96% carbon dioxide, therefore obtaining 59.1 tonnes of carbon dioxide requires processing about 61.6 tonnes of atmosphere. The density of the atmosphere at the surface of Mars is about 0.02kg/m^3, so this is about 3.1 million cubic metres of atmosphere.

If our goal is for the MAV to be fully fuelled within 20 months (the time difference between the arrival of the MAV at Mars and the departure of the crew from Earth), that means processing about 103kg (5130m^3) of atmosphere per day. It remains to be seen how achievable this is. There is 44 months between the arrival and departure of the MAV, therefore a slower processing rate may still be acceptable. However, if the process takes longer than 20 months the goal of ensuring that the MAV is fully fuelled before the crew leaves Earth would not be met.

Food

The DRA details food requirements for a crew of six on a long-stay human mission to Mars. If Blue Dragon uses the same food as would be used in the DRA (which may also be the same food system developed for the ISS), then the food requirements will be effectively the same because the crew size and duration of both the space and surface element are the same.

However, with new innovations in food technology, it is possible to substantially decrease the mass and volume of food.

Powdered food

New powdered food products such as Soylent (Rhinehart, 2013) are currently emerging, which claim to be nutritionally complete and carry a wide range of advantages. They require minimal time to prepare (just mix with water), require minimal cleanup, produce no waste, have an extended shelf life, and do not require refrigeration or heating. There is also evidence, albeit largely anecdotal at this stage, that subsisting primarily on such foods is beneficial for health and improves mental clarity. By ensuring that all the body's nutritional needs are met in an optimised way, this type of food is arguably far healthier than a typical diet.

Powdered food of this type is extremely well-suited to space missions, being especially lightweight and compact, catering for the crew's complete nutritional requirements in the most mass- and volume-efficient way possible, and optimising physical and mental function of the crew. It would eliminate the need for refrigeration and cooking equipment, thereby greatly reducing associated mass, volume and energy requirements.

A very strong market for no-fuss efficient food of this type is apparent, suggesting that numerous innovations including improved formulas and flavours will emerge during the next 1-2 decades leading up to the first H2M missions. A formula could be developed, perhaps higher in certain minerals and protein, optimised for astronauts spending time in low gravity environments.

It has been claimed the experience of spending time with other crew members in familiar domestic situations such as preparing "normal" meals and eating together, is useful for building relationships and morale. Meal times provides an opportunity for swapping stories and jokes, and there's a concern that providing the crew with nothing but simple powdered food for 2.5 years would deprive them of that joyful, social experience and could potentially induce feelings of boredom or frustration.

However, this is a space mission, not an ocean cruise or analog simulation. Every kilogram saved in terms of food, packaging, and storage and food-preparation equipment means a lighter and cheaper mission, which therefore increases its viability. If we ask a group of astronaut candidates: "Would you go to Mars if it meant living on nothing but powdered food for 2.5 years?" there's no doubt all of them would happily accept that condition.

Indeed, the astronauts may have so much to do, especially once on Mars, that they may appreciate not having to invest significant time each day to food preparation and consumption. To mix and consume a shake 2-3 times per day could reduce food preparation and consumption time to under 30 minutes per day, per crew member.

As powdered food technology develops, there's no doubt that a wide variety of flavours from chocolate to apples to bacon will become available. A range of powdered flavour additives could be included for mixing with a plain blend, allowing the crew to be creative, make their own favourite combinations, and to vary their diet as desired without compromising their nutrition.

It may be that a combination of powdered and "normal" space food is recommended, with powdered food being consumed most of the time, but with a social crew meal perhaps 1-2 times per week or per month.

However, this is probably a luxury and not an essential requirement, and it would require analysis as to whether the additional mass and cost associated with the food storage and preparation necessary for those occasional meals would be worth the psychological benefit, or whether an equivalent psychological benefit could be produced some other way, such as regular meetings over, say, tea.

The high nutritional density of powdered food should result in its highly efficient utility by the body, and thus reduced mass and volume of solid waste. This correspondingly reduces energy required to process waste, or volume required to store it. In addition, as the whole crew is eating the same food for the entire mission, the chemical profile of waste products is highly predictable, which may suggest opportunities for more efficient or useful methods of processing or recycling waste.

Summary of advantages of powdered food:

- Drastically reduce or eliminate mass of packaging, refrigeration and food preparation equipment, utensils and dishes.
- Eliminate energy requirements for refrigeration and cooking.
- Greatly reduce water requirements for washing dishes (everyone just has one shaker each).
- Improved health and mental clarity.
- Reduce quantity of solid waste produced.
- Both solid and liquid waste has a consistent, predictable chemical profile, potentially offering opportunities for more efficient processing or recycling.

ISFP (In Situ Food Production)

Mars explorers and settlers will want to grow their own food on Mars. Even from the very first mission, it's likely that astronauts will want to experiment with growing food. However, Blue Dragon does not propose that the crew should rely on food produced at Mars during the first three missions. Therefore, all the food required for the space and surface elements of the mission is transported from Earth.

As yet, we have no evidence that it will be possible to grow any kind of plant on Mars, although research is being conducted in this area that shows promising results. However, considering the following constraints, it would be safer not to rely on ISFP for at least the first few human missions:

1. With our current level of technology, production of nutritionally-complete food for the crew would require growing a range of different plants. It remains to be seen if a nutritionally-complete set of crops could be reliably produced in a restricted volume.

2. Growing plants requires equipment, such as pipes, hoses, trays, racks, lights, filters, tools, containers and much more. This adds launch mass, probably more than that of prepackaged food.

3. Growing plants requires volume. Whether growing the plants in Martian dirt, or using a hydroponic or areoponic system, a significant volume would be required to produce food for a crew of six; certainly far more than will be required be prepackaged food. Providing this volume would necessitate a larger Hab or a greenhouse module, which would significantly impact the launch mass and the cost and complexity of the architecture.

4. Growing plants requires water. Whether the crew's water is transported from Earth or obtained locally, it will be a precious and valuable resource. ISFP may significantly increase launch mass in terms of either water, or the equipment necessary to obtain it. Although the amount of water required to grow plants could be greatly reduced with an aeroponic system, it remains to be seen if a nutritionally-complete set of crops can be entirely grown aeroponically.

5. Growing plants requires light. Solar intensity on Mars is only about half that of Earth, which is sufficient for photosynthesis, but may result in slow growth in some plant specie, which could be a risk. Artificial light may be a solution, but that would increase energy requirements.

6. Growing plants requires environment control. If the greenhouse is connected to the Hab, then the Hab's ECLSS will need to maintain the temperature and atmospheric conditions of a much larger volume, which will therefore require more energy and a larger ECLSS unit. If the greenhouse is separate from the Hab, it will require its own ECLSS, which will require additional energy and increase launch mass.

7. Growing plants produces waste. Perhaps the waste vegetable matter could be processed into mulch, but this is only relevant if the plants are grown in soil; yet hydroponic or aeroponic systems may be preferred in the early stages of human exploration of Mars. Dumping waste vegetable matter on the surface of Mars may violate planetary protection protocols. The plant waste may need to be incinerated (as with excrement), requiring energy.

With all this in mind, it's better for the crew to bring their own food for the first few missions. Nonetheless, ISFP is a key capability that needs to be developed for human settlement of Mars, and the missions should incorporate experimentation into food production and growing a few simple crops while at Mars. This is mentioned in section 3.2.1.1 of the DRA:

> *There are three resulting objectives in the Mars Human Habitability/ISRU area. The first objective is to develop the capability of providing crew needs from local resources.* ***An example of this is in-situ food production.***

Water

Water is one of the most important elements of life support during the mission, and represents the largest fraction of the mass of life support consumables.

Water requirements

The following nominal values are useful for calculating water requirements (Hanford, 2004). For the sake of this exercise no distinction is made between potable and hygiene water.

Human water needs and metabolic water production:

IVA potable water consumption	3.909	kg/p-d
EVA potable water consumption, additional	0.240	kg/p-h
IVA human metabolic water production	0.345	kg/p-d
EVA human metabolic water production, additional	0.016	kg/p-h

Other water needs (units in kg/p-d):

Urinal flush	0.50	
Oral hygiene	0.37	
Hand wash	4.08	
Shower	2.72	
Laundry	12.47	
Dish wash	0.60	Varies from 5.44kg/p-d in Hanford; based on 3 x 200mL for rinsing personal shaker 3 times per day.
Medical	0.17	Based on 5kg/event, 1 event/p-m.
Total other	**20.86**	

Additional water is required on the surface of Mars for:

- Cooling marssuits during EVA. The maximum value (Hanford, 2004) is 7.3kg/EVA.
- Experiments; for example, ISFP. This amount is hard to estimate without a clear definition of the experiments.

Adeona

For the space element there will be no EVA, however, the crew will be exercising 1-2 hours per day to counteract the effects of μg. We can count these hours as effectively equal to EVA in terms of exertion. Hence the daily potable water consumption is 3.909 + (2 * 0.24) = 4.389kg/p-d, and metabolic water production will be 0.345 + (2 * 0.016) = 0.377 kg/p-d.

Therefore the total water requirement per crew member per day is 4.389 + 20.86 = 25.25kg/p-d. The total received by the recycling system will be 25.25 + 0.377 = 25.63kg/p-d.

Assuming the recycling system has an efficiency of 90%, the amount of water recovered is 25.63 * 0.9 = 23.07kg/p-d. Hence the total water loss per day is about 25.25 - 23.07 = 2.18kg/p-d. For a 360 day space element and 6-person crew, this is 4708.8kg.

We may wish to have in reserve as much as one week's worth of water, allowing up to one week to repair the water recycling system in the event of a malfunction. This would be 25.25 * 6 * 7 = 1060.5kg.

Therefore the total amount of water we initially require in *Adeona* is about 4708.8 + 1060.5 = 5769.3kg. This does not allow for contingencies such as supporting the crew on orbit for an additional 26 months if they miss their launch window.

Hab

For the surface element we estimate an average of 4 EHA's per person per week, with a maximum duration of 7 hours. This comes to an estimated maximum average of 4 hours EHA per day.

Hence the daily potable water consumption is 3.909 + (4 * 0.24) = 4.869kg/p-d, and metabolic water production will be 0.345 + (4 * 0.016) = 0.409kg/p-d.

Each EHA will require up to 7.3kg for marssuit cooling (Larson and Pranke, 1999). This amount be lower for the MCP marssuit design, but will do for a first-order analysis. This gives an average of 4.17kg/p-d.

Therefore the total water requirement per crew member per day is 4.869 + 20.86 + 4.17 = 29.9kg/p-d. The total received by the recycling system will be 29.9 + 0.409 = 30.3kg/p-d.

Assuming the recycling system has an efficiency of 90%, the amount of water recovered is 30.3 * 0.9 = 27.27kg/p-d. Hence the total water loss per day is about 29.9 - 27.27 = 2.63kg/p-d. For a 6-person crew this is 15.78kg/d. This is, therefore, the minimum amount the ISWP needs to provide to the Hab each day.

Again, we may wish to have in reserve as much as one week's worth of water, allowing up to one week to repair the water recycling system in the event of a malfunction. This would be 29.9 * 6 * 7 = 1255.8kg. This is the minimum amount that the ISWP system must store in the Hab's tanks before the crew arrive.

The value of 15.78kg/d is considerably higher than the 3.3kg/sol that the WAVAR (WAter Vapour Adsorption Reactor) device described by Grover *et al.* (1998), is designed to extract from the Martian atmosphere. A scaled-up WAVAR may be able to achieve this, and/or this amount may be reduced in several ways:

- Develop marssuits that require less cooling water.
- Go on EHA less often.
- Restrict water usage for laundry.
- Use a higher-efficiency recycling system (~95%).

If a WAVAR-type device is not capable of providing the necessary water, there are several alternatives:

- Use an AWESOM rover to collect ground water, as for the MAV. This approach is preferred for optimal water security.

- Transport hydrogen from Earth, and combine with oxygen obtained from the atmosphere to provide water. If we aim to manufacture enough water to replace losses for 540 days (8521kg), plus a full week's reserve (1256kg), a total of 9777kg, the amount of hydrogen required is 1086kg (plus a margin to compensate for boil-off). This is the approach taken by the DRA, although the quantity of hydrogen is only 400kg.

MAV

As discussed in the section on ISPP, the amount of water needed by the MAV for the manufacture of propellant is 48.4 tonnes.

ISWP (In Situ Water Production)

Based on current knowledge water can be obtained from three primary sources on Mars:

1. Atmosphere:
   a) Water vapour
2. Ground:
   a) Ice
   b) Hydrated minerals

Each of these represents specific challenges.

The concentration of water in the atmosphere is very low. Atmospheric water may potentially be used to provide water to the Hab using a WAVAR device, which captures water from the Martian atmosphere by adsorption in zeolite 3A.

However, we need significantly more water for ISPP, as the intention is to use Martian hydrogen rather than hydrogen brought from Earth. It isn't practical to try to obtain this much water from the atmosphere, so the ISPP process incorporates a system called AWESOM.

The AWESOME rover traverses across the terrain, extracting water from the top layer of regolith. An RTG (Radioisotope Thermoelectric Generator), like the one used in *Curiosity*, provides both heat and electrical energy. A standard RTG produces about 300W of electricity and 6kW of heat. These can be used in combination, with the electrical energy being used to produce microwave radiation and the heat used directly, to release water from the regolith without the need for scooping up and baking the soil. The frequency of the microwave radiation can be tuned to preferentially heat water molecules rather than dirt. As described in chapter 15 "Resources on Mars" of Larson and Pranke (1999), the rover would have a flexible skirt brushing the dirt, containing the water vapour, which would be condensed onto a cold surface and collected.

The ability to make use of Martian water is fundamental to the Blue Dragon architecture, which means it's important to locate the IMRS in a region where the water content is reasonably high, while still aiming for lower latitudes in order to simplify landing and to maximise solar power. The ground at the proposed location for the IMRS (discussed in the *Location* section) should ideally be at least 7-8% water by mass. It should also be reasonably flat, supporting autonomous water collection by a mobile robot.

If we estimate that the average water concentration of the regolith is at least 7% by mass, and that 80% of this can be extracted from the top decimetre of regolith by heat and microwave radiation, we can estimate the amount of regolith that needs to to be processed.

48.4 tonnes of $H_2O \div 80\% \div 7\% = 864.3$ tonnes

The density of dry Martian soil is about 1400kg/m^3. If the regolith contains 7% water, its density will be about

$1400kg/m^3 \div 93\% = 1505kg/m^3$

The volume of regolith to process is therefore:

$864300kg / 1505kg/m^3 = 574.3m^3$

Assuming we can only extract water from the top decimetre of regolith, the area that must be covered by the rover is about:

$574.3m^3 / 0.1m = 5743\ m^2$

If the AWESOM rover has a 1-metre wide catchment, it must therefore traverse about 58 strips of 100 metres length (or cover a square about 76 metres on a side).

Specifying the same 20 month time constraint, AWESOM must collect 80kg of water per day, which requires covering about 10m^2 of terrain per day. It will be preferable to collect the water as rapidly as possible, for peace of mind, and also because H_2 is needed before CH_4 can be produced. The design goal will be to build the robot to be capable of carrying up to 80-100kg of water, and will return to the MAV to unload at the end of each sol, in order to avoid spending the Martian night with a full water tank, as it may freeze and rupture the tank.

Keeping water in a liquid form within the AWESOM rover will require heat. Some of the heat generated by the RTG can be directed into this function.

Air

Breathable air is required in *Adeona*, the Hab, the Rover, the DragonRider capsules, and in marssuits. Note that, as per NASA policy, the crew will always be wearing their marssuits inside the DragonRider capsules, although they should only need to breathe from the suits during descent to, and ascent from, Mars.

1. ***Adeona***: Although the finer details of the BA 330 are currently unavailable, presumably it will be inflated and pressurised with breathable air from canisters of oxygen and nitrogen. Its built-in ECLSS will maintain the air quality during the outbound and return missions, in much the same way as the ISS, scrubbing excess water vapour, carbon dioxide and other contaminants from the habitat atmosphere, and topping up with oxygen and nitrogen as required.

2. **Hab*:*** The Hab will have air in it when landed, however, it will also have a compact and lightweight ISAP system to manufacture breathable air from the local Martian environment. This is necessary to provide surplus air to inflate inflatable modules, refresh the Rover's atmosphere, refill oxygen tanks for marssuits, and replace losses due to airlock cycling.

3. **Rover*:*** The pressurised Rover, being airtight, will initially contain normal Earthian air on landing, and will include a compact ECLSS to support extended excursions. However, it may also be possible to top up or freshen its air supply by connecting with the Hab.

4. ***Pern-1:*** This DragonRider carries the crew from Earth surface to orbit, then docks with *Adeona*. Therefore it will initially contain normal Earthian air, which will merge with the spacecraft atmosphere after docking. On arrival at Mars, *Pern-1* carries the crew, wearing marssuits, from Mars orbit to the surface. It will initially contain air from *Adeona*. When they arrive at Mars surface and pop the hatch, that air will escape and Pern-1 will fill with Martian atmosphere. However, the crew will be breathing pure oxygen from their suits.

5. ***Pern-2:*** This DragonRider carries the crew from Mars surface to orbit at the end of the surface mission. It will initially contain Martian atmosphere, and the crew will be wearing marssuits and breathing pure O_2. Before docking with *Adeona*, the capsule will be pressurised with O_2 and N_2 from tanks contained in the unpressurised section of the capsule, giving it a matching atmosphere.

6. ***Pern-3:*** This DragonRider is launched from Earth and will therefore contain normal Earthian atmosphere. When it docks with *Adeona* the air in it will mix with the spacecraft atmosphere, which is virtually the same. The crew can then enter the capsule and descend to Earth surface.

7. ***Marssuits:*** Marssuits will provide astronauts with pure oxygen to breathe, and will scrub exhaled carbon dioxide with something like lithium hydroxide canisters. Oxygen tanks for the suits can be refilled from the Hab's ISAP system.

Atmosphere design

Adeona

The atmosphere inside *Adeona* will most likely be very similar to normal Earthian conditions, with one atmosphere (101.3kPa) pressure comprised of approximately 21% oxygen and 79% nitrogen. This matches the ISS, the Shuttle, Vostok, Mir and other space stations and spacecraft.

The reasons why an Earth-like atmosphere is preferred for use in space are:

- Discounting hyopgravity effects, the behaviour of the atmosphere is predictable in terms of its interaction with people, animals, plants and equipment.
- It reduces the cost of equipment inside the spacecraft. Rather than having to design equipment for a specialised atmosphere, as was necessary with Apollo, Skylab and many other early spacecraft, with an Earth-normal atmosphere many ordinary COTS items developed for Earth can be used in the spacecraft.
- No adaptation is required for astronauts when moving between the spacecraft and Earth. Physiological effects of long-term exposure to a reduced pressure or low-oxygen atmosphere are not a consideration.
- No time or energy is required to pressurise or depressurise capsules for crew transport to or from Earth.
- A high percentage of buffer gas greatly reduces fire risk.

Although details about the BA 330 are yet to be made available, it seems highly likely it will be designed for an Earth-normal atmosphere, as one of its proposed applications is space tourism.

DragonRiders

For all DragonRiders, the internal atmosphere will be either Earth-normal (or the same as in *Adeona,* which is virtually Earth-normal), or the crew will be wearing marssuits.

The Hab

For the same reasons as listed above for *Adeona*, it would be especially advantageous if the Hab also has a normal Earthian atmosphere. However, the higher the atmospheric pressure of the Hab, the stronger and therefore heavier it, and any inflatable extensions, will need to be. This is contrary to our requirement of reducing the mass of the Hab as much as possible because of the significant challenge of landing such a heavy object on Mars.

In addition, we are relying on ISAP for habitat air. For both of these reasons, it is preferable to design the Hab for a reduced pressure atmosphere.

Atmospheres in early spacecraft had low total pressure, low oxygen pressure, or both. However, research conducted since then has more clearly defined the limits for extended exposure to artificial atmospheres.

The minimum possible partial pressure of oxygen to support human health is 16kPa, however, a minimum partial pressure of oxygen of 18-19kPa is recommended for long-duration missions (Duffield, 2003). A safe specification would be 19kPa (±1kPa).

The next question is how much buffer gas to include. A pure oxygen atmosphere introduces an unacceptably high risk of fire, as occurred in the Apollo 1 Command Module. Recommendations as to the maximum percentage of oxygen in order to keep fire risk manageable range from about 24-30%. Again erring on the side of caution and specifying a maximum of 24% O_2 gives us a total atmospheric pressure of 79.2kPa.

According to SMAC (Spacecraft Maximum Allowable Concentrations), the maximum CO_2 concentration is 0.7%. A CO_2 concentration of 1% can cause drowsiness, with more serious symptoms occurring at higher concentrations. A typical concentration in normal spacecraft operations is 0.5%, which is a reasonable design goal. This gives us a target CO_2 partial pressure of about 0.4kPa.

With regard to water vapour, NASA specifies a RH (Relative Humidity) of 30-70%, i.e. an average of about 50%. Our target temperature is 295K (about 72°F or 22°C, which is optimal for human comfort), and the saturated water vapour pressure at this temperature and pressure is about 2.6kPa. Our average water vapour partial pressure will be 50% of this, or about 1.3kPa.

Proposed design for Mars habitat atmosphere.

	Partial pressure (kPa)
Oxygen (O_2)	19.0
Carbon dioxide (CO_2)	0.4
Water vapour (H_2O)	1.3
Buffer gas (N_2, Ar, Ne, Kr, Xe)	58.5
Total	**79.2**

The ISAP system manufactures buffer gas from the approximately 4% of the Martian atmosphere that remains after separation from CO_2. Therefore, the amount of buffer gas that can potentially be included in the Hab atmosphere is limited by how much atmosphere can be processed by its ISAP system, which must also be lightweight.

The Hab's atmospheric pressure will reduce over time due to:

- Airlock cycling.
- Purging of waste gases (e.g. CO_2).
- Leaks. Naturally, the Hab will be designed for zero leaks; however, in practicality, some small leaks are possible.
- Refilling of marssuit and Rover tanks from the Hab's supply.

- Experiments.

Pressure loss is managed in the same way as on the ISS. Oxygen and buffer gas are kept in separate tanks so that both the partial pressure of oxygen and the total atmospheric pressure can be precisely controlled. If the partial pressure of oxygen falls below a given threshold, then oxygen is added. However, if the *total* pressure of the Hab falls below a given threshold, then buffer gas is added. The ECLSS controls concentrations of CO_2, H_2O and contaminants such as CH_4, NH_3 and others.

The Rover

Aspects of atmosphere design relevant for the Hab apply equally to the Rover. We wish to provide a safe and healthful atmosphere while keeping the mass of the Rover as low as practical.

It will be advantageous if the Rover atmosphere has the same composition and pressure as the Hab, because that would simplify the design of (and reduce the amount and therefore cost of testing) equipment, such as lab equipment and laptops, that may be used in both environments. Most importantly, the same zero pre-breathe protocol that we desire for the Hab can also be implemented for the Rover.

With both components having the same atmospheres it may also be possible to connect the Rover directly to the Hab: perhaps with a person-sized hatch to make it easy to transfer between them without needing to suit up or go through the airlock, or perhaps simply with a pipe to freshen the Rover's air.

Marssuits

Space suits typically use pure oxygen as breathing gas, which simplifies the PLSS (Personal Life Support System) and reduces the suit mass. Pressures range from 26kPa to 57kPa. Space suits with relatively high pressure of 57kPa are sometimes referred to as "zero pre-breathe", as they permit an astronaut to transition from an Earth-like atmospheric pressure (101.3kPa) to the suit without needing to spend time pre-breathing. Pre-breathing involves breathing pure oxygen for a period of time (30 minutes to several hours) at atmospheric or mid-level pressures in order to purge nitrogen from the blood and other tissues, which is necessary with low-pressure suits to prevent DCS (decompression sickness, also known as "the bends").

Zero pre-breathe suits for Mars are highly desirable (Rouen, 1996), as they would result in considerable saved time and much greater convenience for the crew, who will wish to conduct EVA/EHA most sols. It is easier to achieve this with MCP suits, because gas pressurised suits require as low as possible air pressure in order to facilitate effective mobility and reduce crew fatigue.

The amount of pre-breathing is based on the *decompression ratio* (also known as the R value), which is the ratio between the partial pressure of buffer gases in the spacecraft or habitat atmosphere, and the total pressure in the space suit. From Campbell, 1991:

> *An R value of more than 1.0 may have a risk of decompression sickness. This risk increases with increased R value. The risk of decompression sickness during a mission is statistically cumulative over a number of decompressions during that mission; therefore, the mission duration and frequency of EVA*

must be considered when determining an appropriate value for R for a given mission. A statistical analysis of cumulative risk shows that for R=1.22, the risk of decompression sickness after ten decompressions is 7 percent, while for R=1.4 the risk is 37 percent. Therefore, cumulative risk is an important criterion for long-term planet surface missions and it increases rapidly as R is increased above 1.0. If the decompressions are not separated by enough time to eliminate previously formed gas bubble nuclei from body tissues, the risk of decompression sickness on subsequent decompressions is also greatly increased.

Our crew will be spending approximately 540 days on the surface of Mars, with an estimated four EHA's per week, for a total maximum of around 300 EHA's each. Considering this very large number of EHA's, zero pre-breathe would only be an option for R=1.0, which, if we accept our above habitat atmosphere design, would necessitate a marssuit air pressure of 58.5kPa.

NASA's "Mark III" suit, a prototype gas-pressurised space suit developed by ILC Dover, has an operating pressure of 57kPa, which is very close to this. This is considered a zero pre-breathe suit despite having an R value of about 1.39 when transitioning from a mixed atmosphere with 79kPa nitrogen (such as the ISS), presumably because it's designed for a small number of EVA's.

Current MCP suits are approaching 30kPa. As this is an active area of research, it seems plausible that MCP suits with an operating pressure of 58.5kPa could be developed in time for a human mission to Mars.

ISAP (In Situ Air Production)

The primary constituents of the Martian atmosphere are CO_2, N_2, Ar, whereas Earth's are mainly N_2, O_2 and Ar. Therefore, all the elements required to make breathable, Earth-like air are available in Martian air.

The Hab includes inflatable extensions to significantly increase habitat volume beyond the size of the initial spacecraft. After landing, the Hab is remotely activated from Earth, initiating the ISAP system and causing the inflatable extensions to inflate. As we are sending the Hab one launch window earlier than the crew, we will have about 20 months to inflate the Hab and test its other systems before the crew leave Earth. In order to inflate the extensions, it will be preferable to make the necessary air using ISRU technology rather than bring compressed air from Earth, which would require heavy tanks. In addition, having the capability to manufacture breathable air from local resources will compensate for air losses due to airlock cycling, atmosphere scrubbing and other causes.

The DRA proposes separating N_2 and Ar from the Martian atmosphere for use as a buffer gas. However, it is actually much cheaper and easier to use the gas that remains after CO_2 and dust is removed from Martian air, as this is mostly N_2 and Ar anyway, and simply scrub out any undesirable constituents.

Step 1: Mars atmosphere is drawn into the ISAP system through a dust filter.

Step 2: Water is removed from the gas mix using a WAVAR. The captured water is stored in the Hab's water tank and used to replace recycling losses, and for O_2 production via RWGS.

Step 3: Water is separated into H_2 and O_2 using electrolysis. The O_2 is stored for habitat atmosphere.

Step 4: A carbon dioxide freezer is used to separate CO_2 (about 96%) from the remainder of the gas mix.

Step 5: The CO_2 is reacted with H_2 via the reverse water gas shift (RWGS) reaction:

$$CO_2 + H_2 \rightarrow CO + H_2O$$

The H_2O produced is returned to the water tank, and the CO may be stored for use in fuel cells.

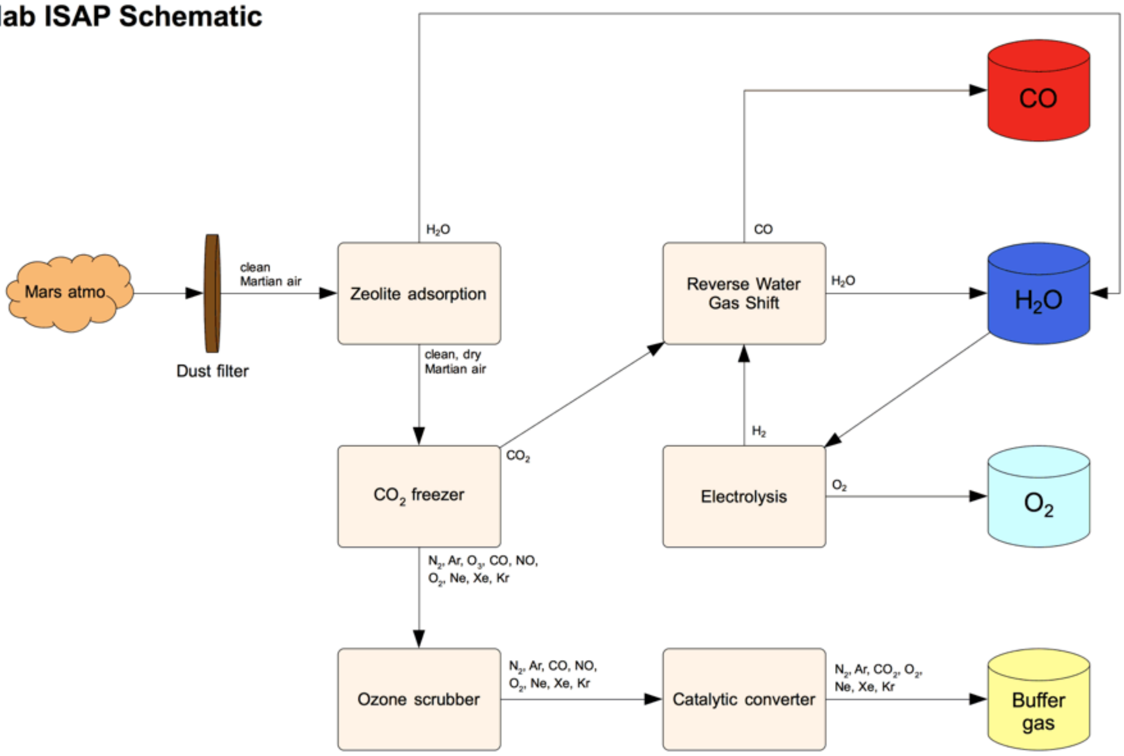
The gas mix that remains after CO_2 is removed is mostly N_2 and Ar, with trace amounts of various noble gases (Ne, Xe and Kr), and some undesirables such as O_3 (ozone), CO (carbon monoxide), and NO (nitric oxide; technically non-toxic, but rapidly oxidises to toxic NO_2 when mixed with O_2).

Step 6: This gas mixture is first passed through an ozone scrubber, which reduces the O_3 to O_2.

Step 7: The resultant gas mixture is then passed through an ordinary automobile 3-way catalytic converter, which converts any CO and NO into CO_2 and N_2.

Step 8: The result is a safe buffer gas comprised mostly of N_2 and Ar, with small amounts of O_2 and CO_2, and traces of Ne, Xe and Kr. This mixture can be combined with additional O_2 to provide breathing gas for the Hab. The CO_2 level in this gas mixture is slightly higher than the proposed upper limit for the habitat atmosphere, but this excess will be removed by the ECLSS.

Hab ISAP Schematic



More research needs to be done into this system. We need to know the rate at which breathing gas can be manufactured, how much the unit will weigh, its volume and power requirements, and how it will integrate with the ECLSS.

Power Systems

One of the primary challenges associated with any Mars mission is the design of power systems.

Power is needed for:

- ECLSS
- Lighting
- Refrigeration and cooking (maybe - see section on *Powdered Food*)
- Computing and multimedia
- Communications
- ISRU
- Airlock operation
- Recharging of marssuit and surface vehicle batteries

For both in-space and surface power systems, the primary options under consideration for Mars are nuclear fission and solar. Each have their pros and cons, however, at this stage it seems more likely that solar will be preferable for both in-space and surface power.

Wind energy may be viable for future Mars settlements, but probably not for early Mars missions:

- Because the air pressure on Mars is so low (less than 1% of Earth), it does not generate enough force to produce much electricity.
- Wind turbines operating in such a dusty environment may require high levels of maintenance that would be difficult to provide.
- Early Mars missions will probably be located in low altitude areas (for warmth), whereas wind turbines on Mars will perform better at high altitudes.

Areothermal energy sources are a possibility, but are yet to be proven or located, and would not be utilised by early missions.

ECLSS

Thermal control

Maintaining a comfortable environment inside *Adeona* and the Hab is a one of the elements that will require the most power.

In *Adeona*, as in the ISS, the primary requirement will be cooling. On the ISS:

> *The large amount of electrical power consumed by the station's systems and experiments is turned almost entirely into heat. The heat which can be dissipated through the walls of the stations modules is insufficient to keep the internal ambient temperature within comfortable, workable limits. Ammonia is continuously pumped through pipework throughout the station to collect heat, and then into external radiators exposed to the cold of space, and back into the station.*

A similar approach may be suitable for *Adeona*, however, the details of the ECLSS in the BA 330 are currently unavailable and appropriate solutions may have already been developed. If not, systems can be adapted from those on the ISS. The thermal environment of interplanetary space is similar to that in LEO, although it will become cooler farther from the Sun, reducing the load on thermal control systems.

Although the priority in *Adeona* will be cooling, in the Hab the primary requirement may be heating. The desired temperature for the internal environment of the Hab will be approximately 295K (22°C). This is, on average, around 80K warmer than the external environment of Mars, although the temperature of the Martian surface can vary from 130K (winter at the poles) to 308K (summer at the equator). Of course, the base will not reach these extremes, being located somewhere between the equator and poles. However, considering that electrical subsystems inside the Hab will also produce heat, and the first surface mission takes place during the three warmest seasons in the northern hemisphere, it's likely that cooling will also be required at times. Therefore, the Hab will require both heating and cooling subsystems, which may be derived from ISS or Apollo (or other space habitat) systems or may be completely new and developed specifically for the unique Martian environment.

To reduce the power required for heating the Hab we can choose a warmer-than-average location. This is discussed in the section about Location.

Ventilation

Because warm air does not rise in μg, ventilation is an issue on the ISS, as it will also be on *Adeona*. Air around laptop computers, for example, can heat up considerably. Maintaining a consistent air flow through the ISS via the use of fans is essential.

Again, it remains to be seen what provisions are made for ventilation in the BA 330's built-in ECLSS. However, it's likely that additional fans will be needed near computers and other electrical equipment installed in *Adeona*.

Within the Hab, even though it will be operating in a gravity environment, ventilation will still be important. Any volume can produce hot and cold spots if air circulation is inadequate. Effective circulation is especially important in an enclosed environment to ensure that accumulated carbon dioxide or ammonia in the atmosphere is effectively scrubbed by the ECLSS.

Nuclear

Nuclear energy has some clear benefits, namely that it can provide an abundant power supply day and night, irrespective of weather or location. A fission reactor could provide ample power for ISRU processes and other electrical subsystems. Furthermore, they do not require energy storage solutions.

In Mars Direct the ERV (Earth Return Vehicle) includes a nuclear reactor to provide energy to the ISPP system. This enables propellant production to occur rapidly, thus ensuring that the hydrogen brought from Earth is converted to methane as quickly as possible to minimise hydrogen boil-off and ensures that sufficient fuel will be manufactured.

Once the ERV lands on Mars, a small robotic truck emerges with an nuclear reactor. The truck carries the reactor some way off, trailing electrical cable connecting it to the MAV. The reason why it must be distanced from the MAV is because the reactor will be unshielded.

On Earth nuclear reactors are normally heavily shielded and encased in multiple containment shells in case of an accident. However, due to the high mass of shielding material, it isn't practical to send such shielding and protective shells to Mars. Shielding is typically very heavy, which would make it even harder to land the already massy MAV on Mars.

However, the MAV is designed to carry people. If an unshielded reactor is operated inside or near the MAV, it would irradiate the vehicle, making it unsafe. Therefore, the unshielded nuclear reactor must be transported some distance from the Hab, and ideally hidden in a depression or behind a hill or crater wall, in order to prevent radiation products from reaching the crew or any other part of the base.

There are some problems with this strategy. If the reactor is unshielded, even if it's moved some distance away from the MAV, it would create a zone around it that would be unsafe for the crew. The MAV may not be affected by radiation from the reactor, but the natural environment surrounding the reactor will be.

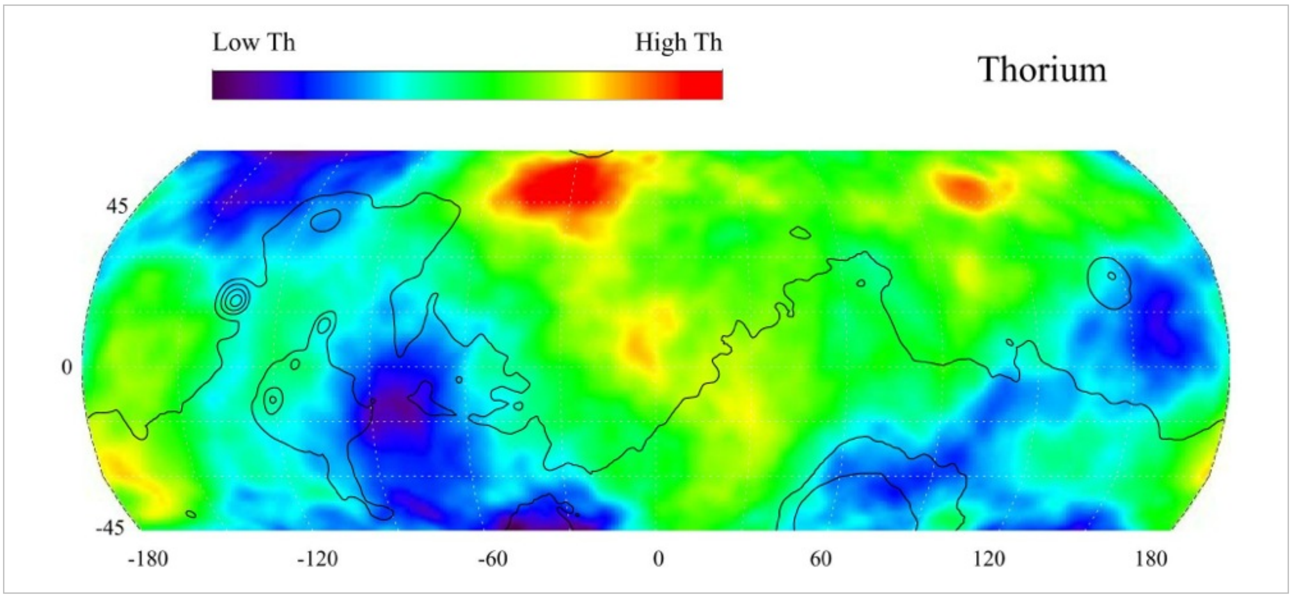
We should treat Mars a little more responsibly than this. What if the reactor is parked near something of scientific interest? What if it needs attention for some reason? What is the long term plan for decommissioning the reactor? Many people who are not advocates of Mars settlement say things like "we messed up one planet with pollution already, should we be messing up another?" If we act in such a way, i.e. operating unshielded nuclear reactors, then such criticism would be justified.

That does not mean fission should be completely ruled out as a power source. There are several new types of reactor currently in development, which do not have many of the problems associated with the existing generation of reactors. Reactors with appropriate shielding may be appropriate. However, there is another problem with reactors in Mars - in the event of an accident, access to the reactor is made more difficult by the Martian environment, and there may not even be people around to deal with it.

LFTR's

One of the most promising new reactor types is the LFTR (pronounced "lifter"). These reactors are fuelled by thorium, a far cheaper and more abundant fuel than uranium. Mars certainly has plenty of thorium. LFTR's produce much less waste, can utilise existing nuclear waste as fuel, operate at much lower pressures, cannot melt down or explode, and the reactors can be of a much smaller scale, which bodes well for space applications. Yet they also retain the established benefits of nuclear reactors of being able to provide an always-on reliable abundant power supply.

LFTRs are still in development and it may well be decades before they are in commercial use. If viable, perhaps they could be developed for Mars. For now we must consider alternatives.



Distribution of thorium on Mars

Solar

Are solar panels a reliable energy source on Mars? Along with many other Mars and space missions, the Mars Exploration Rovers *Spirit* and *Opportunity* were powered by solar energy. *Spirit* was active for six years, and *Opportunity* is still going after almost 10 years at the time of writing. Solar has been shown to be a practical energy source on Mars. Research has shown the modern solar technology can match the mass and volume performance of nuclear energy on Mars, and because of safety, environmental and policy issues, is likely to be preferred (Cooper *et al.*, 2010).

A simple comparison of solar and nuclear, using our hardware cost variables:

Solar c.f. nuclear fission	
Cost of development	Much less

Solar c.f. nuclear fission	
Cost of manufacture	Much less
Cost of transportation	Comparable
Cost of operation	Comparable
Cost of decommissioning	Much less

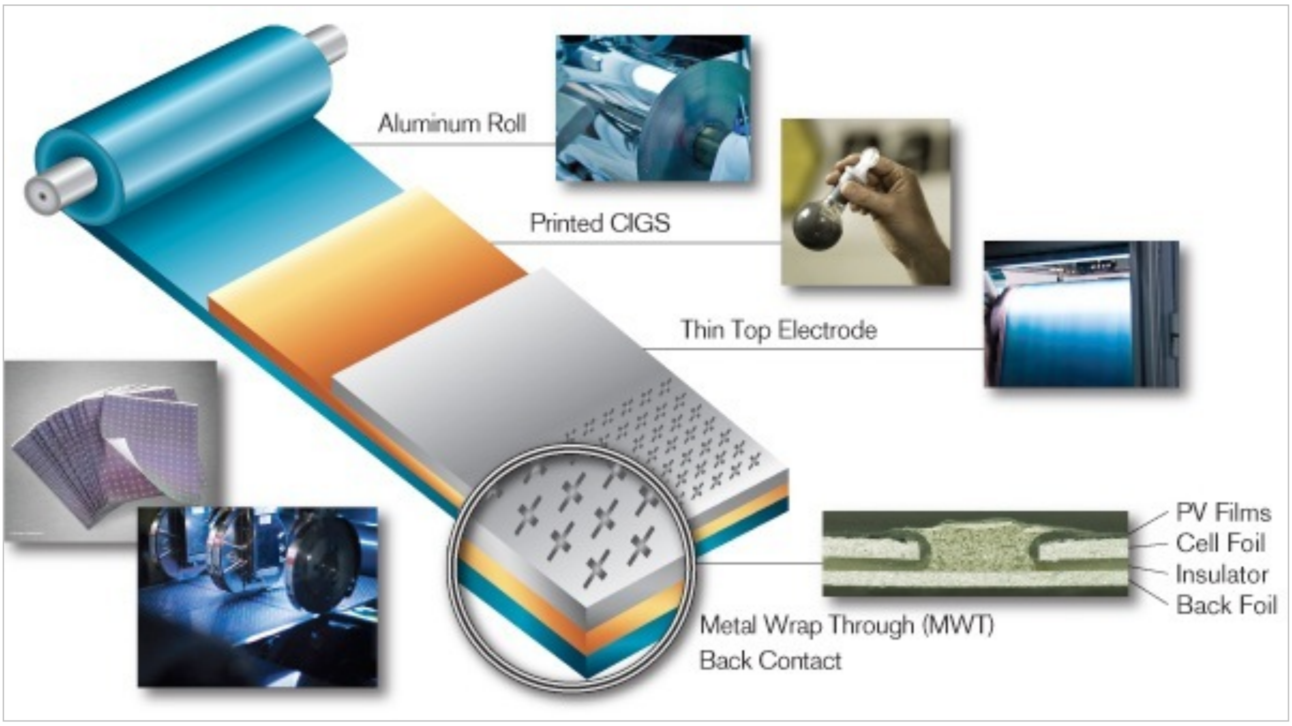
The primary problem with solar panels is that they represent a fluctuating energy source that varies with the diurnal cycle, seasonal cycle, and atmospheric dust levels. As a rule of thumb, daytime solar energy on Mars is about half that of Earth (the solar intensity at the upper atmosphere is 43% of Earth's, but Mars has no clouds). Furthermore, dust can accumulate on panels, reducing their effectiveness, although with a human crew present this problem can be addressed reasonably easily with conventional broom technology.

Solar energy is currently one of the largest areas of investment on Earth, and the technology is advancing rapidly. In 2011 investment in solar peaked at about $157 billion. Investment in rooftop solar peaked in 2012 at about $80 billion. Innovations in photovoltaic technology is producing:

- printable solar material
- materials orders of magnitude more efficient at converting solar energy to electrical energy
- greater precision and consistency with solar cell manufacture, which significantly reduces efficiency losses
- much higher levels of energy produced per square metre of panel

It seems very likely that by the 2030's solar will be a mainstream energy production technology on Earth, and will be entirely suitable for Mars missions, with numerous advantages over nuclear.

Nanosolar is one company at the forefront of technology to "print" solar cells using conventional printing methods. The substrate, printed onto aluminium foil, is 1% as thick as conventional as a typical silicon-wafer cell for the same performance. The result is highly-efficient photovoltaic sheets that can be rolled up, with the result being a much higher rate of power output per unit mass or volume. One or more rolls of solar material of this nature could be transported to Mars and unrolled onto a nearby patch of ground (which may have first been smoothed by the Rover).



Nanosolar printed photovoltaic cell technology

Solar energy for *Success*

One of the reasons for the ERV's nuclear reactor in the Mars Direct architecture is that propellant production can proceed quickly, day and night, in order to minimise hydrogen boil-off and ensure that all the propellant gets made. However, if we commit to using local water as a hydrogen source, hydrogen does not need to be stored, since hydrogen produced by electrolysis of water can be immediately converted to methane. Thus there will be no boil-off, and less urgency to manufacture the propellant as quickly as possible.

We therefore don't need an uninterrupted power supply for ISPP, which means we can use much safer solar energy for ISPP, and simply manufacture propellant only during the daytime when power is available.

We have about 20 months between when *Success* arrives at Mars and when the crew leaves Earth at the subsequent launch opportunity. Even if propellant is only being made during the day, this should still be plenty of time to ensure that *Success* is fully fuelled before the crew leave Earth. In fact, there is about 44 months between *Success*'s arrival and departure (26 between the arrival of *Success* and the arrival of the crew, plus 18 months of surface mission), so extra time is available if needed.

By using solar panels instead of a nuclear fission reactor for ISPP power, we eliminate the mass of the reactor, the robotic truck to relocate it, and the electrical cable that would connect the reactor to the MAV. We eliminate the risk of an unshielded reactor irradiating the MAV, or the surrounding terrain, or the crew.

The Dragon's trunk is already designed to contain solar panels. These may be used to provide some of the power necessary for ISPP (or the trunk may be removed, or it may be reserved for samples and left empty to reduce landed mass). The MAV's ascent stage may also potentially include additional panels as required. However, perhaps the best approach is to include a roll of solar fabric in the lower section of the MAV, which the multi-purpose AWESOM robot can pull out to cover a strip of ground. Another option would be for the outer walls of the descent stage to open up like a flower, revealing solar panels on their inner surfaces. Yet another option would be for some of the outer surfaces of *Success* to be coated in a photovoltaic material or coating. Calculations need to be done to determine precisely what area of PV cells (whether panels, fabric or coating) is required to produce the necessary power, plus a suitable margin.

Solar energy for the Hab

Although we don't need an uninterrupted power supply for propellant production, this *is* a requirement for the Hab because the ECLSS (at least) must operate continuously.

In order to solve the issue of variability of power supply from solar panels, an energy storage solution is required, whereby some percentage of the solar energy collected each day is stored for use during the night. However, due to efficiency losses in energy storage, as well as limits on how much energy can be stored given the mass of batteries (or fuel cells, or other storage solution) that can be affordably be transported to Mars, it's important to minimise the amount of energy to be provided from storage.

Energy required by the Hab during the Martian night, when no solar power is available and the Hab is reliant on stored energy, can be much lower than during the day if we implement a simple rule that the crew sleeps or at least rests while it's dark, i.e. wake at dawn each day and do all work in daylight hours. This minimises the use of power for lighting, and restricts primary power consumption by activities such as computing, communications, laboratory experiments, etc. to the daytime when solar power is directly available.

The main Hab subsystems requiring power during the night will be ECLSS and comms. The nights are naturally colder, so energy requirements for heating will be higher than during the day.

Energy storage

There are several options for storage of solar energy:

- As H_2, CO, CH_4, CH_3OH or other fuel, for use in a fuel cell.
- Batteries.
- Graphene supercapacitors.

Batteries are preferred over fuel cells for several reasons:

1. Battery technology is evolving quickly due to the expansion of the electric vehicle market. The downside of batteries is that they tend to be heavy, but the amount of energy stored per unit mass, or per unit volume, is steadily decreasing.

2. Batteries are mechanically very simple, require minimal maintenance and are more reliable. Fuel cells are more complex, and can break more easily.

Graphene supercapacitors are a technology currently in development that could well be available by 2030, and are far superior to batteries. They can store much more charge per unit volume or mass, and they recharge extremely quickly. For this reason they're receiving considerable interest at this time due to their potential for use in electric cars and electronics, and are likely to evolve rapidly in the next couple of decades leading up to the first H2M missions. Another advantage of graphene supercapacitors that could become more important in the future is that they're made of pure carbon, which means, we can make them on Mars from the atmosphere.

Communications

Between Earth and *Adeona*

Adeona will be equipped with deep space communications equipment. During both the outbound and return journeys, Earth and Mars will be on the same side as the sun and therefore line of sight communications between Earth and *Adeona* will be possible. Although Earth is rotating, the DSN (Deep Space Network), currently comprised of antennas in California, Spain and Australia, maintains the constant connection with Earth.

Between Earth and Mars

Again, the DSN is used for the Earth end of the communications. However, there is not always a direct line of sight between Earth and the IMRS, for two reasons:

- Sometimes the Sun is between Earth and Mars.
- Mars is rotating, therefore, about 50% of the time Mars is between Earth and the IMRS.

To solve the second problem, we could use the same approach currently used by robots on the surface of Mars, which communicate with Earth primarily by relaying messages through orbiters like the 2001 Mars Odyssey, the Mars Global Surveyor, and the Mars Reconnaissance Orbiter. These are closer to the rovers than Earth, which means that the rovers don’t need to generate as powerful a signal; also, the orbiters are in sight of Earth for much longer periods of time.

When the Sun is between Earth and Mars (solar conjunction), for about two weeks out of every two years, thermal noise effectively blocks communications between Earth and Mars. This would only occur once during the Mars surface mission, and may well be an acceptable risk.

A good solution is the one proposed by Mars One (Lansdorp and Wielders, 2013), which uses just two communications satellites to provide almost 100% connectivity between Earth and Mars:

1. An areosynchronous satellite above the base.
2. A single satellite at Earth’s L5 Lagrangian point (i.e. sharing Earth’s orbit, but trailing by 60°).

The second satellite provides connectivity between Earth and Mars during solar conjunction. This is the solution preferred in this architecture, and in this document they’re referred to as the “IMRS Commsat" and the “L5 Commsat”.

This use of an areosynchonrous communications satellite is yet another advantage of the base-first strategy. Areosynchonrous satellites couldn’t be justified for a program where each mission is to a different location.

However, if we're building up infrastructure in a single location to develop a permanent human presence, eventually we will need a dedicated satellite. The sooner it's in place, the better.

Between Hab and Rover

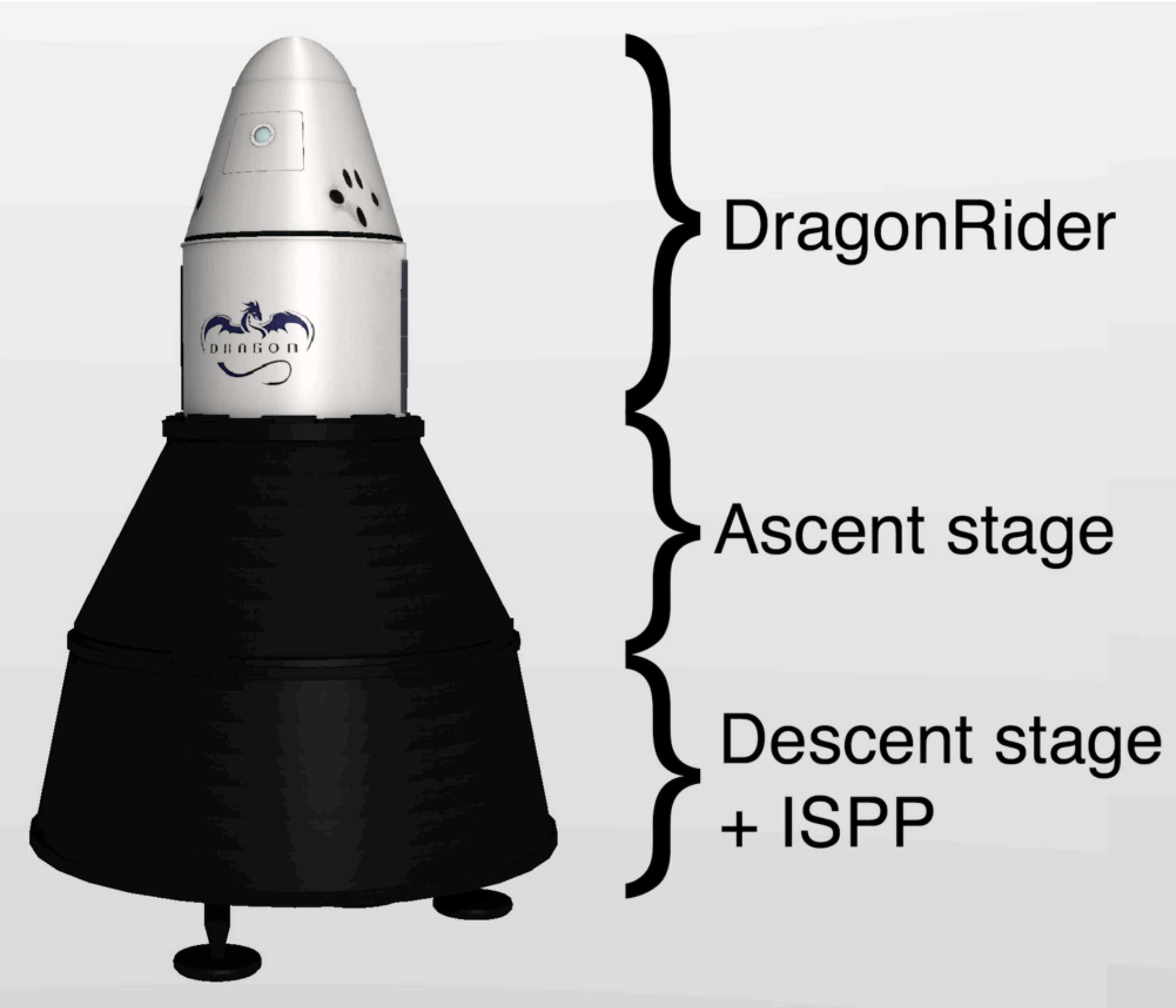
The Hab and Rover will rarely be out of radio comms, especially since we plan to land in a fairly flat location. In the rare event that the Rover does go out of radio contact with the Hab, communications may be relayed between the two via the IMRS Commsat.

Between astronauts and Hab/Rover during EHA/EVA

Astronauts on EHA/EVA will be required to always maintain radio contact with either the Rover or Hab or, ideally, both. In the rare case that this rule needs to be broken - for example, exploring a lava tube or cave - then the pair or group (remembering that the crew always work in groups of 2-3) must remain within radio contact of each other at all times, with at least one in radio contact with the Hab or Rover.

Mars Ascent Vehicle

The MAV will be an VTOL (Vertical Take-Off and Landing) vehicle capable of pinpoint landing on Mars, refuelling from local Martian resources, and carrying up six astronauts to Mars orbit.



The Mars Ascent Vehicle

The MAV has three stages:

1. The lower section is the descent stage, which includes:

    1.1. Descent engines and fuel tanks

    1.2. A sophisticated GNC system

    1.3. One or more rolls of PV material

    1.4. ISPP plant (electrolysis unit and Sabatier reactor)

1.5. A water-mining robot called AWESOM

2. The middle section is the ascent stage and includes:

   2.1. Ascent engines (e.g. SpaceX Raptors)

   2.2. LOX/LCH4 fuel tanks, which are initially empty

3. The upper section is a modified DragonRider with no heat shield. The trunk may potentially be eliminated, or it may be used for solar panels or sample storage.

Ascent Engines

The MAV's ascent stage engines will be LOX/LCH4 (liquid oxygen/liquid methane), which are refuelled from local Martian resources. Several types of engines that burn methane fuel have been developed, however, SpaceX are currently developing a new LOX/LCH4 engine called "Raptor", which is likely to be the preferred choice for several reasons.

Based on SpaceX's record, the Raptor design is likely to be more modern and advanced than existing alternatives. It is also likely to have a high degree of interoperability with other SpaceX hardware used in the mission, such as the Dragon. Furthermore, since SpaceX will already be involved, using more hardware from the same company should, in theory, reduce costs, if for no other reasons that a fewer number of engineers need to be paid, since engineers who understand the Dragon and Falcon are also probably the same people who understand the Raptor engine.

Differences from Mars Direct ERV

The Blue Dragon MAV should be much lighter vehicle than the ERV used in Mars Direct, as it does not include the mass of:

- Six tonnes of hydrogen brought from Earth
- Nuclear reactor
- Light robotic truck for relocating reactor
- Electrical cable to connect MAV to reactor

Instead, it includes:

- AWESOM water-mining robot (note that this could potentially be delivered separately, in a Cargo Dragon, in order to reduce landed mass of the MAV)

- One or more rolls of photovoltaic material

Success' propellant requirements are lower than for the ERV, being required only for Mars ascent and not TEI (same as for the MAV in the DRA). Less propellant means smaller fuel tanks (and therefore lower mass), and less time required for the manufacture of propellant.

There's also no need for RWGS or dissociation of CO_2 to produce additional O_2, as ample is obtained from water electrolysis. This simplifies the design of the ISPP unit, which can therefore be made smaller and lighter.

Mars Transfer Vehicle

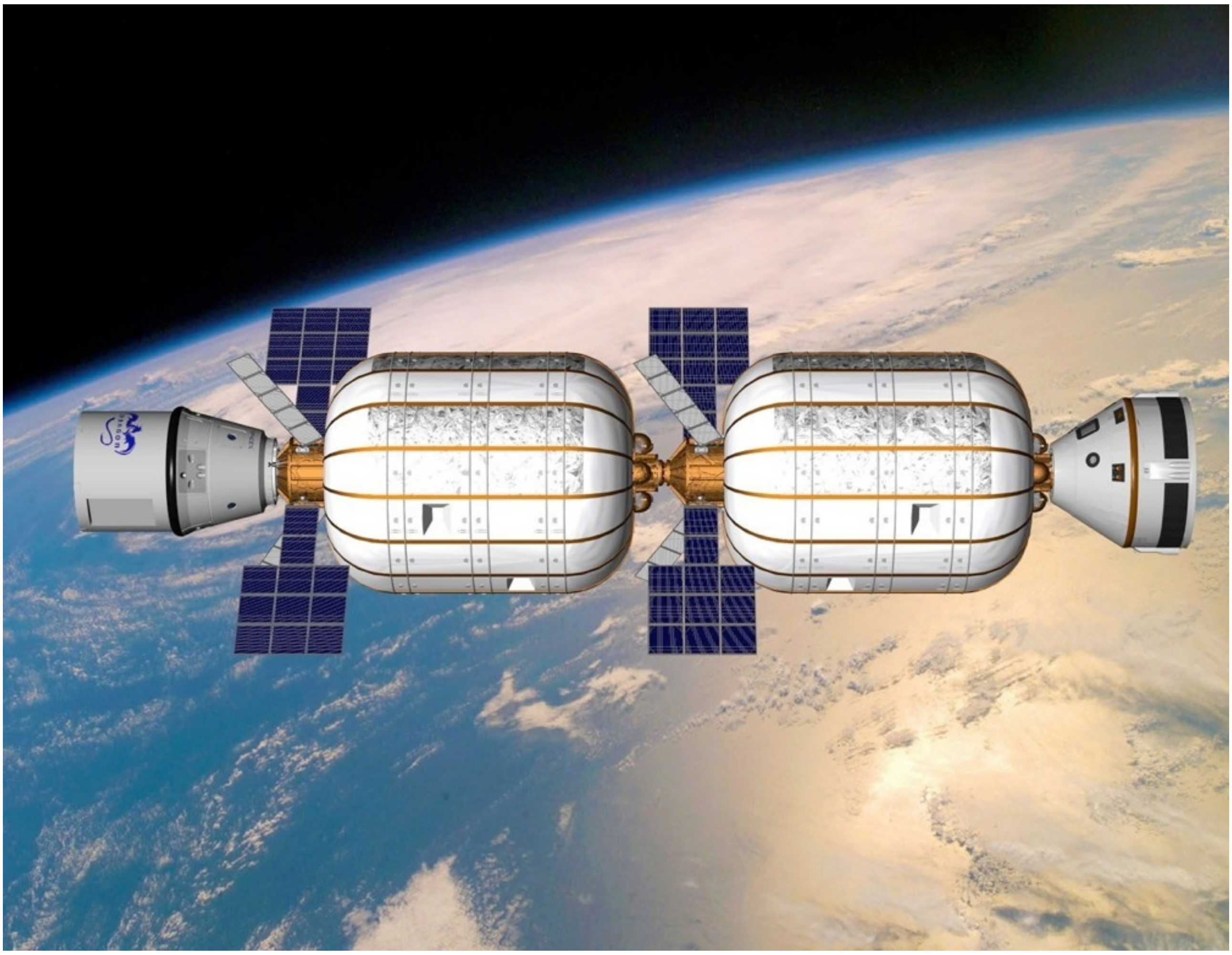
The MTV is constructed on Earth orbit. It's designed to support a crew of six in a microgravity environment for the trip from Earth to Mars and back. It will only be used in space, and will not land on, or launch from, any planetary surface.

The MTV is a spaceship, and ships should have a more interesting name than "MTV". Ours is named *"Adeona"*, the Roman goddess of safe return. It comes from the Latin verb *adeo*, "to approach or visit" as well as "to take possession of one's inheritance". Mars is our inheritance and we hope for a safe return for the crew.

Bigelow Aerospace BA 330

The habitation section of *Adeona* is a single Bigelow Aerospace BA 330 module, a COTS item that is projected to become available from about 2016-17. The BA 330s are inflatable modules with an internal volume of 330 cubic metres, designed for use as space station modules or for interplanetary travel. They include ECLSS designed to safely support a crew of six long term, contained within a solid core.

The BA 330 modules are launched in a deflated state, which permits them to be launched within a small diameter payload fairing, such as an Atlas V. They may be connected together to form larger structures, which is a capability that may be exploited in future vehicles. For example, here is Bigelow Aerospace's concept for their "Alpha Station", which shows two BA 330 modules, with a SpaceX Dragon capsule docked at one end and a NASA Orion capsule at the other:



A volume of 330m^3 is ample for a crew of six, including storage for consumables. The bare minimum free volume per person required for space travel is believed to be 10m^3, although the optimal is about 19m^3. Although full calculations need to be done on the remaining volume after the BA 330 is fitted out and loaded with supplies, it seems the BA 330 should be reasonably spacious, certainly compared with previous space missions.

Since it should be feasible to use only one BA 330, and we're aiming for minimum cost and complexity, Blue Dragon currently specifies using only one.

The skin of a BA 330 is comprised of 24 - 36 layers for ballistic, thermal and radiation protection. The BA 330's radiation protection is equal to the ISS, but its ballistic protection is superior.

Adeona will have a docking port at one end for the DragonRider capsules that will ferry crew members between *Adeona* and the surfaces of Mars and Earth. Apparently the BA 330 is already being designed to support docking with Dragon capsules, as a result of discussions between SpaceX and Bigelow Aerospace, therefore this is a useful design feature we get essentially for free.

The other end of the BA 330 module will be attached to the cruise stage.

Launching the BA 330

The mass of a BA 330 is approximately 20-23 tonnes, and it has an estimated deflated diameter of about 3.5m, and a length of 14m. The rocket currently under consideration by Bigelow Aerospace for launching these to orbit is the Atlas V. The fairing of the current version of the SpaceX Falcon Heavy is not long enough.

The Atlas V Heavy has a payload diameter of 5.4m, a payload length of 16m, and can carry 29.4 tonnes to LEO, which would certainly do the job. However, the Atlas V is a flexible vehicle with a range of payload configurations, including diameters of 4 or 5.4 metres, and lengths ranging from 9 to 16 metres or more. An alternative configuration may be developed specifically for the BA 330, for example, an Atlas V 452, which would have a 4m diameter fairing and be capable of carrying approximately 21 tonnes to LEO.

Cruise stage

Attached to the BA 330 is one or more cruise stages comprised of engines, fuel tanks, RCS (Reaction Control Systems), and deep space communications equipment. Although GNC (Guidance, Navigation and Control) systems are built into the BA 330, additional GNC systems suited to interplanetary travel may also be incorporated into the cruise stage.

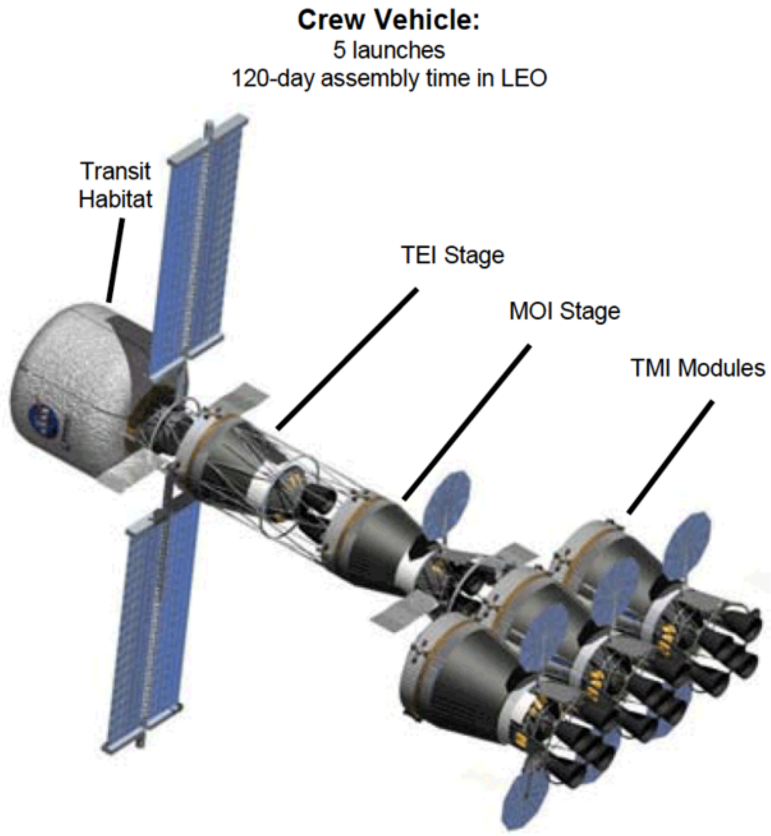
The engine will need to perform four major burns:

1. Trans Mars Injection (TMI) at ~Day 0
2. Mars Orbit Insertion (MOI) at ~Day 180
3. Trans Earth Injection (TEI) at ~Day 720
4. Earth Orbit Insertion (EOI) at ~Day 900

As *Adeona* does not refuel until its return to Earth, it must commence the mission with enough fuel for all four burns plus a suitable margin. This greatly increases the initial wet mass of *Adeona*.

The RCS is used at Mars and Earth to circularise/stabilise orbit or increase/decrease altitude as required. Furthermore, on approach to Mars and Earth orbits, the RCS will be used to rotate the spacecraft 180 degrees such that the main engine is pointing towards the planet in preparation for MOI or EOI.

The diagram below shows the chemical propulsion version of the MTV proposed in the DRA. The “Transit Habitat” is effectively the BA 330. Each engine is an RL10B-2, a LOX/LH2 rocket engine developed by Pratt and Whitney.



For the Blue Dragon architecture the following changes are proposed:

- The addition of an EOI stage so that the vehicle can be captured into Earth orbit. This has several advantages:
    - The spacecraft (particularly the habitat section) can be reused for multiple missions.
    - The crew can be picked up by a Dragon capsule launched from Earth, which means better planetary protection.
    - The deceleration forces experienced by the crew during Earth EDL will be much less if descending from orbit rather than direct entry.
    - The MTV does not need a capsule attached for TEI, making it lighter (although, it will have the mass of the EOI engines and fuel instead).
- The merging, if possible, of all cruise stages into one, to avoid wasting good engines (thus saving money and producing less space debris).

- The use of LCH4 fuel instead of LH2, to reduce boil-of (especially while loitering on Mars orbit) and tank volume and mass.

LOX/LCH4 for in-space propulsion

Nuclear thermal propulsion is not used for in-space propulsion; rather, chemical propulsion using LOX/LCH4 is preferred for a variety of reasons.

- Commonality of hardware elements. Because LOX/LCH4 is being used for the MAV, if the same basic type of engine is used for the MTV, we automatically build redundancy into our knowledge base. Propulsion engineers working on both vehicles will be able to share expertise, resulting in greater synergy and problem-solving capability. It also reduces the number of types of components across the mission.

- Methane has various advantages over RP-1 (Rocket Propellant 1, i.e. kerosone). It's cheaper, as it can be obtained directly from LNG, has a slightly better specific impulse, and is not subject to coking.

- Methane is considerably easier to work with than hydrogen. H_2 must be stored cryogenically, requires large tanks, leaks, causes metal to become brittle, and can cause invisible high-temperature fires.

- Chemical propulsion is much safer than nuclear. Due to mass constraints nuclear engines are unshielded and do not come with the layers of protection built into reactors. If there are any problems with the reactor, such as a meltdown, LOC would be likely and nuclear radiation products could enter the atmosphere and/or orbits of Earth or Mars.

- Cost. Due to the abundance of carbon dioxide and methane in the Solar System, and the benefits of ISPP, methane engines are likely to become more common and less expensive as Mars and Solar System settlement proceeds, which will drive costs down.

No aerobraking/aerocapture

An important consideration in Mars mission design is the amount of fuel to be carried with the spacecraft. In order to reduce the launched mass, aerobraking or aerocapture is sometimes used at Mars to slow the spacecraft and insert it into a Mars orbit, rather than controlling the spacecraft velocity purely using engines.

Aerobraking can take a very long time, up to six months at Mars, which makes it impractical for a humans-to-Mars mission.

Aerocapture is quicker, but the large drag forces could damage solar panels, antennas and other exposed equipment. It also requires a heat shield, and for a spacecraft with a 6.7 metre diameter this would be large and heavy (although an inflatable heat shield may be an option). The would partially or wholly offset the mass of saved fuel.

Aerobraking and aerocapture are also more risky. If the spacecraft hits the atmosphere at a slightly wrong angle, it can skip out and fly right past the planet. Also, due to atmospheric turbulence, variations in temperature, composition, etc., it can be difficult to predict the effects of aerobraking. However, if engines are used to control the spacecraft the effect can be precisely known, and if there are any minor miscalculations, additional small burns can be made to place the spacecraft into the correct, safe orbit.

Therefore, by ensuring we have enough fuel for MOI, and avoiding aerobraking/aerocapture, we gain the following advantages:

1. No risk to damage to spacecraft components through interaction with the atmosphere.
2. No need for a heat shield.
3. Higher predictability of spacecraft motion.
4. Higher certainty that the spacecraft will achieve the desired orbit.
5. No need to endanger the crew by attempting a risky manoeuvre with them on board.

The trade-off is additional fuel and a therefore a larger cruise stage.

Artificial gravity is not used (or required)

DRA does not specify whether AG (Artificial Gravity) should be used, although it does discuss the topic. It states that AG would be far more important for a short-stay, opposition-class mission due to the longer time spent in space.

The use of AG in Blue Dragon would significantly increase the cost of the mission due to additional mass of both spacecraft and fuel, and increased complexity of propulsion, navigation, communications and power systems. It introduces additional hazards and failure modes, and would increase the cost of development as well as operation. It would also compromise the interior design, as a spaceship designed for microgravity can be made more space efficient.

The benefits of AG don't warrant these sacrifices. We have considerable experience with astronauts spending months in microgravity. On return to Earth, some are able to walk away from the spacecraft and some are not, but all recover and readapt to Earth gravity in time. On arrival at Mars it's expected that the crew will need a couple of weeks to adapt from microgravity to Mars gravity, but since they have 18 months on the surface, this comparatively brief recovery period will barely affect the surface mission. The astronauts will be eager for EVA and will push themselves to recover quickly.

The crew of the Blue Dragon mission will spend time each day doing exercise, either in *Adeona*'s small gym or by doing EHA at Mars, to offset deconditioning. They will be administered drugs to minimise or prevent bone loss, and will have a diet high in protein and minerals. Leveraging months of experience in microgravity on the ISS, modern training principles and equipment, and appropriate nutrition and drugs, it is very likely that the crew will be totally physically able after spending six months in microgravity. Therefore we can safely spare the cost and complexity of implementing AG.

The entrepreneur Dennis Tito is currently developing a mission to send two people on a Mars flyby, which will require them to spend more than 1.5 years in microgravity. This mission will go a long way towards answering the question of whether it will safe to send a crew to Mars surface and back on a 2.5 year mission. Mars One also does not make use of AG.

Reusability

Once back in Earth orbit, *Adeona* can be refuelled and re-used. Instead of building a new spacecraft every time, we can refurbish, expand and improve on the one we have. This is obviously cheaper than constructing a new spacecraft each time. We could add on another inflatable module, upgrade the engine, solar panels or computer systems, or make any number of other improvements.

Adeona could become something like the MDRS (Mars Desert Research Station), with subsequent crews drawing inspiration from, and adding to, the marks and refinements made by previous ones.

Of course, sometimes we will want entirely new spacecraft. But this reusability feature will drastically reduce the cost of future missions, thus increasingly the likelihood that they'll fly.

Most importantly, the familiarity of reusing a habitat that has been successfully inhabited by previous crews, and which may contain such relics as photographs, flags, signatures, and various user-friendly tweaks to the environment, can have important psychological benefits and create a powerful feeling of connection between crew members past and present. This has been demonstrated and reported many times by crews of FMARS and MDRS.

On-orbit construction

Adeona is assembled in LEO from sections that will need to be launched separately, due to their size:

1. The BA 330 module. This is launched deflated and inflated once on orbit.

2. The cruise stages, comprised of engines, fuel tanks, fuel, navigation and communications.

On-orbit assembly is sometimes seen as a drawback because of the additional cost and risk involved. One of the features of Mars Direct is that no on-orbit assembly is required. However, in order to achieve this, the architecture required the development of a specialised HLLV in order to launch the hab-vehicle in one piece.

The SLS (Space Launch System) currently in development at NASA may fulfil the role of the HLLV described in Mars Direct, or the proposed Falcon X or the Chinese Long March 9.

For the sake of the exercise, however, the goal is to make use of what is currently available. At this time SpaceX is the preferred candidate for launching the sections of *Adeona*. An Atlas V can deliver the BA 330 to orbit, and Falcon Heavies, each able to deliver 53 tonnes to LEO, can launch the fully-fuelled cruise stages.

Although it adds some additional cost and complexity to the architecture, on-orbit assembly is no longer a significant space engineering challenge. The ISS was assembled in LEO and was much more complex than *Adeona*. Admittedly, we will not have access to the Space Shuttle, which was a key element in ISS construction; however, we can do it without the Shuttle. The Apollo LEM and command modules were docked on orbit without the benefit of the Space Shuttle.

On-orbit assembly makes Blue Dragon slightly more complex than Mars Direct or even DRA, but it's still much simpler than von Braun's MarsProjekt, or the 90 Day Report, and simpler than the ISS. Most importantly, it allows us to build a better vehicle.

The BA 330 must be launched deflated, and will therefore be empty after inflation. An additional launch is therefore required to deliver a fit-out/construction crew of 2-4 people to load supplies and construct the inside of the ship, including floors, cupboards, beds, gym, laboratory, and solar storm shelter (the bathroom is built into the BA 330 core).

A BA 330 module weighs 20-23 tonnes, whereas an Atlas V Heavy can deliver 29 tonnes to LEO. Therefore, in order to reduce the amount of supplies to be brought with the construction crew, the central core of the BA 330 will be packed with as much food, water and other supplies as possible.

At least 5-6 launches are necessary to build *Adeona*:

1. Atlas V Heavy delivers deflated BA 330, packed with food and water, to LEO. The BA 330 module is then inflated.

2. Falcon Heavy launches cruise stages (fuelled) to LEO. Cruise stages docked to BA 330. Estimate 3-4 launches.

3. Falcon 9 launches DragonRider with extended trunk, carrying a construction crew of two, plus equipment and supplies including tools, floor and wall panels, furniture flat packs (Ikea), computers, laboratory equipment, beds, exercise equipment, personal items, etc.

4. Construction crew spend 2-3 weeks transferring equipment and constructing the interior of *Adeona*.

5. Construction crew returns to Earth in the now-empty DragonRider.

6. Repeat steps 3-5 if required for additional fit-out or supply.

Additional Falcon 9 launches will be necessary for one or more on-orbit training exercises, and to deliver Alpha Crew to *Adeona* prior to TMI.

The Hab

The Mars Surface Habitat, a.k.a. “the Hab”, is a custom-built piece of hardware designed to accommodate a crew of six astronauts on the surface of Mars. It must therefore include cabins, common areas (kitchen/dining), laboratories and other work areas, ECLSS and power systems.

The intention for the Hab is that it will also include ISRU equipment capable of making water and air from the Martian atmosphere, in order to maintain supplies for the crew and compensate for losses due to leakage, recycling, airlock cycling and other factors. It therefore includes appropriate tanks to store sufficient quantities of these fluids.

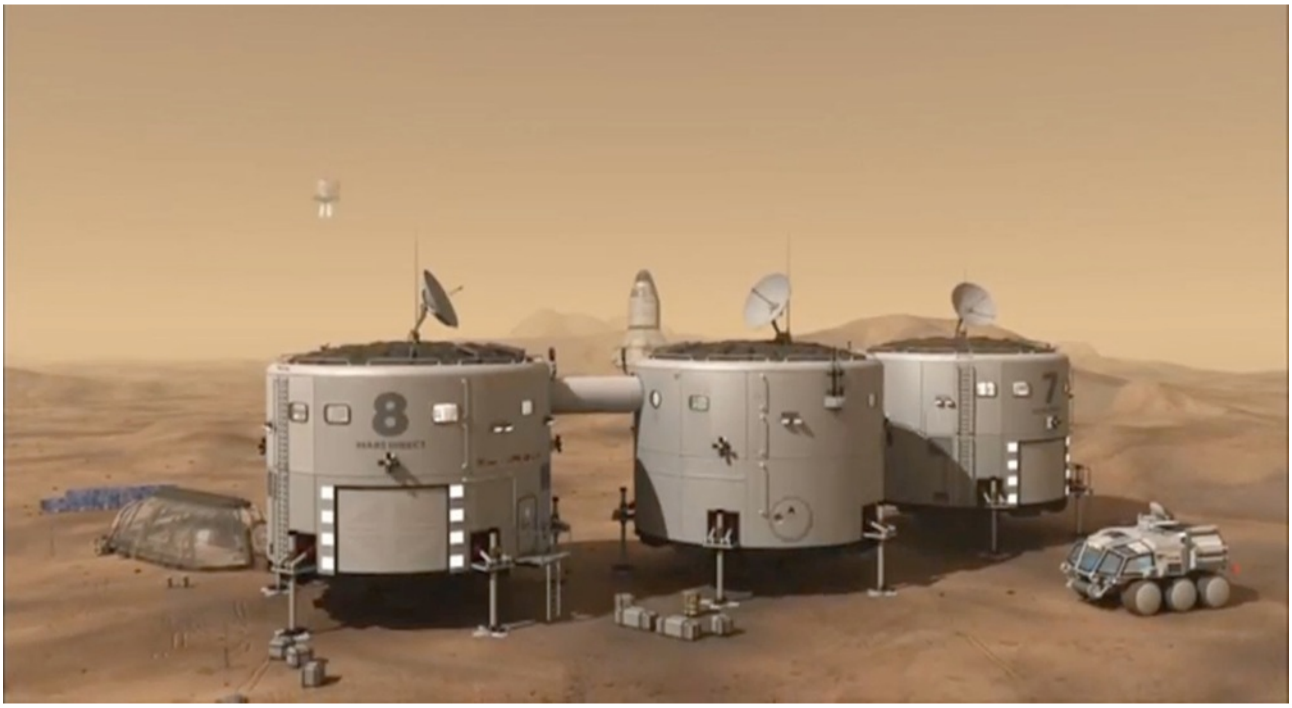
The Hab may also include inflatable modules, inspired by the work of Dr. Janek Kozicki (Kozicki, 2011). These will be inflated using oxygen and nitrogen obtained from the Martian atmosphere during the 26 months between arrival of the Hab and arrival of Alpha Crew.

As discussed earlier, the Hab is landed uncrewed for reasons of improved safety and reduced program cost. It is to be sent to Mars at approximately the same time as the MAV and landed nearby (within approximately 1 km). On arrival at Mars surface:

- Rolls of photovoltaic fabric will be unrolled with the help of the Rover, and the power system will be activated.
- Hatches containing inflatable modules will open.
- The ISAP unit will be activated and harvesting of O_2, N_2 and H_2O will commence.
- The inflatable modules will inflate, and the water tanks will fill.
- Once the hab is inflated, the O_2 and buffer gas tanks will also fill.

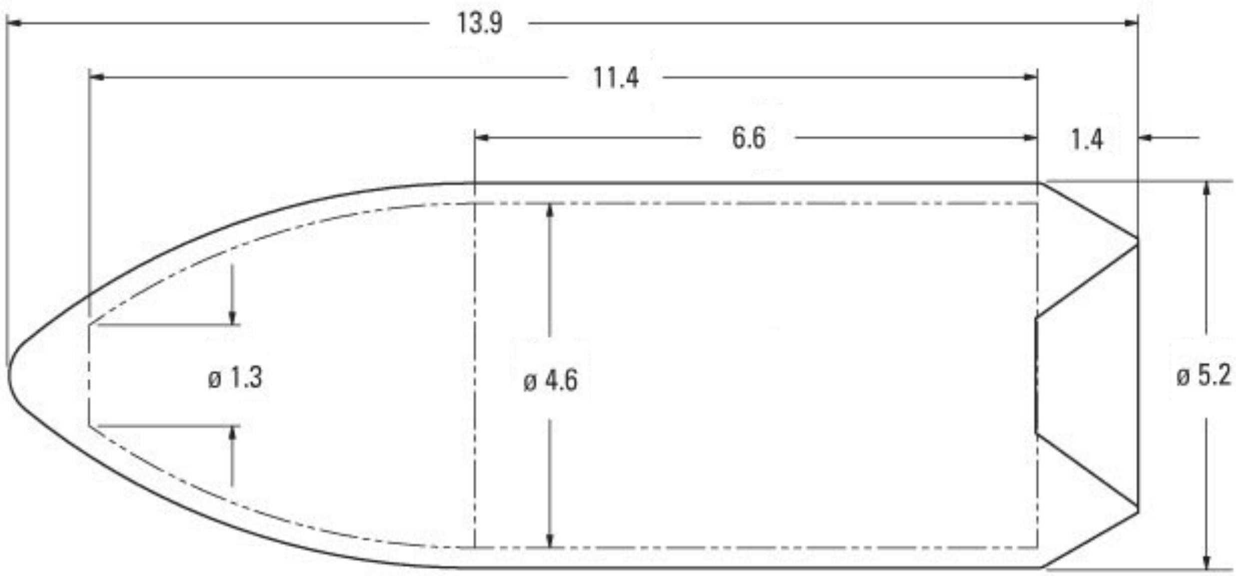
Design

For the basic form of the Hab, previous architectures such as Mars Direct and DRA5 have primarily focused on a vertical cylinder, or the so-called “tuna can” model:

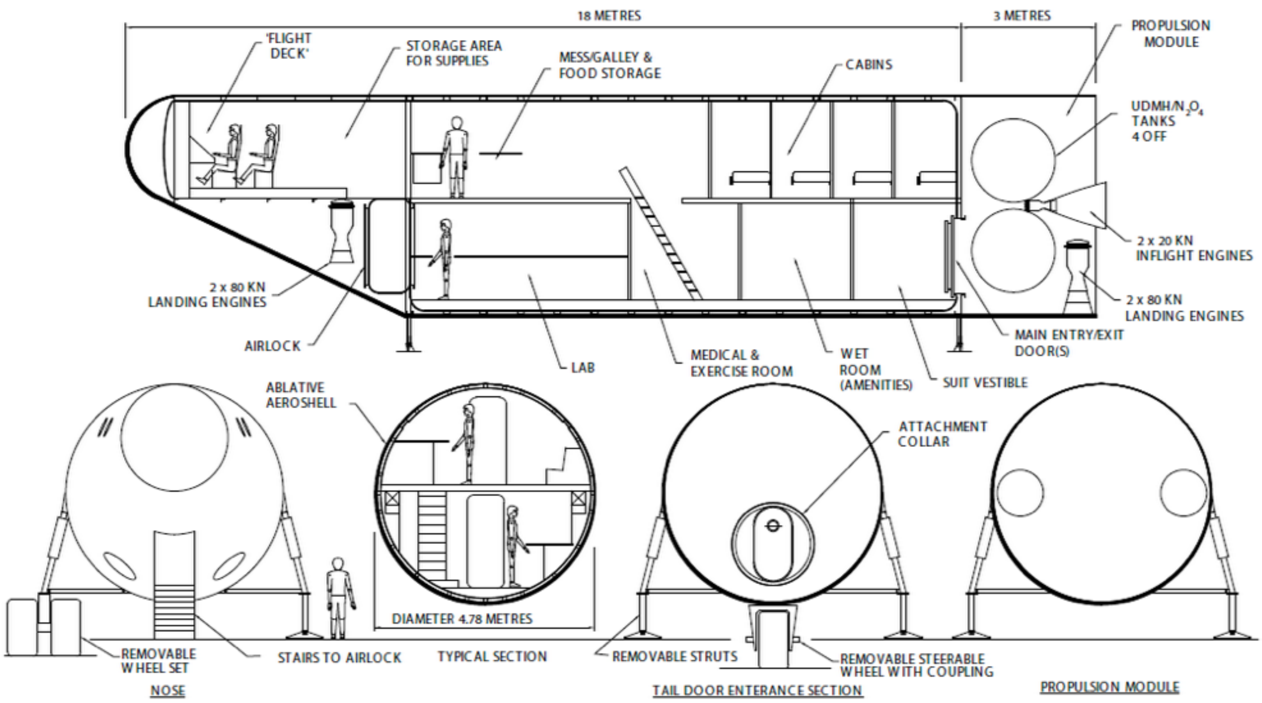


This design of habitat usually has a diameter of around eight metres. This will fit inside the fairing of a Space Launch System heavy lift rocket, which will have a diameter of 8.4 metres. The proposed SpaceX super-heavy lift vehicle called the Falcon X will also have a fairing diameter of about 8m.

It is preferable, however, to base the architecture around vehicles that are currently available, such as the Falcon Heavy, which can throw 13.2 tonnes to Mars. By using inflatable modules it may be possible to develop a habitat design that will fit within the launch capabilities of a Falcon Heavy. The dimensions of the the Falcon Heavy payload fairing are as follows:



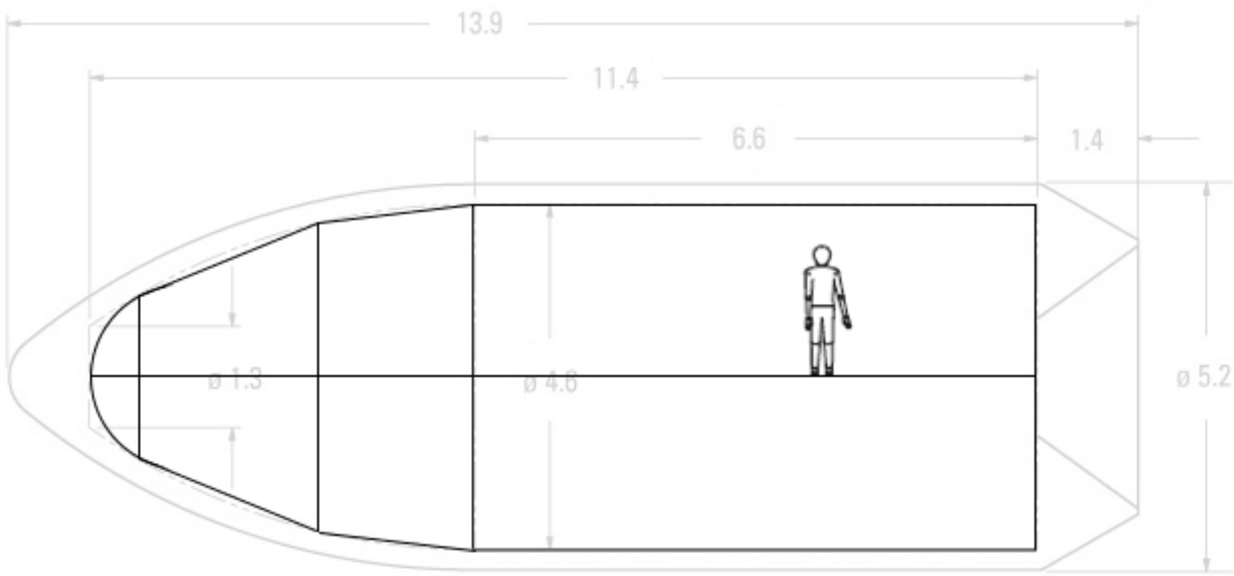
Although a diameter of 4.6m would probably not work for a vertical cylinder configuration, it may be suitable for a horizontal cylinder. Jonathan Clarke and David Willson from Mars Society Australia have studied horizontal habitats based on a bent sphere-cone design:



The MARS-OZ Habitat

This habitat design is 18m long, with a diameter of 4.78m, which would almost fit inside a Falcon Heavy fairing. It's designed to accommodate a crew of four. This design offers several other advantages. For starters, the bent sphere-cone shape has a better lift-to-drag ratio than the traditional vertical cylinder, and is therefore easier to land. In addition, it can be lengthened by attaching additional sections delivered as part of the cargo module. A horizontal cylinder permits longer cargo length (such as a rover), and a loading ramp with a smaller gradient.

This design will not fit within a SpaceX Falcon Heavy fairing. It's a bit wide, much too long, and the bent sphere-cone shape wouldn't fit into the fairing. But, it can be used as inspiration for one that will fit:



In this sketch the Hab is shown fitting as snugly as possible within the fairing, implying that thrusters, legs, etc., are set into the habitat shape. The fairing can double as an aeroshell during EDL at Mars.

The biconic shape offers a significantly improved lift-to-drag ratio.

Volume issues

This volume may be slightly small if we decide to stick to our desired crew size of six, considering that it must include the ECLSS and ISAP system, and food and water for 1.5 years. However, there are a few things we can do about this:

- Reduce the crew size.
- Send two of them.
- Add inflatable modules.

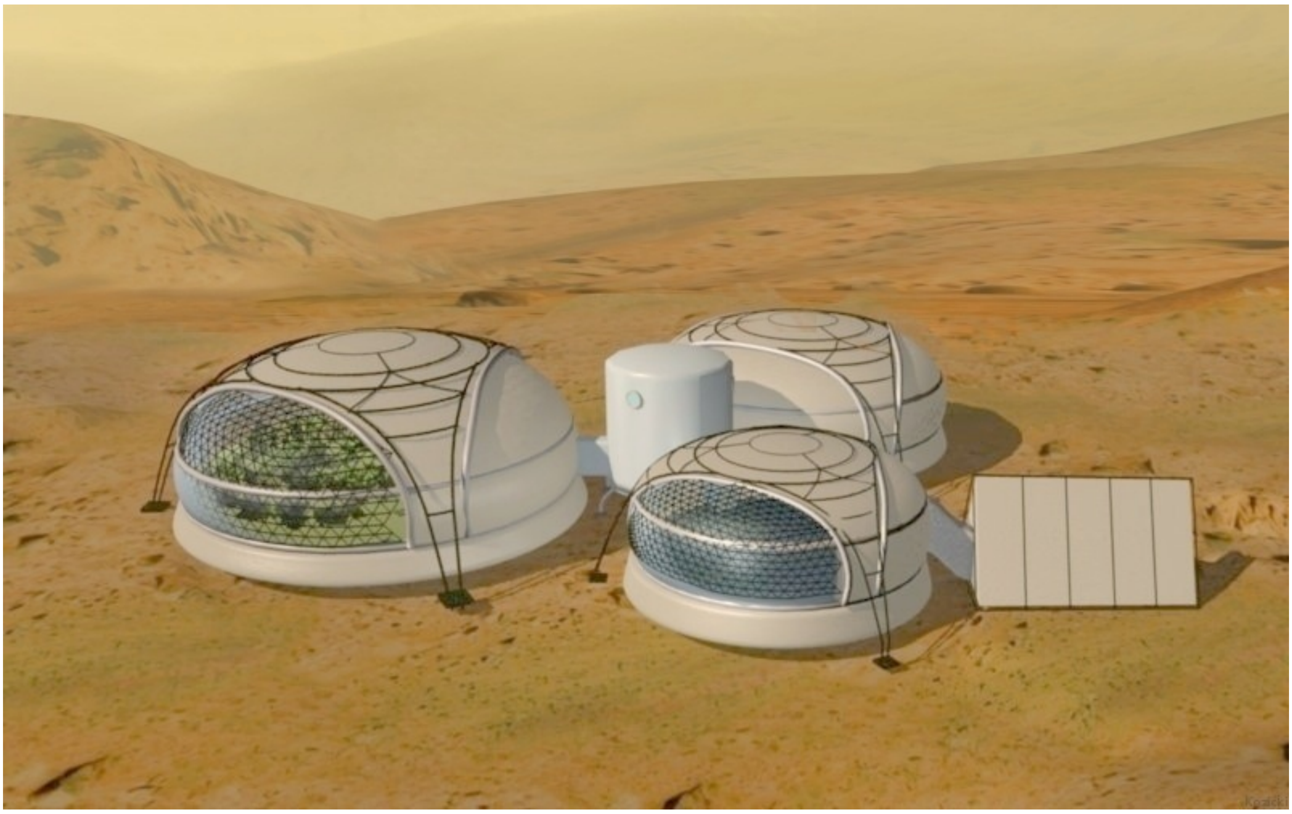
The first option is undesirable - as discussed, a crew size of six is most efficient given the available hardware. However, the second two options are both desirable and achievable.

Sending two habitats at consecutive launch opportunities has a lot of merit, as long as it's affordable. It will enable testing of the habitat EDL system and, if both landings are successful, will provide a redundant backup Hab.

Therefore, in 2029, we send the first Hab. If it crashes or doesn't work, figure out what went wrong and improve the design before sending another in 2031. If the second one lands safely, we can make do with just one. If the first Hab lands safely, however, then we still send a second Hab in 2031, and enjoy the additional living volume.

Inflatables

The idea of adding inflatable modules has been proposed before, including recently by Polish engineer Dr. Janek Kozicki, whose design concept is based on the 8m diameter tuna-can hab described in the DRA, plus several inflatable extensions:

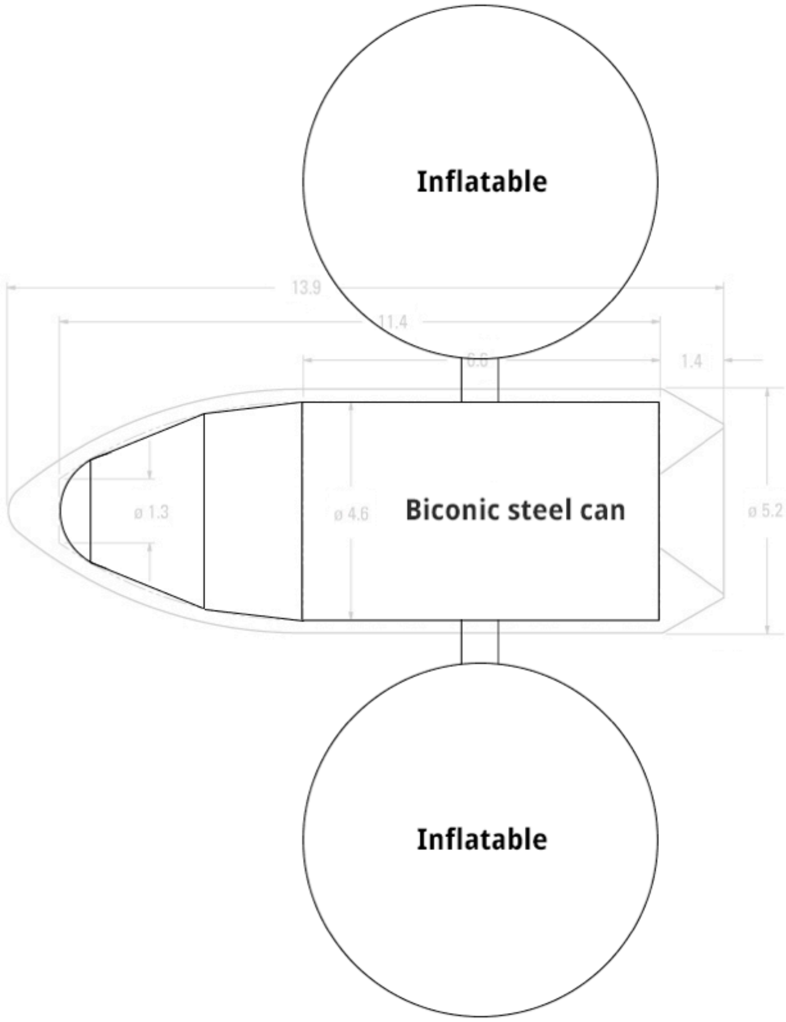


Concept for Mars habitat with inflatable modules

The addition of three inflatable modules to the central hab significantly adds to the total pressurised volume. This is an innovative solution with considerable value, especially when you consider that each Falcon Heavy launch costs $128M. This way we can keep our crew size of six.

In the above image there is so much inflatable material that it couldn't be packed into the central habitat. It would have to be transported separately and attached, probably by the crew, which means they would have to be inflated after crew arrival.

Inflatables like this could be added to our horizontal biconic cylinder as follows:

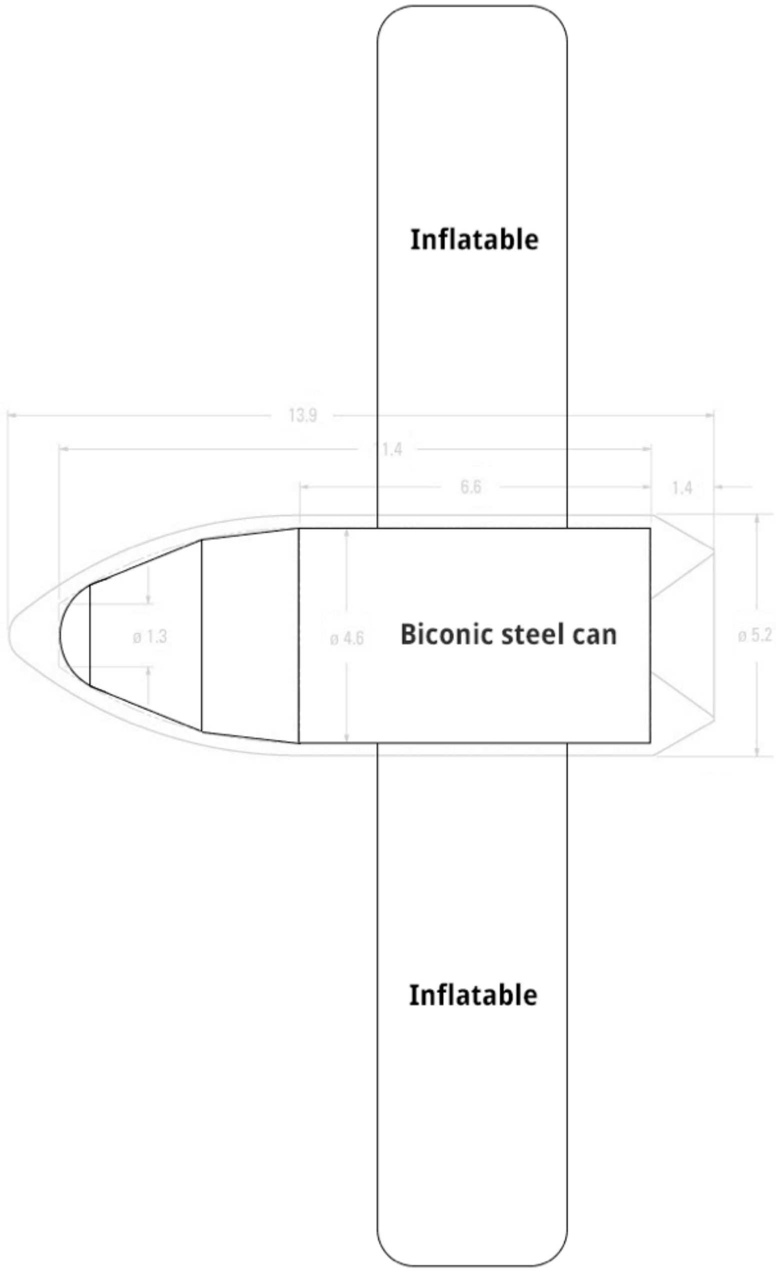


These inflatables are smaller, would be initially packed inside the Hab, and the material would expand outwards, through the doors, as air is pumped into the Hab from the ISAP system. Although this requirement constrains the size of the inflatables, it will still greatly expand the available volume and it would eliminate the need for connecting up the inflatables manually. In other words, the inflatable sections of the above Hab could be inflated before the crew arrive, and potentially before they even leave Earth.

The inflatable material must be strong enough to hold the final atmospheric pressure of the Hab, and needs to be made of (or coated with) a material that will block the strong ultra-violet radiation on Mars. The inflatables may not provide much protection from cosmic rays or solar flares, however, it may be possible to pile dirt on top of them, as well as the central cylinder.

After both the Hab and Rover have landed, the Rover, with its earth-moving attachment, will be remotely operated from Earth and used to pile dirt on top of the Hab, including one of the inflatable sections. The other inflatable section will be left uncovered to allow sunlight in. This will be the greenhouse, sunroom and viewing room, to allow the crew to sit in the sunshine or look out at the Martian landscape for at least a few minutes a day, which will be psychologically beneficial.

Another version, which uses horizontal cylinders for the inflatables instead of vertical, could look something like this:



An advantage of this version is that it would be easier to pile dirt on top of, as the Rover can approach each side of the inflatable and more easily deposit dirt directly over the centre of the roof.

The interior of the Hab will be fitted out with ward rooms and work spaces, ECLSS and ISAP systems, storage tanks and food. In addition, the free volume in the Hab will be packed with the inflatable material. If mass and volume permits, equipment (e.g. lab equipment, hydroponics) and furniture flatpacks to be installed in the inflatables will also be packed in the Hab. Any supplies and equipment that will not fit into the Hab due to mass or volume constraints will be delivered in Cargo Dragons.

An additional inflatable could be attached to the rear of the biconic can, depending how much mass and volume is available.

Mass issues

The Falcon Heavy can only throw 13.2 tonnes to Mars, which must include the Hab as well as the engines and fuel for EDL (Entry, Descent and Landing). Yet most estimates of habitat mass for a humans-to-Mars mission are at least 30 tonnes. Further calculations are necessary to determine if launching the Hab using a Falcon Heavy is realistic, even if we use inflatable extensions and deliver supplies separately. If not, there are two options:

1. Like *Adeona*, the Hab can be constructed from two separate parts that are connected on orbit: the Hab itself, plus a cruise stage that will handle TMI and Mars EDL.

2. Design a larger Hab and deliver it using a super-heavy lift rocket such as an SLS, Falcon X or Long March 9.

The Rover

The architecture calls for a very capable, multi-purpose pressurised Mars rover (“the Rover”). This versatile vehicle will be central to the surface mission from beginning to end. Being a rather large and heavy vehicle (estimate 3-8 tonnes), the intention is to deliver this separately using a Falcon Heavy.

1. On arrival, the Rover will explore the surrounding environment seeking out, and forming, safe pathways between base components (e.g. between the LZ of *Pern-1* and the Hab). They will also locate suitable regolith that may be used for Hab shielding.

2. The Rover may assist the MAV and the Hab in deployment of their photovoltaic blankets, or this may be more effectively achieved using the AWESOM rover.

3. The Rover will pick up the crew from the LZ when they first arrive, then transport them to the Hab.

4. With the earth-moving attachment, the Rover will be used to clear “roads”, and for piling dirt on top of the Hab.

5. The Rover will be used on a regular (daily to weekly) basis for exploring the surrounding environment.

6. At the end of the surface mission, the Rover will carry the crew and their samples from the Hab to the MAV.

Since the Rover will pick up the whole crew from the LZ of *Pern-1*, it must have a seating for the whole crew of six.

The Rover will have radio communications. It will constantly report its current condition (atmospheric atmosphere, pressure and constituents; levels of oxygen, buffer gas, water and food; amount of charge) to the Hab, where the control room is located. In this way the Rover can be monitored while the batteries (or graphene supercapacitors) charge in the Sun. Also, the crew at the Hab could be alerted to potential Rover-related problems while other crew members are out exploring with the Rover.

Airlock and dust mitigation

The Rover will not have suitports, because, as discussed, these are too bulky to wear in the DragonRider capsule, and it would be impractical to have six suitports on the Rover. Instead, the Rover will have an airlock that can accommodate two people at a time. For the whole crew to enter or exit, it will therefore need to be used three times. However, for normal usage only 2-4 people will use the Rover at a time.

In order to mitigate dust migration into the vehicle, and therefore the potential of any dust-related respiratory issues, the airlock will include two powerful handheld vacuum cleaners. The two people in the airlock will use these to remove as much dust as possible from their own and each other's suits. The dust will be blown outside.

Arms/Manipulators

The Rover will have two powerful robotic arms, one on each side, that can be controlled from within the vehicle, or remotely from MCC.

The arms will have grippers that may be used for several purposes:

- Picking up rocks and placing them in sample boxes at the sides of the Rover.
- Picking up heavy pieces of equipment or cargo so they can be relocated.
- Gripping and moving the earth-moving bucket.

Earth-moving capability

The Rover will have an earth-moving attachment that can be easily attached or detached. This can be used for making smooth paths between major base components such as *Pern-1*, the Hab and the MAV.

When the Hab is inflated, the Rover's earth-moving capability will also be used to pile dirt on top of the Hab perhaps also one or all of the inflatable sections. This will provide additional radiation protection and thermal insulation.

Power system

The Rover will be electric and solar. The Rover will have high-efficiency solar panels on the roof, and solar energy will be used preferentially. The Rover will also have batteries or graphene supercapacitors to provide additional power. These would be charged by the solar panels when surplus solar energy is available; for example, when the Rover is not in use.

Electric vehicle technology is currently receiving considerable investment by the automobile industry, and advancing at a rapid rate. Battery technology in particular has improved considerably in recent years, especially since the emergence of Tesla Motors.

Although it should rarely be necessary, since, for safety, the Rover should not be used in low visibility and therefore low sunlight, it should be able to operate from 100% battery power if necessary. When heavy lifting is required, such as when the earth-moving attachment is attached and the Rover is piling dirt on the Hab sections, the batteries can provide additional power.

Features to support marssuits

The intention is that the astronauts will wear their marssuits inside the vehicle, since, generally speaking, they will need to be wearing them before entering and after exiting the vehicle. However, the Rover will have racks along one wall for hanging up backpacks and helmets, and sockets for plugging suit batteries in for recharging.

It is possible that the Rover could be used for extended, multi-sol excursions, especially to distant locations. In this case, storage for marssuits as well as casual clothes would be useful, as would narrow bunks.

Marssuits and airlocks

Marssuits

Neither the Hab nor Rover will have suitports. Because the entire crew are landing in a Dragon capsule, and must transfer to the Rover on arrival, it is impractical that they should be wearing suits designed for suitports, as these are large and bulky. In addition, it would not be practical to have six suitports built into the Rover.

Instead, it's assumed that MCP (Mechanical Counter-Pressure) suits, also known as SAS's (Space Activity Suits), will be available in the timeframe of the mission, as these are already reasonably well-advanced and are a field of active research. These are skintight suits, somewhat like SCUBA wetsuits, with a solid helmet and backpack.

The backpack, helmet and hard-shell parts of the suit contain life-support, communications, navigation and computing technology.

Airlocks

Both the Rover and Hab will have an airlock that will permit two people at a time to enter or exit.

One advantage of suitports is that they prevent migration of dust into the vehicle or habitat. When lunar dust migrated into the Apollo Lunar Excursion Modules, the astronauts experienced a number of respiratory issues. Although Martian dust is quite dissimilar to lunar dust, there is naturally a risk that similar problems could occur; for example, Martian dust is known to be high in perchlorates, which causes thyroid dysfunction. Therefore, dust migration into the Hab and Rover must be kept to a bare minimum.

To solve this problem, the airlocks in both the Hab and the Rover will be fitted with two powerful handheld vacuums with brushes. After entry from the Martian surface into the airlock, during the 20 minutes or however long it takes to exchange the Martian air for breathable air, the two crew members will use the handheld vacuums to clean their own and each other's suits as meticulously as possible. The dust captured by the vacuum will be blown outside.

Suit storage and recharging bay

Inside the Hab will be racks to hang up to six marssuits. Two spare suits will be transported to Mars with the Hab, along with patch kits.

The suits will be powered by rechargeable battery packs, most likely Li-ion or graphene supercapacitors. In the area in the Hab where the suits are stored, and also in the Rover, there will be charging sockets where the suits' battery packs can be recharged from the Hab or Rover's power system.

Precursor Missions

The human missions to the Moon, Apollos 11-17, succeeded because the preceding hardware tests and Apollo missions tested and proved each element of the target mission.

A program of precursor missions is not often described in conjunction with H2M architectures, perhaps because of the exorbitant cost of sending packages to Mars, or perhaps because the human mission itself is complex enough to describe. However, if the Red Dragon technology can indeed reliably deliver a 1-2 tonne package to Mars surface for under $200M per launch, including capsule, we can afford, and should implement, a program of precursor missions that prove and develop the technology and build the necessary confidence for the human missions.

Green Dragon

Green Dragon is a precursor to Blue Dragon; a proposed mission program that will land 1-3 Dragon capsules on Mars containing integrated ISRU hardware capable of manufacturing several important products from local Martian resources.

Green Dragon builds on the success and findings of the *Ice Dragon* mission, and is designed to advance our capabilities and build confidence in two main areas: EDL and ISRU.

EDL (Entry, Descent and Landing)

One of the main reasons for Green Dragon is to gain further practice landing Red Dragon capsules on Mars, refine the technology, and build confidence that this can be done repeatably and safely. If Mars One is successfully implemented before Blue Dragon, then arguably this EDL system will have been proven. However, either way, the more experience we have, the better.

Ideally we will have the opportunity to construct a Green Dragon mission using both small and large Dragon capsules.

It is also necessary to test and, if possible or necessary, improve the accuracy of landing.

By the time we land a crew on Mars in a DragonRider, we will ideally have landed a minimum of four Red Dragon capsules:

- 1 for Ice Dragon
- 1 for Green Dragon
- 2+ cargo capsules for Blue Dragon
- Any launched by Mars One

The more Red Dragon capsules we land on Mars before sending humans, the more confidence we will have in the technology before using a DragonRider to land a crew on the surface of Mars. We need to know exactly how the capsule behaves during EDL to Mars, how it interacts with the Martian atmosphere and surface (especially dust), how to land one of these things on a dime, and where the strengths and weaknesses are in this approach. This knowledge can only be obtained with practice.

ISRU (In Situ Resource Utilisation)

The intention is to test ISRU systems for producing LOX/LCH4 bipropellant, water, and breathable air (O_2 and buffer gas) and, potentially, to create backup caches of resources near the IMRS.

A design goal of Blue Dragon is to not take any hydrogen, water, air or ascent propellant to the surface of Mars, but to obtain these from local resources. Developing the necessary technology to achieve this will greatly reduce the mass of consumables that need to be transported to Mars, both now and in the future, thus reducing the cost of Mars exploration.

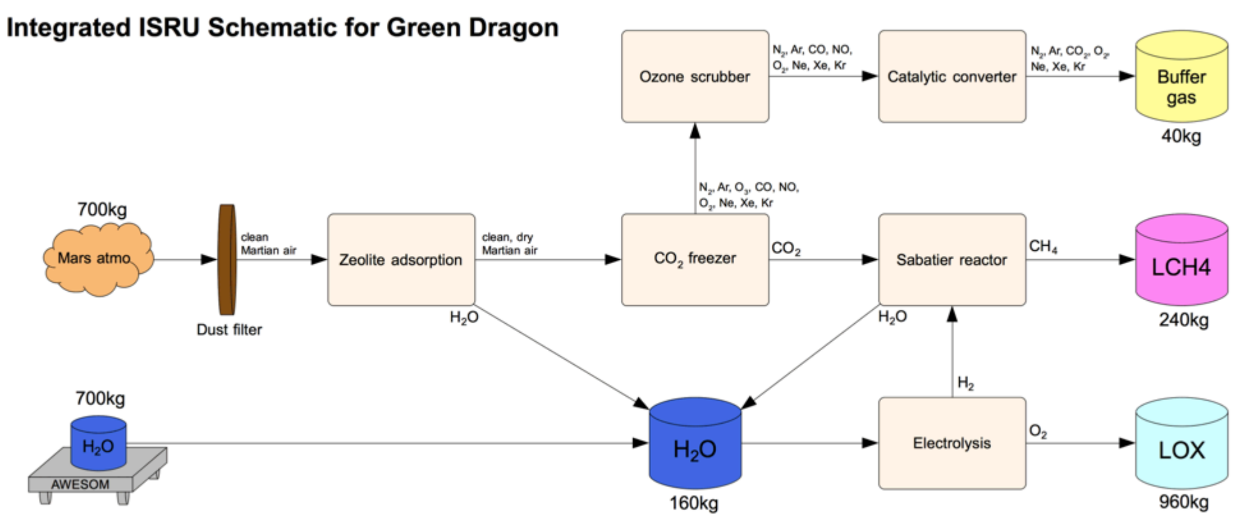
Proposals for ISRU tech for Mars have traditionally been fairly conservative, mainly because these resources are in the critical path for the mission and no-one wants to risk LOC. However, with the success of recent, complex missions such as *Spirit*, *Opportunity*, *Phoenix* and *Curiosity*, we can afford to be more confident. The purpose of the Green Dragon program is to increase the TRL of ISRU technology in preparation for sending humans to Mars.

Green Dragon contains a set of three integrated ISRU experiments:

ISWP (In Situ Water Production) - Water is extracted from the surrounding regolith using microwave radiation and a small rover.

ISPP (In Situ Propellant Production) - Water is electrolysed into hydrogen and oxygen; hydrogen is reacted with carbon dioxide (CO_2) to produce methane (CH_4).

ISAP (In Situ Air Production) - Oxygen is obtained by electrolysis of water; buffer gas is produced by cleaning the gas mix that remains after dust, water and carbon dioxide is removed from Martian air.



Green Dragon will be powered by photovoltaic fabric in the same way as the MAV; however, energy can also be produced by burning manufactured LCH4 and LOX in a fuel cell.

The integrated ISRU approach proposed for Green Dragon is similar to the work done on the MARCO POLO mission (Interbartolo *et al.*, 2013).

Gold Dragon

Gold Dragon is simply a MAV test. Launching from the surface of Mars is one of the greatest challenges in a humans-to-Mars architecture, which is why it was omitted from Mars One, and why many people favour one-way architectures.

Nonetheless, considering SpaceX's *Grasshopper* RLS technology, Masten Space Systems' *Xombie* rocket, Blue Origin's *New Shepard* VTOL rocket, and other developments currently underway in the space industry, it seems very likely that a vehicle that can be adapted for Mars ascent will be available in the near term; certainly within the time frame of the Blue Dragon architecture.

The MAV in the Blue Dragon architecture performs EDL at Mars. Then the propellant for the ascent stage is manufactured from local Martian resources. At the end of the surface element, the ascent stage plus DragonRider capsule launches from Mars, leaving the descent stage and ISPP hardware behind. On reaching space, the ascent stage separates and falls back to Mars, and the DragonRider performs MOR with the MTV. All of these operations are more-or-less impossible to properly test on Earth, and it would be risky (possibly unacceptably so) to attempt to launch humans from the surface of Mars without having tested this launch system at least once.

The Gold Dragon MAV will be flown to Mars, landed somewhere close to the proposed IMRS base, fuelled and launched to Mars orbit. As there will be no MTV in orbit at the time, the only part of MAV lifecycle that would not be tested would be docking of the DragonRider. It could be picked up later, or allowed to fall back to Mars.

The intention is to send a Gold Dragon mission at least once, and perhaps again if results indicate that the vehicle needs to be further improved before it can be declared human-rated.

Conclusions

Like the DRA, this architecture is incomplete. Considerable work still needs to be done, particularly on the transportation, habitation, EDL, ISRU and ECLSS systems, and the schedule of crew activities for both the surface and space elements.

However, several improvements on the DRA are described that will greatly improve the viability and outcomes of the architecture and the program:

1. Adopting a base-first strategy, send all three missions to the same location, rather than a single location. This will significantly reduce costs through reuse of major hardware components, in particular the habitat, surface vehicles (rovers), ISRU equipment and communications satellite.

2. Land the crew in a capsule rather than a habitat. This saves costs by enabling a single habitat to be reused for multiple missions (as above), and is also significantly safer, making use of an EDL system (Red Dragon) that will have been tried and tested several times already.

3. Make use of existing commercial hardware where possible in order to reduce costs and support the development of the burgeoning global space industry. Incorporate commercial partners into the program and encourage intra- and international networking and collaboration.

4. Make more ambitious use of ISRU to manufacture propellant, potable water and breathable air from the local Martian environment. Achieving this is technically straightforward, greatly reduces launch mass and therefore cost, and develops key enabling technologies for settlement of Mars. Robotic precursor missions to demonstrate ISRU capabilities will be worth the investment.

5. Manufacture buffer gas more cheaply than has been previously proposed by simply removing dust and carbon dioxide from the Martian air, and scrubbing out harmful constituents such as ozone, carbon monoxide and nitric oxide.

6. Use mechanical counter pressure, zero pre-breathe suits for use on Mars, which will greatly improve mobility, reduce crew fatigue, and save time.

7. Avoid nuclear thermal rockets and instead use chemical propulsion engines, which are cheaper, safer, have a higher TRL, and are available as COTS products.

8. Avoid the use of artificial gravity in the Mars Transfer Vehicle, thereby reducing costs and complexity. Counteract the effects of microgravity using osteoporosis drugs, resistance training and correct nutrition.

9. Instead of discarding the entire MTV, perform EOI on return to Earth and launch a new DragonRider capsule up to rendezvous with the spacecraft and ferry the crew back to Earth. This permits reuse of the space habitat (saving money plus psychological benefits), results in a much safer EDL at Earth with reduced velocity and g-forces (no need for a customised capsule, as a standard and therefore cheaper DragonRider will do), avoids the need to transport a capsule to Mars and back simply for Earth EDL.

10. Provide the crew with a diet of 100% powdered food, similar to Soylent, in order to maintain optimal health and mental clarity, produce waste with predictable constituents, reduce amount of solid waste produced (thereby resulting in a lower mass system for processing it), greatly reducing packaging and associated waste, save time spent preparing meals, reduce water required for washing dishes, and eliminate refrigeration and food preparation equipment and the associated mass, power requirements, and cost.

11. Conduct the program as an international consortium of the world's top 10 space agencies. Establish an International Mars Research Station and a permanent human presence on Mars, drawing on the experience gained from the International Space Station and the Mars Analog Research Station program. This strategy will serve to distribute the cost across multiple partners, is highly beneficial for international cooperation and world peace, and demonstrates to everyone that Mars is being opened for all humanity rather than a single Earthian nation or ideology. Future exploration missions can be launched from the IMRS far more cheaply than from Earth.

Acronyms

Numerous acronyms appear in this document; all are listed here for easy reference. They are drawn primarily from the space literature, with a few adopted from military and mining, and a few newly invented for the purpose of this document

To reduce the need to reference this page, acronyms are expanded on first usage. Acronyms specific to the architecture are highlighted in orange.

AEB	Agência Espacial Brasileira	The space agency of Brazil.
AG	Artificial Gravity	An artificial sensation of gravity, usually produced using centripetal force.
ATV	All Terrain Vehicle	A quad bike suited for driving on rough terrain, such as on Mars.
AWESOM	Autonomous Water Extraction from the Surface Of Mars	A method for robotically mining water from Martian regolith.
BPS	Ballistic Protection System	A system, technology or device for providing protection against projectiles (e.g. micrometeorites). See RPS, TPS.
CDR	Commander	The person in charge of the mission.
CME	Coronal Mass Ejection	Massive burst of electrons, ions and atoms from the Sun's corona into space.
CNSA	China National Space Administration	The space agency of China.
COTS	Commercial Off The Shelf	A component that can be purchased from a commercial vendor, rather than custom-designed and built from scratch.
CSA	Canadian Space Agency	The space agency of Canada.
DCS	Decompression Sickness	A condition arising from bubbles of gas (typically nitrogen) forming inside the body on depressurisation; commonly called "the bends".
DRA	Design Reference Architecture	A description of NASA's fundamental architecture and assumptions for sending humans to Mars.
DRM	Design Reference Mission	What the DRA used to be called before v5.
ECLSS	Environment Control and Life Support System	A system for maintaining the internal atmosphere of a vehicle or habitat at the right pressure, temperature and composition to support human life.
EDL	Entry Descent and Landing	Process of landing a spacecraft on a planet with an atmosphere.
EHA	Extra-Habitat Activity	When an astronaut goes outside a surface habitat wearing a spacesuit.
EOI	Earth Orbit Insertion	An orbital manoeuvre that moves a spacecraft into Earth orbit.
EOR	Earth Orbit Rendezvous	When two spacecraft meet and dock in Earth orbit.
ERV	Earth Return Vehicle	A vehicle to carry humans from Mars to Earth.
ESA	European Space Agency	The space agency of Europe, comprised of 20 member nations.
ETO	Earth To Orbit	A movement from the surface of Earth to Earth orbit.
EVA	Extra-Vehicular Activity	When an astronaut goes outside a vehicle (e.g. spacecraft or rover) wearing a spacesuit.
FMARS	Flashline Mars Arctic Research Station	A MARS in Haughton Crater on Devon Island, Nunavut in the Canadian Arctic.
GNC	Guidance, Navigation and Control	System for monitoring and controlling the position and movements of a spacecraft.

GPS	Global Positioning System	A navigation system that can pinpoint your location anywhere on Earth.
H2L	Humans to Luna	A type of space mission that sends humans to Luna (the Moon).
H2M	Humans to Mars	A type of space mission that sends humans to Mars.
ICT	Information and Communications Technology	Computer hardware and software, networking, internet, receivers, transmitters, communications satellites/beacons.
IMRS	International Mars Research Station	The goal of the Blue Dragon program.
ISA	Iranian Space Agency	The space agency of Iran.
ISAP	In Situ Air Production	Producing breathable air at a location, e.g. Mars.
ISFP	In Situ Food Production	Producing food at a location, e.g. Mars.
ISPP	In Situ Propellant Production	Producing rocket propellant at a location, e.g. Mars.
ISRO	Indian Space Research Organisation	The space agency of India.
ISRU	In Situ Resource Utilisation	Making use of resources from the local environment (e.g. space, Mars) rather than relying on resources brought from Earth.
ISS	International Space Station	A space station built by international partners.
ISWP	In Situ Water Production	Producing water at a location, e.g. Mars.
IVA	Intra-Vehicular Activity	When a crew member is inside the spacecraft.
JAXA	Japan Aerospace Exploration Agency	The space agency of Japan.
JSA	Job Safety Analysis	Risk assessment tool to identify and control workplace hazards.
KARI	Korea Aerospace Research Institute	The space agency of South Korea.
LCH4	Liquid Methane	A versatile and inexpensive rocket fuel.
LEO	Low Earth Orbit	An orbit around Earth that is low (e.g. the ISS is in LEO at about 300k up).
LFTR	Liquid Fluoride Thorium Reactor	A new type of nuclear reactor that is especially safe and economical.
LH2	Liquid Hydrogen	Hydrogen in liquid form, as used in rocket propellant.
LION	Landing with Inertial and Optical Navigation	An algorithm for pinpoint landing that uses a database of major landmarks.
LMO	Low Mars Orbit	An orbit around Mars that is low.
LOC	Loss Of Crew	Something bad that could happen during a mission.
LOM	Loss Of Mission	Not as bad as LOC, but still, it's not what we want.
LOX	Liquid Oxygen	Oxygen in liquid form, as used in rocket propellant.
LPS	Local Positioning System	A navigation system that covers only a small area of land (c.f. GPS), usually defined by three or more signalling beacons.
LZ	Landing Zone	An area where aerial or aerospace vehicles can land.

MA365	Mars Arctic 365	A 365-day simulated Mars mission to FMARS, commencing in 2014.
MARS	Mars Analog Research Station	A simulated Mars base built in a Mars-like environment on Earth, where simulated missions are conducted.
MARS-OZ	Australian Mars Analog Research Station	A simulated Mars base to be built near Arkaroola in South Australia.
MAS	Mars Activity Suit	An MCP marssuit. See MSS, SAS.
MAV	Mars Ascent Vehicle	A vehicle to carry people from Mars surface to Mars orbit.
MCC	Mission Control Centre	Entity comprised of engineers, flight controllers, etc., that manages a space mission from start to finish.
MCP	Mechanical Counter-Pressure	A style of skin-tight spacesuit similar to a wetsuit; contrasts with a more traditional gas pressurised spacesuit.
MDRS	Mars Desert Research Station	A MARS in Hanksville, Utah.
MER	Mars Exploration Rover	Refers to the twin rovers *Spirit* and *Opportunity* that have spent many years exploring Mars.
MEV	Mars Excursion Vehicle	A pressurised rover for driving around on Mars.
μg	Microgravity	Weightlessness, also called zero gravity.
MOI	Mars Orbit Insertion	An orbital manoeuvre that moves a spacecraft into Mars orbit.
MOLA	Mars Orbiting Laser Altimeter	A spacecraft orbiting Mars that records topographical data.
MOR	Mars Orbit Rendezvous	When two spacecraft meet and dock in Mars orbit.
MSH	Mars Surface Habitat	A habitat for the surface of Mars.
MSL	Mars Science Laboratory	A robotic spacecraft currently on Mars that is tasked with climbing to the top of Mt Sharp while snapping photos and performing geochemical analysis.
MSS	Mars Surface Suit	A spacesuit for the surface of Mars (a.k.a. “marssuit”).
MTO	Mars To Orbit	A movement from the surface of Mars to Mars orbit.
MTV	Mars Transfer Vehicle	A vehicle to carry humans from Earth to Mars.
NASA	National Aeronautics and Space Administration	The space agency of the United States government. The most successful space agency in Mars exploration.
NTR	Nuclear Thermal Rocket	An especially high-thrust propulsion system in which reaction mass is heated to a high temperature in a nuclear reactor.
OMS	Orbital Manoeuvring System	A system for manoeuvring a spacecraft in orbit.
OTE	Orbit To Earth	A movement from Earth orbit to the surface of Earth.
OTM	Orbit To Mars	A movement from Mars orbit to the surface of Mars.
PHP	Permanent Human Presence	When there is always one or more people at a location.
PHP-L	Permanent Human Presence on Luna	When there is always one or more people on the Moon.
PHP-M	Permanent Human Presence on Mars	When there is always one or more people on Mars.

PLSS	Personal Life Support System	Part of a spacesuit that handles life support functions.
PV	Photovoltaic	Capable of converting light into electricity, as in photovoltaic panels, also known as solar panels.
RH	Relative Humidity	The water vapour partial pressure as a degree of saturation at the given temperature.
RLS	Reusable Launch System	A rocket that can be reused many times.
RKA	Russian Federal Space Agency	The space agency of Russia.
ROI	Return On Investment	What you get back from an investment in a project or business.
RP-1	Rocket Propellant-1 *or* Refined Petroleum-1	A type of kerosene used as rocket fuel.
RPS	Radiation Protection System	A system, technology or device for providing protection from radiation. See BPS, TPS.
RTG	Radioisotope Thermoelectric Generator	An electrical generator that obtains its power from radioactive decay.
RWGS	Reverse Water Gas Shift	A useful chemical reaction for making O_2 from CO_2, when used in conjunction with electrolysis: $CO_2 + H_2 \rightarrow CO + H_2O$
SAS	Space Activity Suit	A mechanical counterpressure spacesuit.
SLS	Space Launch System	A new heavy-lift rocket currently under development by NASA.
TBD	To Be Determined/ Discussed/Decided	Something that hasn't been agreed upon, solved or investigated yet.
TEI	Trans Earth Injection	An orbital manoeuvre that puts a spacecraft on a trajectory towards Earth.
TMI	Trans Mars Injection	An orbital manoeuvre that puts a spacecraft on a trajectory towards Mars.
TPS	Thermal Protection System	A system, technology or device for providing protection from extreme heat or cold. See BPS, RPS.
TRL	Technology Readiness Level	The level of maturity of a technology; an assessment of its suitability for space applications.
UV	Ultra-Violet	Electromagnetic radiation with a frequency higher than visible light but lower than X-rays.
WAVAR	WAter Vapor Adsorption Reactor	A device to extract water from the Martian atmosphere by adsorption in zeolite 3A.

Chemical Symbols

The following elements and molecules are mentioned in this document.

Elements

Chemical symbol	English name	Notes
Ar	argon	An unreactive noble gas. About 1% of the atmosphere of Earth, and about 2% of the atmosphere of Mars. Used in welding.
C	carbon	One of the most useful and abundant of all elements. Definitive element of organic molecules. Found in wood, plastic, steel, diamond, nanotubes and many other materials.
H	hydrogen	The lightest and most abundant element in the universe. The main element in stars, commonly found in water and hydrocarbons.
Kr	krypton	An unreactive noble gas. A minor constituent of the Martian atmosphere.
N	nitrogen	An essential element for life, found in all living things. Comprises about 80% of Earth's atmosphere.
Ne	neon	An unreactive noble gas. A minor constituent of the Martian atmosphere.
O	oxygen	Essential element for life, and extremely abundant - found in water, air as (O_2), and rocks (as oxides).
Xe	xenon	An unreactive noble gas. A minor constituent of the Martian atmosphere.

Compounds

Chemical formula	Name	Notes
CH_4	methane	Simplest hydrocarbon, non-toxic, major constituent of natural gas, great propellant.
CH_3OH	methanol	The simplest alcohol, and a useful fuel.
CO	carbon monoxide	Toxic gas found in car exhausts. Can be used as a fuel.
CO_2	carbon dioxide	Non-toxic in small concentrations, exhaled by animals and consumed by plants via photosynthesis. Comprises about 96% of the atmospheres of both Mars and Venus.
H_2	hydrogen	The lightest and most abundant gas in the universe.
H_2O	water	Essential for life, extremely abundant in the universe, an excellent solvent, we're mostly made of it, our planet is mostly covered in it, you can swim in it, wash in it, throw it on people during Thai New Year, and even drink it.

N_2	nitrogen	Non-toxic. Effective buffer gas. Comprises about 80% of the atmosphere of Earth and about 3% of the atmospheres of both Mars and Venus.
NH_3	ammonia	A metabolism product. Important component of fertiliser.
NO	nitric oxide	A minor component of the Martian atmosphere. Also found in car exhaust gas. Non-toxic.
NO_2	nitrogen dioxide	Brown toxic gas found in car exhaust gas and nuclear explosions.
O_2	oxygen	Inhaled by animals, exhaled by plants. Extremely abundant in the universe, and comprises about 20% of the atmosphere of Earth. In liquid form, a typical oxidiser for rocket propellant.
O_3	ozone	A toxic gas that is nonetheless useful for blocking UV radiation.

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