A PROPOSED MARS BASE DESIGN ADOPTING A HORIZONTALLY LANDED BENT BICONIC VEHICLE

Mars Society Australia

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ABSTRACT

Mars Society Australia has proposed the construction of a simulated Mars Base to explore the technical and physiological issues related to long term living on a similar base on Mars. The project is called MARS-OZ and is one of a series of similar projects constructed under the auspices of the international Mars Society. Others are located in Utah and Devon Island in the Canadian Arctic. A third has been built and will be deployed in Iceland.

The MARS-OZ simulated base employs a different configuration from the other simulated Mars bases. Rather than consisting of vertical cylinders, MARS-OZ employs modules that are based on horizontally landed bent biconic lifting bodies. The MARS-OZ mission concept is based on the 'Mars Semi-Direct' mission architecture, as used by NASA's design reference mission, resized to a four-person crew.

This paper explores the technical issues underlying a horizontally landed bent biconic vehicle and demonstrates the feasibility of the unique MARS-OZ mission concept configuration. The issues of mission architecture, vehicle shape, vehicle mass, a Mars base assembly sequence and interior design to form an extendable long-term integrated base is discussed and evaluated. We conclude that the configuration is overall superior to others with reference to both Mars landing and surface utilisation.

CONTENTS

1. INTRODUCTION AND BACKGROUND

In 2001 Mars Society Australia (MSA) commenced researching design concepts for their proposed simulated Mars base, MARS-OZ [1]. A long, low structure that could be deployed on site as a prefabricated unit was strongly preferred for logistic reasons. Such a configuration was consistent with a range of Mars lander concepts developed in the former Soviet Union by the Energia Group[2] and the International Space University[3] (ISU) that utilised a range of horizontally landed biconic vehicles. A family of biconic landers had also been studied in the United States under the auspices of the "Case for Mars"[4] [5] conference series and others[6]. After considerable discussion and debate a unique Australian design was developed.

The selected design is compatible with 'Mars Semi-Direct' mission architectures[7] used by various iterations of NASA's design reference mission[8] (DRM) and others[9]. Mars Semi-Direct entails the use of 3 vehicles, a Habitat vehicle (or Hab), the Cargo vehicle which both land and a Mars Transfer Vehicle (MTV)[10] that remains in orbit. A Mars Ascent Vehicle (MAV) that is carried within the cargo vehicle lifts the crew from the surface to the MTV in low Mars orbit. The MTV transports the crew back to Earth. Table 1 describes the functions of the MARS-OZ mission proposal vehicles.

This paper only covers the design details of the components that actually land on the Mars surface, the Hab and Cargo Vehicles. In brief the paper covers:

- Why we need to research a Mars Base design, in the light of 30 years of space station design, in section 2;
- The assumptions underpinning the Mars vehicle designs in section 3;
- The functions of the various vehicles and a description of the base assembly sequence on Mars in section 4;
- An assessment of the vehicle bent biconic shape compared to other shapes in section 5;
- The vehicle geometry and dimensions including an overview of the MAV in section 6;
- A brief look at the vehicle design issues for hypersonic flight and the heat shield mass in section 7;
- A discussion of the parachutes and engine design for landing on Mars in section 8;
- A description of the base layout, dust management and base expansion in section 9. This section also covers in detail the process plant and the in-situ manufacture of water, oxygen, methane and carbon monoxide for the crew, MAV and rover as well as the power budget for travelling and living on Mars; and finally,
- The Hab and Cargo vehicle mass budget with their associated low Earth orbit payloads are covered in section 10.

The paper concludes with a discussion of the clear advantages of these horizontally landed bent biconic vehicles as components for Mars bases.

2. WHY RESEARCH A MARS BASE DESIGN?

Previous plans to travel to Mars were focused on travelling to Mars rather than and exploring Mars. The explorers were to spend up to 2½ years in space on spacecraft either en-route to or in orbit around Mars. The actual Mars landing was planed as short visits similar to the Apollo 'sleep overs' on the moon.

However during the last 25 years, time spent in Earth orbit, on space stations has shown that over the long term, loss of calcium from astronaut's bones and the effects of low-level cosmic radiation is accumulative and detrimental to the health of astronauts[11].

In the early 1990's Robert Zubrin[12] planned missions to Mars based on the following criteria:

- The safest place to be during a mission to Mars is on the Mars surface. The time spent in space is to be kept to a minimum and time on Mars is maximised. This is nominally 4 to 6 months per interplanetary transfer and 18 months duration of the surface;
- In-situ manufacturing of fuel for the return journey from the Martian atmosphere can considerably reduce the cost of a Mars mission; and
- The primary mission objective of the first Mars missions is to explore Mars and secure resources for its long-term habitation. The Mars base is to be designed for this purpose.

For these reasons the Mars base structure and functionality becomes the centrepiece for the success of a mission to Mars. The spacecraft travelling to and from Mars are designed to reach the safe haven on Mars as quickly as possible. There has been a 30-year history of design and research of spacecraft fit for long term living in Earth orbit. Examples include Skylab, Salyut, Mir and the International Space Station. Little research or experimentation has been conducted for the design of habitable structures or vehicles for Mars or the moon that suit the above criteria. Before commencing this design process a discussion of the basic assumptions deserves consideration.

3. ASSUMPTIONS

The outcome of the initial MARS-OZ research[13] and further debate resulted in the following design assumptions:

- The preferred architecture is the 'Mars Semi-Direct', as used in various iterations of NASA's DRM and a number of other studies;
- A trans-Mars vehicle mass of 40 to 46 tonnes as recommended by Zubrin[14] is adopted as the basic Habitat and Cargo vehicle mass. This is the payload of the Shuttle-derived Ares booster, a rocket with capacity equivalent to an upgraded Saturn V, can deliver to the Martian surface;

- The vehicle shape is a horizontally landed bent biconic lifting body. It differs from NASA's and Zubrin's various base concepts of two or three deck vertical cylinders.
- The six-person missions used by Mars Semi-Direct and the NASA DRM iterations are downsized to four persons to allow a payload mass as recommended by Zubrin.
- The use of nuclear power on the surface of Mars and nuclear engines for propulsion is to be avoided. Public support and funding for a Mars mission may be reduced due to the risks, perceived and real, involved in launching nuclear reactors. We believe that recent advances in solar cell technology make their use feasible, even with the known losses due to reduced insolation and dust adherence. Our calculations provide a complete power budget on that basis (see section 9.4).
- In-situ fuel production for the MAV ascent to Mars low orbit during the return trip is incorporated as per the Mars Semi-Direct missions.
- The interior design of the Hab is optimised for living on Mars rather than for travelling to Mars. Furnishing suitable for weightlessness during space travel is excluded.
- The issue of reducing radiation on the Martian surface is not discussed. We assume that a Mars base will erect a regolith or water filled roof over the modules to reduce the effects of radiation, if required. The mass of the roof frame is not expected to be high enough to affect the overall outcomes discussed in this paper.

These assumptions raise the following question: can Mars landers based round horizontally landed bent biconic lifting body vehicles work within the constraints of the Mars Semi-Direct Mission Architecture? This is covered in the following section.

4. THE 'MARS SEMI-DIRECT' MISSION ARCHITECTURE AND HORIZONTALLY LANDED BENT BICONIC LIFTING BODY VEHICLES

As discussed in the introduction, 'Mars-Semi Direct' type missions require three vehicles with separate functions. To reduce cost, the vehicles are to share a similar basic design. Our horizontally landed bent biconic vehicles are to fit these functions. These are listed in Table 1.

This paper will leave open the options of whether the crew travel to Mars in the Hab or alternatively in the MTV vehicle, transferring to the Hab in Mars orbit for descent and landing. Assuming the crew, Hab and Cargo vehicle have landed safely on Mars, the base components must be towed together and assembled to form a base. This process was reviewed drawing from the unique Australian mining experience, the outcome shown in Figure 1.

Observations of multi-trailer truck movements on rough mine sites in the Western Australian 'outback' desert regions influenced the assembly sequence as shown in figure 1. The long horizontal Hab and Cargo vehicles match containers and trailers being moved by trucks on these mine sites. The design enables the cargo section, carrying the rover to be easily disconnected from the chemical processing plant and the Mars Ascent Vehicle section. Disconnecting the garage effectively separates the livable portion of the base from the potentially hazardous fuelled up Mars Ascent Vehicle section and chemical processing plant.

Table 1. Vehicle functional description

Vehicle	Function Detail
Hab	Travels to the Martian surface, direct from earth and becomes the core of the Mars base. It consists of a cabin, propulsion module, heat shield, landing engines and parachutes.
Cargo Vehicle	Transports equipment to the Martian surface direct from earth. The equipment consists of a MAV, hydrogen stock fuel, a chemical processing plant, a pressurised rover and surface supplies for the crew. It also has a propulsion module, heat shield, landing engines and parachutes.
Mars Transfer Vehicle (MTV)	Travels to low Mars orbit from earth. It transports the crew back to Earth. It consists of a cabin, landing capsule with heat shield, and propulsion module for Mars escape.

The disconnected garage section can be towed across the Martian surface for short distances by the rover and connected to the Hab. The mine site observations suggest the success and range of this operation is dependant on the rover drive power, wheel size and the traction of the wheels to the ground. We expect a 4 or 6 wheel drive rover with 1.1 metre diameter wheels would move the structures. Thus a base can be assembled from the Hab and Cargo vehicles making efficient use of landed payload mass and increasing the habitat volume. A tubular adaptor module with multiple docking hatches would be required to complete the connection. A growing Mars base can be constructed similar to arranging and connecting containers in construction camps or the early Antarctic bases. The structures would expect to have a minimum life 20 years given the high transport costs. Improvements and upgrades to the base would occur every 2-years matching the 2-year mission cycles.

We can now return to a more detailed look at the vehicle shape.

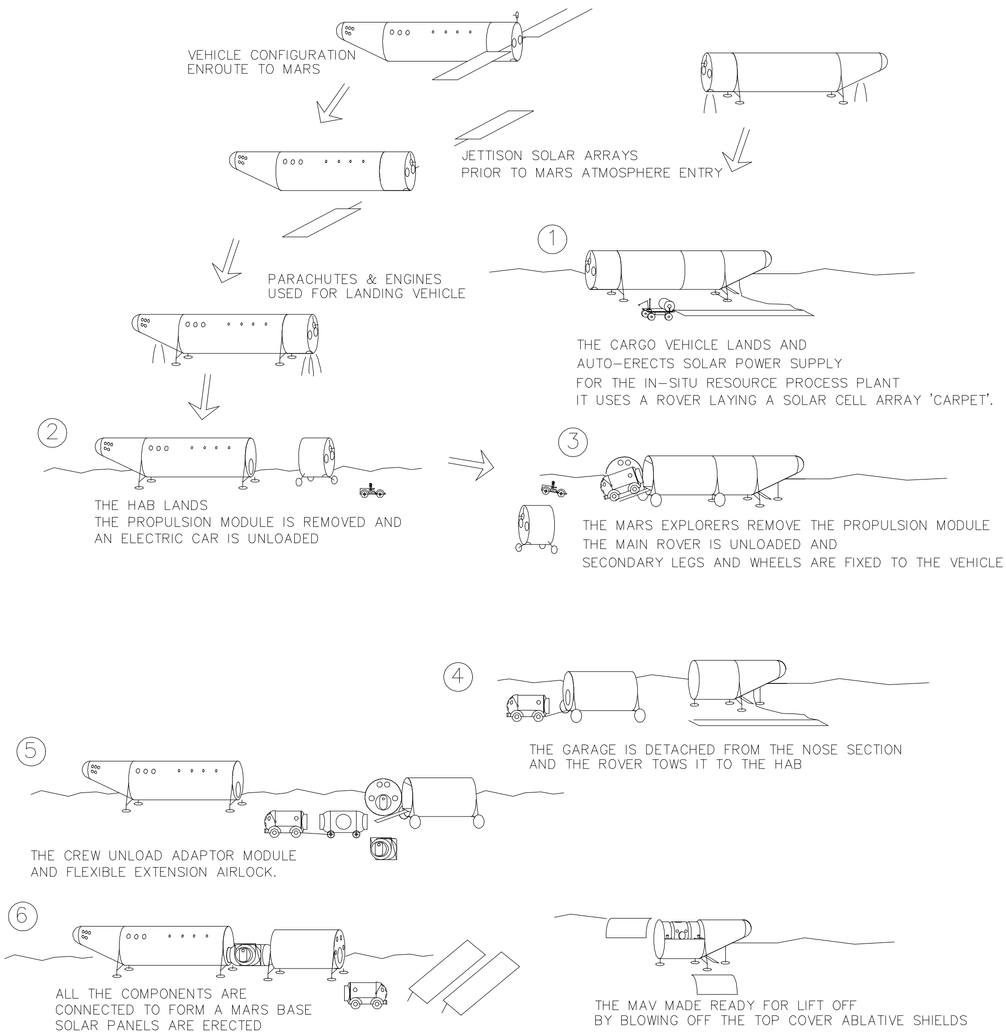


Figure 1. The MARS-OZ Base Assembly Sequence

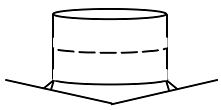
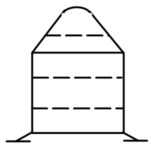
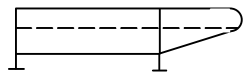
5. THE VEHICLE SHAPE

Version 3.0 of the NASA DRM[15] used landers in the form of a tail landed biconic shape. The compartments in the Hab are stacked vertically over several decks in the cylinder and nose. An aeroshell covers the entire vehicle. It enters the Martian atmosphere nose first.

The “Mars Direct” and version 1.0 of the NASA DRM proposal recommended a two deck vertical cylinder with a coolie-hat shaped fold out aeroshell under the base[16]. The vehicle enters the Martian atmosphere tail first and the aeroshell is dropped just prior to landing.

In comparison the ISU[17] and Energia[18] studies have proposed horizontally landed bent biconic vehicle. An aeroshell covers the entire the vehicle and enters the Martian atmosphere nose first. Biconic landers were first proposed in 1984[19] to take advantage of the high L/D and manoeuvrability offered by such configurations. Such shapes have been extensively researched for manoeuvrable missile warheads[20], applying the design to Mars landers offers a more productive use of such technology. Both these early studies were all tail landers, although it was envisaged that cargo modules would be rotated and lowered to the ground after landing (this issue will be discussed later). Table 2 compares the 'Mars Direct' two-deck cylinder, the NASA DRM 3.0's tail landed biconic and the horizontally landed bent biconic shape.

Table 2. Comparisons Vehicle Shape Design Issues

Design Issue	Mars Direct: Tuna can 2-deck shape with mushroom aeroshell under base.	NASA DRM 3.0: Tail landed 3 deck Biconic and all covering aeroshell shroud.	ISU, Energia and MARS-OZ: The Horizontally landed bent biconic and all covering aeroshell.
The Shape (Not to scale)			
The Mass/Volume ratio.	**Best** This has the minimum surface area for a given enclosed volume.	**Not as good** The shape is less mass efficient than the Mars Direct tuna due to the longer length.	**Not as good** The shape is less mass efficient than the Mars Direct tuna due to the longer length.
The aeroshell mass.	**Good** Dropping the aeroshell prior to landing is a mass advantage.	**Not as good** Retaining the aeroshell prior to landing has a mass penalty.	**Not as good** Retaining the aeroshell prior to landing has a mass penalty.
The aeroshell design.	**Not as good** The base fixed aeroshell interferes with orbital corrections by the engine	**Good** The tail engine is free of obstructions to allow orbital corrections.	**Good** The tail engine is free of obstructions to allow orbital corrections.
The Propulsion masses	**Good** A minimum of 1 engine is required in the base. This is the most mass efficient landing system.	**Good** A minimum of 1 engine is required in the base. This is the most mass efficient landing system.	**Poor** A minimum of 2 engines is required one at each end of the tube. This is the least mass efficient landing system.
The lift/drag ratio during re-entry into the Martian atmosphere	**Poor** The aeroshell shape has a poor lift/drag ratio. This implies little room for manoeuvrability and high G forces during re-entry.	**Better** The aeroshell shape has a better lift/drag ratio. This implies better manoeuvrability and lower G forces during re-entry compared to the tuna can shape.	**Best** The aeroshell shape has the best lift/drag ratio. It has the best manoeuvrability and lowest G forces during re-entry compared to the other concepts.
The cargo carrying capacity.	**Poor** The vehicle diameter (8 meters) limits the length of the cargo.	**Better** The vehicle length allows longer cargo to be carried. However its tail-landing aspect makes unloading long	**Best** The vehicle length allows longer cargo (up to 17 m long) to be carried. Its horizontal landing aspect

		cargos difficult.	makes easy unloading.
Possible vehicle expansion or upgrades.	**Poor** The shape has little capacity for expansion unless made wider.	**Better** The shape has capacity for expansion. The vehicle can be made longer. However it's tail landing aspect limits the usefulness of the extension.	**Best** The shape has capacity for expansion. The vehicle can be made longer. Its horizontal landing aspect allows the full use of the extension.
The vehicle stability after landing.	**Good** The squat shape is stable on steep ground	**Poor** The tall vehicle is least stable on steep ground. Loss of a leg would be catastrophic.	**Good** The low lying shape is stable on steep ground
The ease of installing radiation protection in the form of Earth filled roof.	**Moderately difficult** Radiation protection can be installed over the vehicle The roof would be 7 meters high.	**Difficult** The high vehicle height would make installing a roof very difficult.	**Best** The horizontal landed 4.7-meter diameter tube makes this shape the easiest to install a roof.
The ability to be connected to other vehicles forming an integrated base.	**Good** The tuna can vehicle shape can be moved and connected to other similar vehicles.	**Difficult** The tail landed vehicle shape is very difficult to move and assemble and connect to other vehicles to form an integrated base.	**Best** The horizontal landed tube shape allows easy moving and connecting to other similar vehicles to form an integrated base.

In summary it can be argued that the tuna can shape and tail landed biconic are more mass efficient shapes for travelling to Mars. They are well suited to single 'scouting' missions to different parts of Mars. On the other hand the horizontally landed bent biconic vehicle concept is better suited for moving around on the surface and connecting together to build an integrated long term Mars base. The shape has an advantage in carrying and unloading large and long cargo. It is easier to add a regolith or water filled roof for radiation protection as it is lower to the ground than other structures. Long-range rovers would be used for distant Mars exploration.

It could be argued that the cargo vehicle and Hab be made to tail land on the surface. This would save propulsion engine mass and complexity. Indeed, this approach was used by the early "Case for Mars" studies[21 22]. The vehicles would have to be lowered to the horizontal orientation to allow better cargo unloading and enable integration to other vehicles. This would be a 'high' risk operation. Damage to the structures could be disastrous for the crew. The tail land option may be adopted when the base is established and cranes are available. Crew entry and egress in tail landers is also problematic, involving, in the "Case for Mars" studies an external ladder at least 15 m high. This also involves considerable risk, even with the reduced gravity.

Before we determine the vehicle mass we need to discuss the geometry of the vehicle and related issues.

6. VEHICLE GEOMETRY

A number of issues drive the external and internal geometry. These are: vehicle diameter, length, volume, hypersonic flight issues, engine location management of dust, sound control and the methods of connecting to other modules and rovers to assemble bases.

The Hull diameter of the MARS-OZ concept vehicle diameter has been made to 4.7 meters. The diameter does not include the aeroshell (see section 7). This minimum diameter allows for 2 decks that satisfy the geometry constraints given below:

- The hull thickness is 75 mm. This thickness allows room for an inner 5 mm aluminium pressure shell, circular stiffeners, longitudinal stiffeners and an outer aluminium shell. Insulation is sandwiched between the shells.
- The lower deck and upper deck room height is 2.1 meters. 2.1 meters height provides a comfortable headroom for tall people and is higher than building standards.
- The lower deck width is 1.6 meters allowing room for equipment and through way for the crew.
- The mid-deck thickness is 100 mm thick to allow room for deck stiffeners and sound proofing.

The Hab cross-section is shown in fig 2. The 4.7 metre diameter hull and the internal room dimensions require 'human factors' research to ensure the living areas are workable. Long term living in a simulated Hab will be required to prove these dimensions and different internal configurations[23] can be assessed.

The vehicle length is some 4.4 times the diameter, similar to the ISU and NASA's biconics. The overall length chosen is 21 meters. This includes a 3-meter propulsion module. Increasing the diameter or length will inturn increase the vehicle overall mass We will show that the Hab with this geometry will result in a payload mass equal or greater than our 46 tonnes listed in the assumptions.

The Hab occupied volume consists of the 12-meter cylindrical length and the upper half of the 6 meter bent biconic section. The habitat volume is nominally 210 m^3, That is 52 m^3 available for each of the 4-person crew. It includes space used by supplies and furnishings. When the Hab is assembled to the rover garage section with connecting modules and external airlocks, the space volume increases to 312m^3. In comparison, Salyut 7's habitable volume was 108 m^3 (with two docked Soyuz Ts)[24] for a four-person crew, Skylab's internal volume was 367 m^3 (with a docked Apollo CSM) [25] for a three-person crew and the completed Mir complex was 284 m^3 (with two Soyuz)[26] for a 6-person crew.

A Mars Ascent Vehicle (MAV) must also fit in Cargo vehicle cross section. Fig 3 shows a concept MAV in the cargo vehicle. The MAV design is conceptually similar to the ascent stage of the Apollo LM. The cabin is a 2.6 diameter cylinder located between 2 LOX tanks. Under these tanks are 2 methane tanks with one engine located in-between. The vehicle burns methane and oxygen using the high performing RL10 engine. We have assumed a 3.9 tonne dry mass and calculated a fuelled mass of 18 tonnes to achieve Mars orbit. These dimensions and masses are consistent with other studies for 4-person MAVs[27 28]. In comparison NASA's MAV 6 man vehicle dry mass is 5 tonnes. The calculation method is discussed in section 7. The details of the Mars Ascent Vehicle are in Table 4.

Table 4. Mars Ascent Vehicle Details

Item	Details
Mass	18 tonnes all up mass. 3.9 tonnes dry mass.
Engine	1 off 101 kN RLa10-4-1 Pratt & Whitney engine[29] burning LOX and Liquid methane. Isp = 386 sec
Liquid Methane fuel	3.1 tonnes in 2 tanks
Lox Oxidant	11 tonnes in 2 tanks
Cabin	2.6 m diameter x 2 m long with volume = 10 m^3
Vehicle delta V	5.7 kM/sec required to achieve low Mars orbit.
Orbit height achieved	500 kM height. Circular

The table and matching sketch in Fig 3 show that the MAV can fit in the cargo vehicle cross section.
We can now look at the bent biconic shape in hypersonic flight.

7. HYPERSONIC FLIGHT

Hypersonic flight studies have been made on bent biconic vehicles. In particular French[30] indicated that vehicles require a lift/drag ratio of a minimum of 0.6 to 1.5 to overcome inaccuracies in navigation during the re-entry process and bring the craft near the landing target. The high L/D ratio enables human tolerable G forces during re-entry from an interplanetary trajectory. The landing accuracy would be further assured by using radio beacons on rovers on the Mars surface. The shape shown in Fig 2 is a simplified bent biconic shape compared to the vehicles proposed by the ISU and Energia. Our vehicle design shape combines a landed configuration that favours long term occupation on Mars with one that maximises efficiency during hypersonic flight when entering the Martian atmosphere. This paper does not study the detail of the Mars re-entry and hypersonic flight in detail.

However it is expected the vehicle trajectory will enter the Martian upper atmosphere on a trajectory of 15° to the horizon suggested by Turner[31]. Rough calculations show that the vehicle is stable at hypersonic speed with at nose up attitude of 37°. We note the cargo mass in the cargo vehicle garage is limited to less than 5 tonnes to maintain stability during the hypersonic flight period. The vehicles have a L/D ratio of 1.3. Varying the C of G location or reducing the nose sweep angle can considerably improve the L/D ratio and lower the nose up attitude angle. The nose geometry may alter with more detailed design. An ablative aeroshell shield would be required for re-entry.

The thickness of this shield needs to be much greater than the material burned off in order to minimise heat transfer. We have chosen the Apollo capsule Avcoat heat shield and nominal thickness for keeping design simplicity in calculating the aeroshell mass budget. This had a density of nominally 515 kg/m^3.

The heat shield thicknesses chosen are 65mm in the high temperature areas on the nose and underside of the vehicle, 40mm on the vehicle sides and 20 mm on the top. This is a conservative choice given that detailed computer thermal analysis of the vehicle has not been done. Note that the Hab will require a heat shield fit for return to earth in the event of a mission abort if he crew are travelling in the Hab.

This provides an aeroshell mass budget on the combined hab and propulsion module of 6.3 tonnes. Detailed work with different materials can reduce the aeroshell mass.
After the hypersonic re-entry, a drogue chute is release to provide stability at lower speeds. Then the parachutes are deployed followed by ignition of landing engines for final landing. This process is discussed in the next section.

8. LANDING ENGINES AND PROPULSION MODULE LOCATION AND PARACHUTES

A brief design of the en-route course correction and landing engines was done to ensure the engines fit within the vehicle physical size. Zubrin's vehicle delta V of 0.7 kM/sec has been chosen to provide for an emergency return to Earth orbit if the trans-Mars insertion burn fails[32]. Otherwise we require nominally 0.2 kM/sec delta V is required for corrections and the remaining 0.5 kM/sec delta V can be used for landing. The en-route course correction engines in the tail (refer to Fig 2) can be small and efficient with large expansion ratios. We have adopted 1 mPa pressure fed UDMH/N2O4 propellant to ensure reliability due to the mult-engine design for these engines and the landing engines.

There are a number of engine arrangements that enable the vehicle to land in the horizontal attitude rather than on its tail. The simplest method is to locate the landing engine at or near the vehicle centre of gravity and use small vernier engines to maintain the vehicle attitude. The propellant should be located near the centre of gravity. This would be a third or half way along the vehicle from the nose. Since our vehicle concept aims to keep this area free, we have chosen a more complicated arrangement of locating engines in the nose section and in a 'propulsion module' section attached to the tail. This section houses the 8.6 tonnes of propellant in 4 pressurised spherical tanks. During the landing process the engines would require continuous and complex throttling to offset the change in C of G as the fuel in the tail is burnt. Also the engines are throttled to enable the vehicle to hover and allow a controlled touch down without air-bags.

The landing engines are required to be compact to fit in the vehicle. We have 'clipped' their large expansion ratio nozzles suited for the thin Martian atmosphere. As such they are not as efficient as theoretically possible. The propellent mass has been calculated for a delta V of 0.7 kM/sec by the course correction engines using the standard expression:

Initial mass/ Final mass = $e^{\Delta V/\Delta v}$;
where ΔV = Velocity change achieved by the rocket; and
Δv = Rocket engine exhaust velocity.

An addition to the landing engines we require parachutes as part of the landing process. We have adopted 4 x 40 meter diameter parachutes for the parachute phase of the landing. The chutes are calculated to slow the vehicle to 130 m/sec even if one chute failed to open. A drag coefficient of 0.8 has been used for this calculation. The vehicle would be travelling nearly vertically after release of the parachutes. Details of the landing process and equipment are shown in table 5.

Table 5 Landing Details

Item	Details
Course Correction engines	2 x 20 KN at 1mPa operating pressure with Isp = 316 sec
Landing engines	4 x 80 KN at 1mPa operating pressure with Isp of 270 sec
Altitude to release chutes and commence landing with engines.	3400 m
Expected landing burn time	Nominally 55 seconds to bring craft to stop and 30 seconds to hover and land
Parachutes	4 off 40 m diameter parachutes located in the vehicle mid section.

The landing process would consist of a controlled hypersonic speed period in the upper Martian atmosphere followed by a supersonic speed period. The vehicle would require a stabilising drogue chute during the supersonic period. As it passes over the landing area it would release the main chutes and slow to vertical speeds. At 3500 meters altitude the main parachutes would be jettisoned and the landing engines ignited. By 3000 meters the pilot would have chosen the landing site within an ‘operating envelope’ cone made 30º to the vertical from the vehicle. The operating envelope is calculated on the vehicle landing before exhausting its fuel supply. In this manner the pilot would direct the vehicle to a choice of landing sites covering a conservative radius of 1.5 Kilometres below the ‘release of the parachutes’ location. There is enough fuel for a 30 second ‘hover’ period just prior to landing. The pilot would be ‘side slipping’ vehicle during the final landing stages due the cockpit windows located on the vehicle sides providing little forward vision.

After landing the crew can commence surface operations. The surface operations have a clear impact on the design of these vehicles covered in the next section.

9. SURFACE OPERATION

9.1 ENVIRONMENTAL MANAGEMENT

A range of issues including dust management, traffic control, accessibility, and acoustic management has driven the interior layout of the Hab and base. The interior layout is shown in Figure 2.

Dust management and suppression is major issue in Mars exploration[33]. The crew enter the base through the main inflatable airlock and vacuum clean their suits before storing them in the suit storage vestibule in the Hab. The lab, wet room, and exercise/medical room are located on the lower deck. These 'working ' areas and can become dirty. A choice of vacuum cleaners, steam cleaners, scrubbers, electrostatic and HEPA filters could be employed to clean the air and equipment from dust. The method(s) of dust suppression requires further study.

The galley-mess area, control station (cockpit) and bedrooms are located on the upper deck. These areas are to be kept clean. The upper deck bedrooms are located away from the lab to escape the lab noise. The cockpit would be converted to a meeting room and office area after landing by packing away the seats and installing a table.

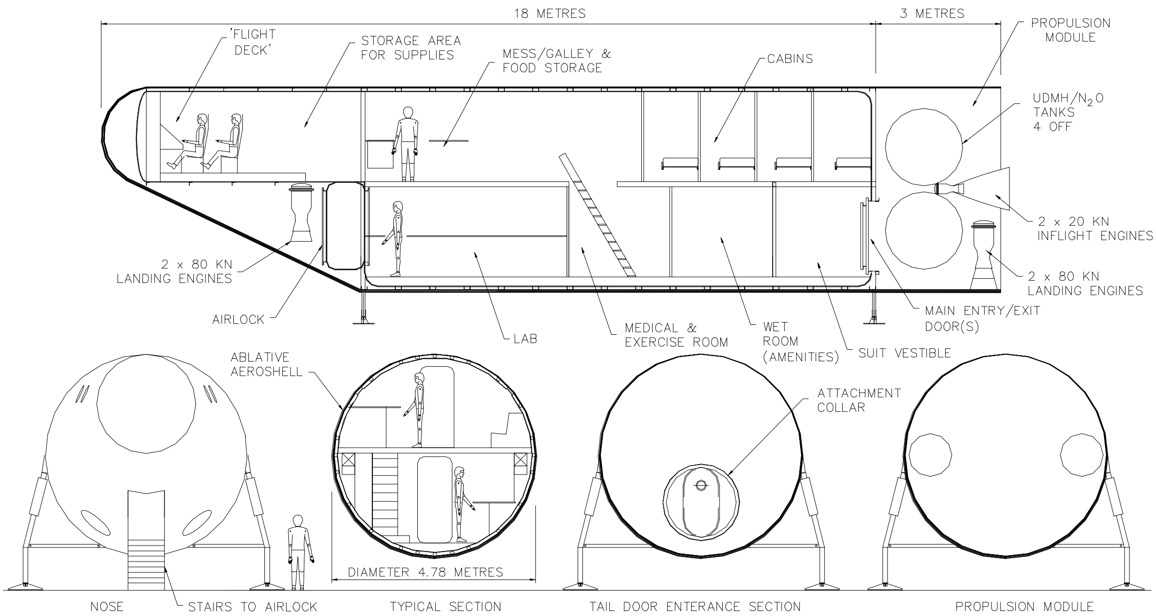


Figure 2. Hab Vehicle Sketch

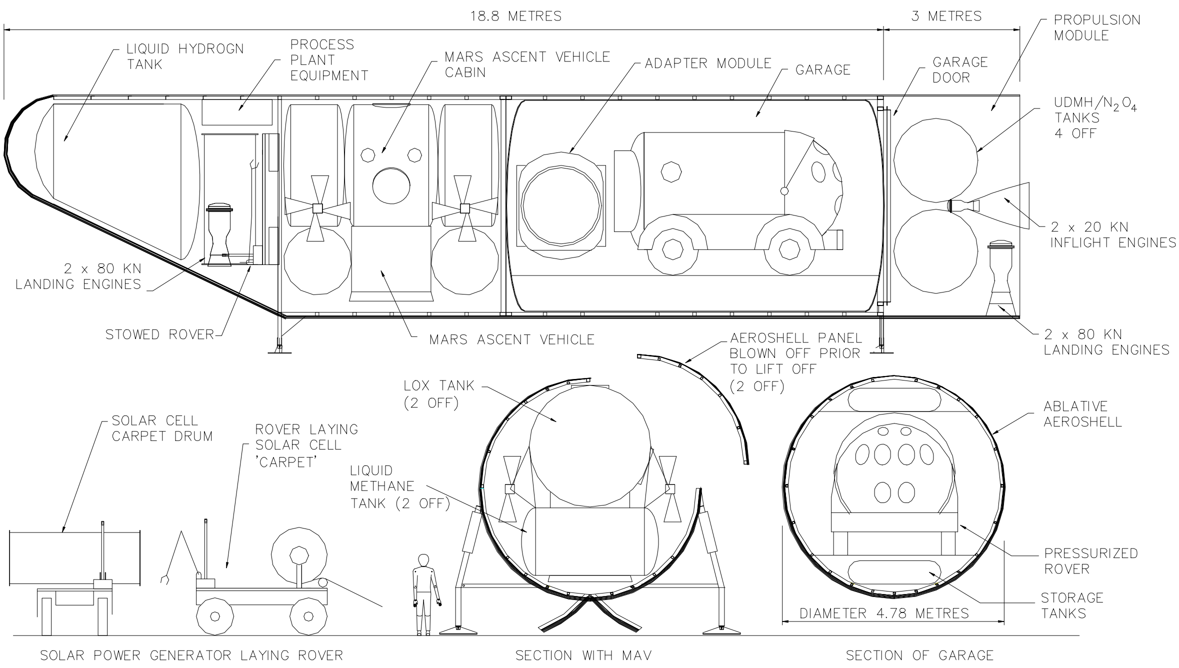


Figure 3. Cargo Vehicle Sketch

9.2 BASE EXPANSION

The future Mars base, can be expanded through a number of stages as shown in fig 4. There are several evolving configurations. The first is where the Hab has just landed and is in a ‘stand alone’ condition ie of not being connected to the Garage. The second is when the Hab is connected to the Garage via the adaptor module. Finally as the Mars base grows the various module components are to be flexible to adapt to different base configurations as well as incremental growth.

When the Hab lands the service module at the tail must be disconnected or blown clear to expose the Hab tail door. A small airlock is located in the nose section for crew exit for this purpose. Fig 4 shows the room layouts with airlock at the nose end and the suit storage vestibule in the tail. This is not the best configuration but the ‘stand alone’ condition is temporary until the garage is detached from the cargo vehicle and towed to the Hab.

When the Hab is connected to the Garage section an adaptor module is attached to the Hab tail door. The adaptor module is a connection tube with hatches at each end and both sides. The garage is attached to the other end of the adaptor module. The module has a short flexible section to cater for misalignment between the structures. Behind the Hab rear hatch is a suit storage vestibule. An inflatable main airlock is attached to one of the adaptor module side hatches. This is the main entry point to the base. It has a hatch that can be docked to a matching hatch on the rear of the rover. When this occurs the crew can move between the Hab and Rover without climbing into space suits and stepping outside. The pressurised rover would be locked down to a ramp that is attached to the base. The rover uses the ramp to align hatch with the airlock hatch and help prevent the rover from rolling away after parking.

As the Mars base grows, components would change their functions. For example the garage is large enough to house the rover, aluminium adaptor module and an extendable airlock module for the voyage to Mars. It can be argued the rover would be designed to remain permanently outside the garage. The garage can then be transformed into a lab/workshop or green house as required. It can also be used as a storage room and for recycling biological waste. It has a large hatch to enable the rover to exit the structure after landing. The large hatch is fitted with a small hatch that matches the adaptor module and inflatable airlock hatches. This feature allows the alternative arrangement of fixing the inflatable airlock to the garage and the rear of Hab to be expanded to other geometries.

Before calculating the mass of the above structure we must diverge and discuss in-situ resource utilisation and the electric power needs of and Cargo vehicle.

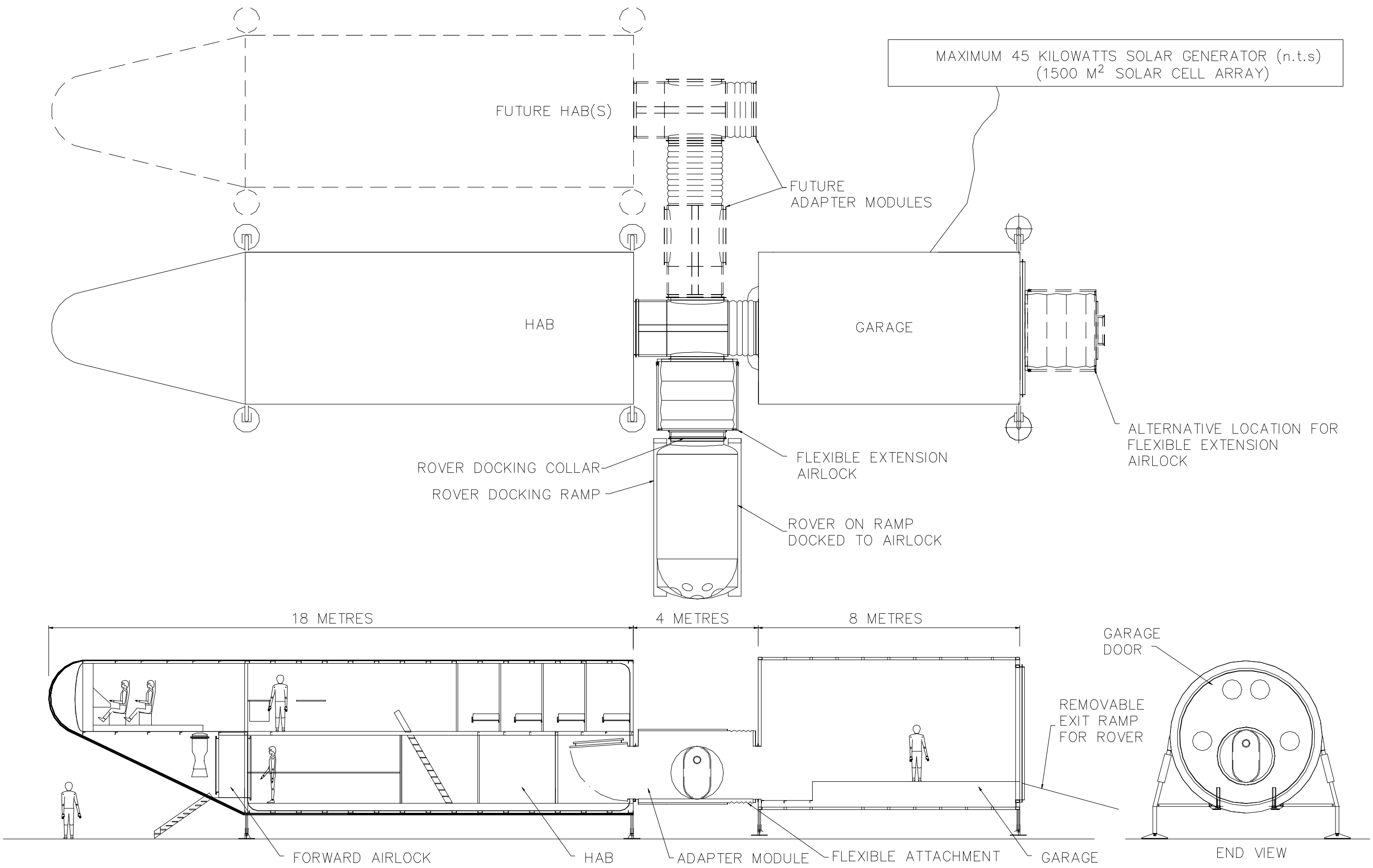


Figure 4. MARS-OZ Base Sketch

9.3 IN-SITU RESOURCE UTILISATION

In-situ resource utilisation is driven by the low power availability due to not providing a nuclear power source and the limited storage space for liquids in the cargo vehicle. The mission requires the manufacturing of propellant for the MAV, propellant for the rover, and water and oxygen for the crew.

We have adopted the Sabatier reactor and the reverse water gas shift process[34] for the method of resource production. This extracts carbon dioxide from the Martian air, combines with hydrogen stock brought from earth and makes methane, oxygen and carbon monoxide products. Water for the crew can made by re-combining the hydrogen stock and oxygen product or extracted from the Martian air.

However we will show water extraction is very energy intensive to the extent that the ‘topaz’ type nuclear power plant would be required. Thus we have adopted to carry hydrogen to Mars for production of water for the crew. Zubrin[35] recommends water recycling and a top up of 2.6 kg water/person/day is a mission requirement. This comes to a minimum of 6.5 tonnes of water for 4 people for the 600 day surface stay. 0.8 tonnes of hydrogen stock has been provided for the water production.

As stated earlier methane and oxygen propellant for the MAV has been adopted. An additional 0.8 tonnes of hydrogen stock is required for these products.

Finally the rover requires propellant. Methane and oxygen can be used but we suggest carbon monoxide and oxygen. This combination can be extracted from the Martian air without the need for hydrogen, but it is not as efficient[36] as the methane/oxygen mix. Also the by product of burning methane and oxygen is water which, due to its scarcity, would need to be recovered by the rover drive. This would add to the complexity of the rover. We recommend the latter option to keep the rover drive and power system as simple and robust as possible.

In total, this concept plans to deliver 1.6 tonnes of liquid hydrogen stock to the surface. This allows the processing plant to combine the hydrogen stock with Martian air and to make liquid methane, liquid oxygen for the MAV, and liquid carbon monoxide liquid oxygen for the rover and drinking water for the crew. This is summarised in figure 5 with the estimated power usage. We recommend that the oxygen gas for the crew also be produced in a reverse water gas shift reactor located in the Hab.

The 1.6 tonnes of liquid hydrogen stock requires 25 m^3 storage volume including spare volume for the 10% ‘boiled’ off hydrogen. The hydrogen is stored in the vehicle forward tank with 15 m^3 and the MAV oxygen tanks with 10 m^3. Hydrogen ‘boil off’ is covered in the next section. Upon landing, the 1.6 tonnes hydrogen is converted to water and methane with oxygen from the Martian atmosphere through the Sabatier reactor. The water is stored in garage tanks and the methane in the MAV (refer to Figure 3).

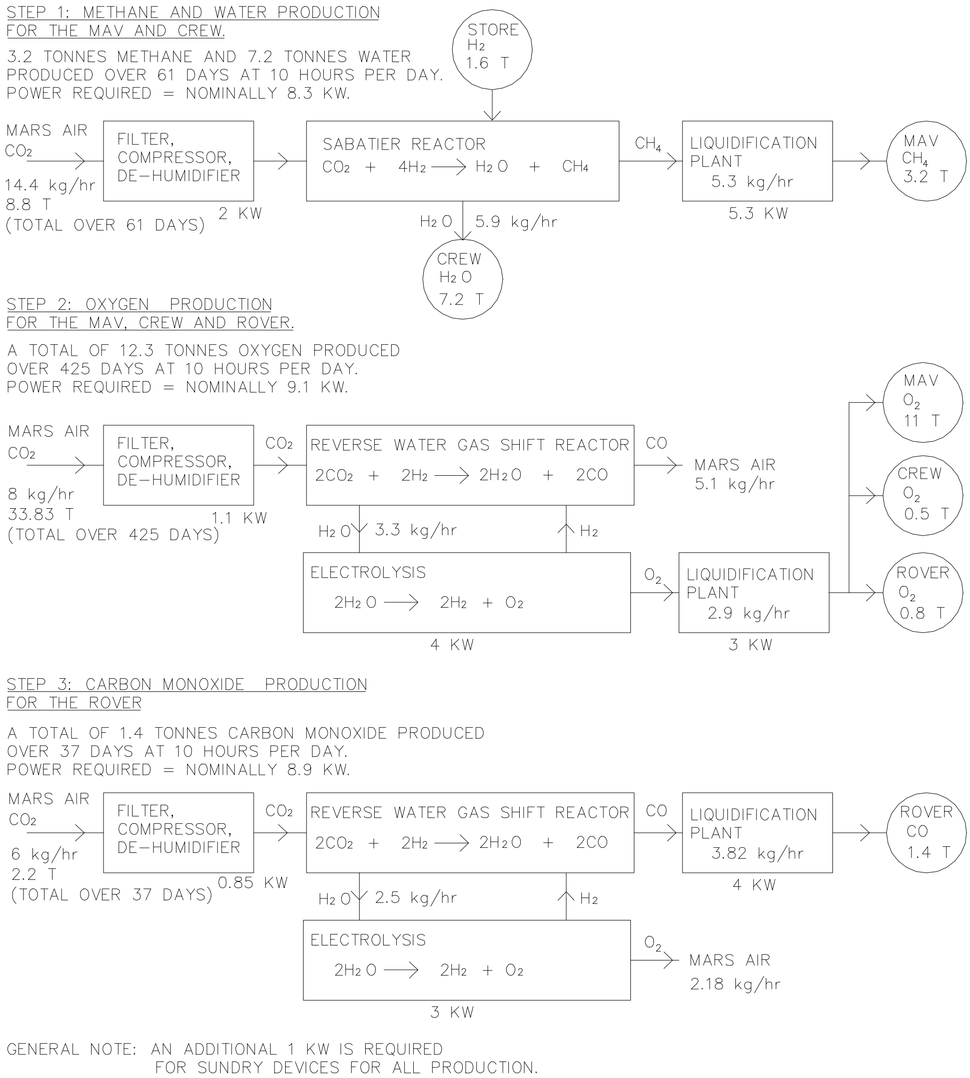


Figure 5. Process Plant Process Diagram

The oxygen for the rover and crew is stored in the old hydrogen tank and carbon monoxide is stored in tanks the above the nose landing engines. The rover is assumed a propellant usage of 2 kg/km with a 3 tonne rover mass. The 2.2 tones of propellant will provide the rover a working radius of 500 kM. These calculations have been based on Zubrin's[37] CO/CO2 estimate for rover propellant usage.

The process plant does not manufacture oxygen and carbon monoxide simultaneously to keep the power consumption down. The Sabatier reactor with a nickel catalyst and reverse water gas shift reactor with a copper catalyst does not require power to operate. The gases must be at 400º C for the reactions to work. This is achieved by the gases gaining energy after being compressed to 1 Bar from the Martian air pressure of 6.1 millibars. Over the operating period 2,625,000 m^3 of Martian air will be processed.

Collection of Nitrogen for the crew can be easily added as the Martian air is 2.7% Nitrogen. Additional oxygen needed to replace cabin air lost due to leakage and airlock operation as been excluded in this design. Further study will be required to estimate the amount due to leakage. Also collection of water from the Martian air can be done but with water concentration of 1 Kg per 500,000 m^3 little water will be collected.

The processing plant must complete its processing operation before the crew depart from the Earth. This is a time period of 580 days. The plant can only operate during the daylight period of nominally 10 hrs/day due to the solar cell power source. The process plant compressor power requirement has been determined through standard compressor calculations. Standard industrial liquification systems can produce liquid oxygen at 0.86 kW-hr/Kg[38]. We have chosen a conservative power usage of 1 kW-hr/Kg to allow for the small scale of the plant and the daily start and stops.

9.4 POWER BUDGET

Eliminating nuclear power from our power source choices is a driver of the base design and poses some challenges. The base must rely on solar or wind energy for power. It can be argued a nuclear power plant puts ‘all the eggs in one basket’ and in the event of failure an alternative power source would be required. Zubrin[39] suggest the mass of a nuclear power plant of 3.5 tonnes. The equivalent mass of solar cells on framed structures provides at least 23.1 kW with near total reliability. An energy store is required for night periods.

Sunlight in Mars orbit 44% as intense as in Earth orbit, on Mars it is 22% as intense as in Earth orbit and during a major global dust storm is as low as 6.5% as in Earth orbit[40]. The solar energy flux in Earth orbit is 1.37 kW/m^2[41]. Thus the solar cell power generators have been sized for on Mars at 30 W/m^2 and in Mars orbit at 60 W/m^2. We have used an efficiency of 10% power conversion, a mass of 30 watts/kg in earth orbit, 13.2 watts/kg in Mars orbit and 6.6 watts/kg on Mars. These are conservative generic figures used in satellite solar generator design[42].

The mission power requirements are divided into the phases:

- The Hab power for the voyage to Mars;
- The Cargo vehicle power for the voyage to Mars;
- The in-situ resource processing power;
- The base consisting of the combined Hab and garage power.

We suggest the Hab power requirement for the voyage to Mars to be an average of 8 kW. In comparison the Salute and Mir[43] core block space station and Spacelab used 3- 4 kilowatts average power for environment control and 8-9 kW peak power when operating scientific equipment. This can be provided by solar cells. The Hab will only require power for the environmental control, communications and control and minor science equipment. The solar panels are sized for Mars orbit at 13.2 watts/kg and jettisoned prior to entry into the Martian atmosphere.

The cargo vehicle power requirement for the voyage to Mars is mostly for the refrigeration of liquid hydrogen stock. The cargo vehicle departs LEO with 1.6 tonnes of hydrogen with active refrigeration and an allowed loss of 10%. Turner[44] has estimated that 524 W/tonne is required for the refrigeration process, implying a 2 kW requirement to prevent hydrogen boil off. We suggest the cargo vehicle power budget en-route to Mars to be 4 kW provided by solar cells. This provides power for control and communication. The solar panel mass is again taken as 13.2 watts/kg and jettisoned as per the Hab.

After landing the cargo vehicle must auto extend new solar cells to run the in-situ resource utilisation processing plant. We plan to use a rover controlled from Earth carrying a solar cell ‘carpet’. Note that the pressurised rover could also be modified and used for this task as well. The rover is unloaded and travels forward ‘laying’ the carpet of solar cells. We suggest a 2.5 metre wide x 200 metre long carpet will provide 15 kW power. ISU 91 suggest the carpet mass could be as low as 22 g/m^2[45] but we have used 4 kg/m^2 providing a tough fabric base for the cells. The rover will also peg down the edges of the carpet and be available at a later stage for remote operations by the crew. The recent Spirit and Opportunity rovers found a performance loss of up to 25% due to dust landing on the cells The performance loss appears to have stabilised.[46].

As such we have designed the process plant to run on 10 kW for 10 hours per day form the power generated from the solar cell ‘carpet’ generator.
Figure 5 shows the plant production rates and calculated power usage. An additional 1 kW power is required to operate sundry devices such as control and heating systems. The process plant would not operate during major dust storms.

The base solar power generation consisting of the combined Hab and garage power is designed for 45 kW. This is larger than the Mir space station which operated with a 2-6 crew on 25 kW[47]. The solar cell size has been designed for the worst case dust storm period combined with a 10 hr day and 14 hr night. During these rare periods, the base would go to a very low power mode. The ECLSS recycling life support system discussed later would be turned off, and a low energy non-recyclable CO2 removal system would be operated. In this manner the power usage, during the storms, can be reduced to levels matching the Salut space station at 3 kW. The crew can take a holiday during this period. Afterwards the cells would be wiped clean by the crew.

Power generation would also be required to recharge the batteries at 60% efficiency to maintain the systems over night. In a 10 hour daylight period 10 kW would need to be generated. Thus, the solar cells size after factoring the 30% of normal solar energy flux orbit and the 25% performance loss due to dust on the cells, would be nominally 45 kW. We suggest, the base solar cells are carried in the Hab and garage in the form of ‘blanket’ fixed to a clip together scaffold-like frame with a mass estimated at 4.6 kg/m^2. 15 kW is carried in the Hab and 35 kW in the cargo vehicle forward section. The solar power generator is erected by the crew on the Martian surface.

With the primary systems specified we are now in a position to review the mass estimates.

10. MASS ESTIMATES

10.1 THE HAB MASS

The estimated Hab mass is given in table 6. The mass estimate is conservative. Is stated earlier, the Hab will require a long life with low maintenance. The masses have been calculated from general design principles derived from the following parameters:

- The mass of the structure, internal bulkheads, partitions, decks and furnishing mass is derived from detailed drawings and a computer stress analysis model of the simulated MARS-OZ base. This is available from the authors. A 5mm aluminium pressure shell and stringers spaced at 800mm centres was adopted for the pressurised section The aeroshell and parachute mass has been calculated based on the details in section 7 and 8.

- The food and water mass is based on the conservative case of a crew of 4 travelling to Mars in the Hab as per Zubrins[48] estimate. In this case the food mass requirement is for 800 days and water for 200 days. The bulk of the water for the time spent on Mars is made from some of the hydrogen brought to Mars in the Cargo vehicle. Supplies for the voyage home is in the orbiting MTV.

- The Power storage mass budget is based on lithium ion batteries. The batteries have a capacity of 100 Whr/kg providing 150 kW hours[49]. It is assumed at this stage, batteries are the dominant power store. Fuel cells may not have the reliability for long life;

- The mass of the life support system is based on an Environmental Control and Life support System (ECLSS)[50]. The system cited does have a high power usage of 9 kW peak power. Work will be required to reduce the power consumption particularly on the en-route to Mars mission segment. On the first mission water is provided from the Sabitier reactor only and not extracted from the atmosphere.

- The dry mass of the propulsion module is calculated on the 4 off 1.8 meter spherical aluminium tanks thick enough for 12 bar pressure housed in a stiffened aluminium drum and clad with Avcoat heat shielding similar to the remaining Hab.

- The landing and en-route engine mass budget is 250 kg each including plumbing. As stated the engines have been sized for geometry.

- The reaction control system mass is as per the system used in the Apollo command module.

Table 6. The Hab Mass Estimate

Item	**Hab mass estimate with a 4 person crew. Tonnes.**
Main structure	6.5 tonnes
Aeroshell on Hab	5.4 tonnes
Internal bulkheads and partitions, decks and furnishing.	4.4 tonnes
Communications & information management	0.2 tonnes
Life support system	3 tonnes
Power storage - Batteries	1.5 tonnes
Food and Water	7 tonnes
Reaction control system	0.5 tonnes
Landing engines in the Hab nose mass	0.5 tonnes
Crew (4 off) and 4 off suits	0.8 tonnes
15 kW solar power cells to be erected on the surface	2.3 tonnes
Open rover and lab equipment	1 tonne
Propulsion module dry Mass estimate inc aeroshell.	3.5 tonnes
In flight and Landing propellant	8.6 tonnes
4 parachutes and a drogue chute	0.8 tonnes
8 kW Solar Power for flight to Mars	0.6 tonnes
Vehicle Mass at start of trans-mars injection	**46.6 tonnes**

We see that our Hab mass is 47 tonnes which is a little more than the 46 tonne mass discussed in the assumptions.

10.2 THE CARGO VEHICLE MASS

Similarly we can list the component mass of the cargo vehicle. The vehicle in Figure 3 consists of a nose section carrying hydrogen stock fuel, a hold for the Mars Ascent Vehicle, a processing and liquefaction plant and a detachable pressurised garage for the rover or cargo.
Other cargo vehicle masses have been calculated from general design principles derived from the following parameters:

- As per the Hab, the structure is derived from detailed drawings and a computer stress analysis model of the simulated MARS-OZ base. A 5mm aluminium pressure shell and stringers spaced at 800mm centres was adopted for the pressurised garage section;

- The remaining mass assumptions are as per the Hab.

We noted, the cargo vehicle garage payload mass is limited by the vehicle balance requirement at hypersonic speeds. Unless additional mass is carried in the forward section the payload in the garage section must remain under 5 tonnes. Further design will improve this outcome.

Table 7. The Cargo vehicle Mass Estimate

Item	**MARS-OZ Cargo Vehicle mass estimate Tonnes**
Garage structure and aeroshell	8.6 tonnes
Nose section structure, landing engine mass and aeroshell	5 tonnes
Mars Ascent Vehicle (dry mass)	3.9 tonnes
Batteries	1.5 tonnes
Hydrogen Stock + tank in nose	1.9 tonnes
15 kW solar cell power for process plant + solar cell carpet laying rover	2.25 tonne
Process plant	0.5 tonnes
Equipment for Mars surface	4.7 tonnes
Additional 30 kW solar cells for the mars base.	4.55 tonnes
Reaction control system	0.5 tonnes
Propulsion module dry Mass estimate including aeroshell.	3.5 tonnes
In flight and Landing propellant	8.6 tonnes
Parachute	0.8 tonnes
Solar Power for flight to Mars	0.5 tonne
Vehicle Mass at start of trans-mars injection	**46.6 tonnes**

10.3 HEAVY LIFT BOOSTER SIZE

The MARS-OZ Hab mass at the commencement trans Mars injection is 47 tonnes. The possible sizes of the low earth orbit payloads have been calculated and shown in Table 8.

Table 8. Mass of Low Earth Orbit payloads

Hab Payload Mass at commencement of trans Mars injection	**Booster dry mass**	**Required DV for Trans Mars injection.**	**Mass of Low Earth Orbit payload (Hab + booster) At start of Trans Mars injection.**
47 tonnes	10 tonnes	3.6 km/sec for slow 6 month journey to Mars[51]	127 tonnes
	12 tonnes	5.08 km/sec for fast 4 month journey to Mars[52].	182 tonnes

The Booster dry mass is based on the mass of the LH/LOX third stage of the Saturn V vehicle[53].
The booster engine is more efficient and based on the LH10 engine with exhaust velocity of 4.5 km/sec[54]. The equation shown in section 5 calculated the final low earth orbit mass.

The heavy Ares launcher used by ‘Mars Direct’ places 140 tonnes in low Earth orbit. Version 1.0 of NASA’s DRM required a booster with a 200 tonne[55] capacity. The table shows the MARS-OZ booster requirements are 130 tonnes for the slow 6-month journey, or 184 tonnes for the fast 4-month journey. Thus the MARS-OZ mission proposal is within the performance of boosters conceived for alternate mission strategies.

The MARS-OZ plan does not quite achieve the fast 4-month journey desirable for a crewed transit with the mass limit of 140 tonnes in low orbit. We would need to reduce the Hab mass to approximately 35 tonnes to achieve this outcome. If the Hab travels to Mars un-crewed, with the crew in the MTV, this is no longer an issue.

11. CONCLUSIONS

We conclude that a realistic Mars mission scenario, which we call the MARS-OZ mission proposal, can be designed around modules of under 50 tonnes utilising a horizontally landed bent biconic configuration. These modules offer considerable advantages with respect to deceleration G loading, good manoeuvrability during Mars entry and accurate placement of payloads on the surface compared to other Mars landers.

However, bent biconic vehicles are not as mass efficient as other lander configurations such as vertical cylinders in a number of respects. These include: a less efficient mass to volume ratio, an aeroshell mass penalty at touch down, a higher landing engine mass and complex landing engine throttling due to the propellant location.

We also conclude that the horizontally landed configuration is superior to all others once landed on the surface because of superior cargo carrying capacity, especially with respect to bulky items, easier loading, unloading, entry and egress. The configuration also offers the most growth potential through by simply lengthening the module. Horizontally landed modules also offer good static and mobile ground stability and, being comparatively low to the ground, are much simpler to provide radiation protection using regolith materials, either through burial or erection of a regolith-covered roof. Lastly, their long low shape facilitates repositioning on the surface of Mars and construction of a larger base complex by the docking of multiple units.

We find the most important mission requirement for a Mars lander module is its efficient functioning as a component of Mars base. Once on Mars it will have to function for many years. It is therefore desirable that landers be designed to optimise their utility in this role, rather than the relatively short journey to Mars. Our conclusion is that horizontal landed modules such as the MARS-OZ conceptual vehicles, have significant advantages in this respect over other configurations.

It is the objective of the Mars Society Australia to field research further aspects of the surface utility of the horizontally landed bent biconic configuration when the MARS-OZ simulated Mars base discussed in the 'Abstract' section of this paper, has been built.

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