A Practical Architecture for Exploration-Focused Manned Mars Missions Using Chemical Propulsion, Solar Power Generation and In-Situ Resource Utilisation.

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1 Introduction

In 2001 Mars Society Australia (MSA) commenced researching design concepts for their proposed simulated Mars station ‘MARS-Oz’[1] to be located in the South Australian outback. This project is intended to provide a platform for field research into human factors and design issues surrounding human Mars missions and for outreach and education, including workshops for school students and space enthusiasts to ‘Explore the art of living on another planet’.

At the same time the MSA conducted a theoretical exercise as to how a Mars station similar to MARS-Oz[2] could be put on Mars using current technology. This research greatly increased our understanding of the difficulties and risks in undertaking a manned Mars mission and was a source of great debate amongst the Australian Mars Society members.

The outcome of this research was the development of a mission architecture as discussed in this paper. This is similar to the Zubrin and Weaver ‘Semi direct’ approach[3], later adopted by NASA in their series of Design Reference Missions[4] (DRM). A ‘family’ of concept vehicles was engineered to a level to provide shapes and masses suitable to plan the infrastructure for manned Mars missions. A number of interesting conclusions were revealed. We will not delve into all the reasons underpinning our conclusions in this discussion as they have been published in the Journal of the British Interplanetary Society. The conclusions will be discussed later but first we begin with a description of our mission architecture and vehicle design.

2 The Mission Architecture

As stated above we adopted NASA’s ‘Semi Direct’[5] mission architecture involving four vehicles. The path that lead to the Semi Direct mission architecture commenced by setting out a number of design assumptions. These were:

- We chose a set of design priorities. These were in order of priority;
    - To provide for the lowest cost mission to encourage the funding of the mission;
    - To maximize safety;
    - To minimize the mission complexity to optimize reliability; and,
    - To provide the best science return given the above constraints.

- We chose not to use nuclear power generators. This is due to their un-proven reliability and the political and safety issues of sending them into space;

- We adopted In-situ Resource Utilization (ISRU), developing rocket fuel from the Martian atmosphere and imported hydrogen supplies;

- We adopted the aerobrake process to achieve Mars orbit instead of using rocket power; and,
- We adopted the low orbit payload capacity to be no greater than 130 tonnes. This is slightly more than the 125 tonne payload expected from NASA's 'Aries'[6] rocket presently in the planning phase. We expect the larger payload is possible in the circumstance suggested in this paper.

The first choice set the need for a minimum number of vehicles, adopting proven technology where possible, allowing abort options in the event of failure, designing for science outcomes and as shown later in the vehicle drawings encouraged us to simplify the Mars station building process.

The second choice of not using nuclear power generators implied the need to rely on solar power generation. This placed a limit on the available electric power. A solar cell farm on the Martian surface, with an efficiency of 10 W/kg (refer to Appendix 2 for details) providing 40 kW of power during the daylight hours is equivalent in mass to a SP100 type[7] nuclear generator providing 100 kW of continuous power.

This power limit, in turn put limits on the amount of rocket fuel that could be manufactured on Mars, the number of crew that could supported on the surface and vehicle surface operations.

However, as to our third choice, we found a 30 kW ISRU plant could manufacture enough liquid oxygen and methane over 18 months for a small Mars ascent vehicle. This vehicle could ferry the crew into a low Mars orbit to rendezvous with another vehicle for earth return. We suggest a 30 kW solar cell carpet could be deployed and kept clean by an Earth controlled robot rover during the propellant manufacturing period[8]. The crew would erect a separate 45 kW[9] solar cell farm for the Mars station.

As such we needed another vehicle, the 'Mars Transfer Vehicle'(MTV), to wait in low Mars orbit to ferry the crew home. This vehicle could also be used to ferry the crew to Mars orbit from Earth. These three choices invoked the adoption of the Semi Direct architecture instead of the Zubrin and Baker Mars Direct approach. This is shown in figure 1

The fourth choice of aerobraking into Mars orbit saved a lot of fuel and cost but the need for heat shields drove us to particular vehicle shapes with complex solar panel extension and retraction system.

Finally, the last choice of limiting the LEO payload to 130 tonnes placed a clear limit on the size of the vehicles that could be sent to Mars. This limit had the greatest effect on the MTV.

As such, in summary, we propose 5 basic vehicle types; the Hab, the Cargo vehicle, the Mars ascent vehicle, the Mars Transfer vehicle and the Trans-Mars Stage. A brief functional description of the vehicles is shown in table 1. The vehicle design concepts, drawings and supporting information are shown in the following section.

Table 1. Vehicle Functional Description

Vehicle	Function Detail
Habitat (Hab) LEO mass: 62 tonnes	It travels to Mars low orbit and waits for the crew to arrive in the MTV. It lands on the Martian surface with crew and becomes the core of the Mars station for a minimum of 4 people. It consists of a cabin, propulsion module, heat shield, landing engines and parachutes. The propulsion module is removed after landing enabling other structures to be mated with the HAB forming a larger station.
Cargo Vehicle LEO mass: 62 tonnes	It transports equipment to the Martian surface direct from earth 2 years prior to the arrival of the crew. The vehicle is in two parts. The first forward section consists of a Mars Ascent Vehicle (MAV), hydrogen stock fuel and an in-situ resource utilization processing plant. The second rear section is a detachable garage carrying a pressurized rover and surface supplies for the crew. It also has a propulsion module, heat shield, landing engines and parachutes. The Cargo section of the vehicle can be detached, towed to the Hab and connected together to form the Mars station
Mars Ascent Vehicle (MAV) Dry mass: 4 tonnes	It lifts the crew from the Mars Surface to low Mars orbit. It is located in the forward section of the cargo vehicle It has room for 4 –6 crew with a 2 day flight duration.
Mars Transfer Vehicle (MTV) LEO mass: 130 tonnes	It transports the crew from low Earth orbit to low Mars orbit with the crew. Capture into Mars orbit is by aerobrake and meets the Hab in low Mars orbit. The crew transfer to the Hab for landing. The MTV remains in low Mars orbit while the crew are on the surface. It transports the crew back to Earth from low Mars orbit. The crew land on direct earth in a capsule It consists of a cabin, water lined storm shelter, landing capsule, heat shield, a science and supply module to be jettison in Mars orbit and propulsion module for Mars escape. It has supplies for 400 days for a minimum of 4 people.
Trans-Mars Stage (TMS) LEO mass: nominally 110 tonnes	It boosts the payloads on a trajectory from low earth orbit to Mars. The TMS propellant is assumed to be liquid Hydrogen and Liquid Oxygen. The tanks would require insulation on the to enable long periods of loitering in LEO. One TMS would be required for boosting the HAB and Cargo vehicles to Mars. Two TMSs would be required for boosting the MAV to Mars.

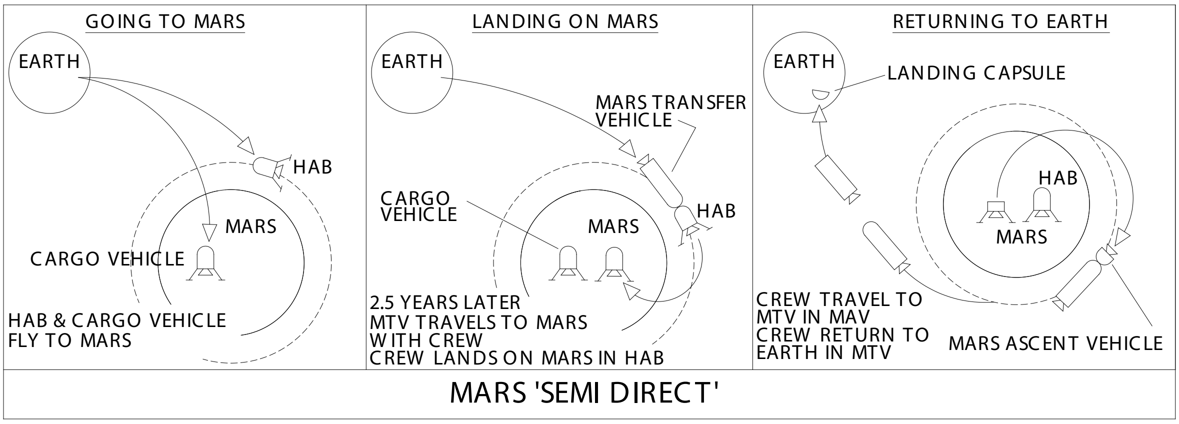


Fig 1: The ‘Semi Direct’ Mission Architecture showing the Hab, Cargo vehicle, Mars Ascent vehicle and the Mars Transfer Vehicle

3 The Vehicle Design Concepts

A stated above, we have covered a Mission Architecture, a family of vehicles to achieve our Mars mission and a set of design assumptions. The ‘Semi Direct’ mission architecture is shown in figure 1. Our mass estimates, discussed later, assumes the journey to Mars takes nominally 200 days, 600 days is spent on the surface and the return journey to Earth takes 200 days[10]. We will not discuss the various types of orbital trajectories in this description.

However, with these basic assumptions and choices in mind we looked at the concept vehicle designs.

3.1 The Hab and Cargo Vehicle

First we looked at the vehicles located on the Mars surface. What kind of vehicle shape is best to use for constructing a Mars station? Do we need to move the vehicles to better locations after landing? How much effort can the crew allocate to building a Mars Station? How can we assemble a Mars station safely with minimum need for construction equipment in a dusty hostile environment.

We decided the long cylinders were the best shapes for a Mars Station construction. Horizontal cylindrical modules can be easily moved on the surface on wheels and can be ‘bumped’ together to form larger structures similar to the early stations in the Antarctic. They are easy to reconfigure to suit the needs of a ‘growing’ Mars station. They are the easiest structure to cover with soil for radiation protection compared to tail landed ‘tuna can’ structures suggested by others[11]. This idea came from long haul truck and mobile machinery experience used in the Australian mining industry.

In addition the cylinders can be developed into bent biconic vehicles clad with a heat shield suited for aerobrake into the Mars atmosphere. These vehicles have a higher lift/drag ratio and better landing accuracy than the ‘tuna can’ type vehicle mounted on inverted china hat heat shields[12]. They would be landed in the horizontal configuration with rocket engines located in the forward and tail sections of the vehicle.

We suggest the landing sequence for a bent biconic Hab, for example, begins with a controlled hypersonic speed period upon entering the upper Martian atmosphere. Hypersonic ‘wing-lets’ on the vehicle tail are used to control the vehicle during this period. The vehicle speed reduces to mach 2 where a drogue chute is released to stabilize the vehicle until subsonic speeds are achieved.

As it passes over the landing area it releases the main chutes and slows to vertical speeds. At 3500 meters altitude the main parachutes are jettisoned and the landing engines ignited. By 3000 meters the pilot chooses 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 directs the vehicle to a landing site within a conservative radius of 1.5 kilometers. Fuel is available for a 30 second hover period just prior to landing. The pilot ‘side slips’ the vehicle during the final landing as the cockpit windows are located on the vehicle sides providing little forward vision. After landing the crew can commence surface operations.

The main design difficulty for this type of landing is that the engines require continuous and complex throttling to offset the change in C of G while the propellant in the tail tanks is burnt. Pumping the propellant into separate tanks to balance the vehicle is not preferred. We prefer to design the propellant tanks such that they can be totally detached from the habitat sections for long term habititaton. In addition the complex four-engine system used for a horizontally landed machine would be heavier than the minimum one-engine system on a tail landed vehicle.

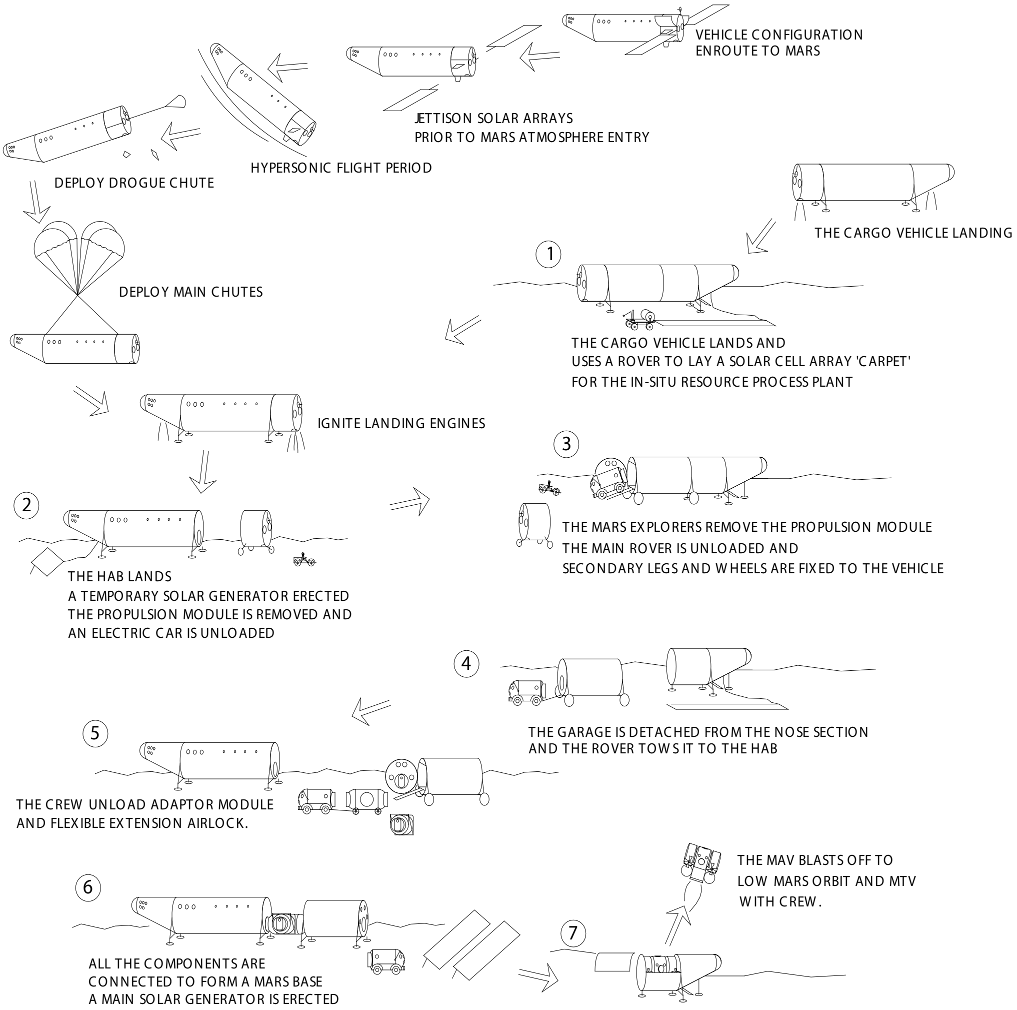
However, the advantage is that a horizontal landed vehicle is the best configuration for removing the propulsion module and mounting the structure on wheels for moving. Also larger cargo sections are easier to unload compared to a tail landed structure. This is shown in figure 5.

Figure 2 shows the HAB and Garage bent biconic vehicles, landed horizontally and assembled to form a Mars station.

The sketches show the Cargo vehicle first landing and deploying a robot rover controlled from Earth. It lays a 25 - 30 kW solar cell carpet that runs the ISRU plant. The rover keeps the carpet clean while the plant processes the hydrogen stored in the Cargo vehicle and MAV tanks into methane.

18 months later the Hab lands with the crew. The crew unload a small electric rover and drive to the Cargo vehicle. They unload a large pressurized rover from the Cargo vehicle and the ‘garage’ section is detached from the forward section and towed to the Hab. We suggest the horizontally landed cargo vehicle in the manner shown in figure 5 is safer to unload and can carry longer cargo structures than the tail traditional landed vehicle.

Upon arrival the crew can unload a connecting module and flexible airlock and plug together the various sections of the station. Refer to figure 3.



Detaching the propulsion module and the ‘garage’ section can be done with explosive bolts equivalent to jettisoning a Soyuz spacecraft propulsion module. Removing the legs and bolting on wheels for towing is a similar process to that used by trucks moving trailers and equipment on Earth. The equivalent Martian weight of the landed modules is 15 tonnes (weight).

Fig 2: Building the Mars station

Figure 3 shows the assembled Mars station. Solar based radiation protection has been achieved by locating a soil filled roof jacked up over the connecting module. Unfortunately this provides no protection against cosmic rays. If long-term exposure to cosmic rays is shown to be a hazard then another Cargo vehicle carrying earth moving equipment and larger roof to cover the entire station would be required. In this scenario the station would be buried the under 3 meters of soil

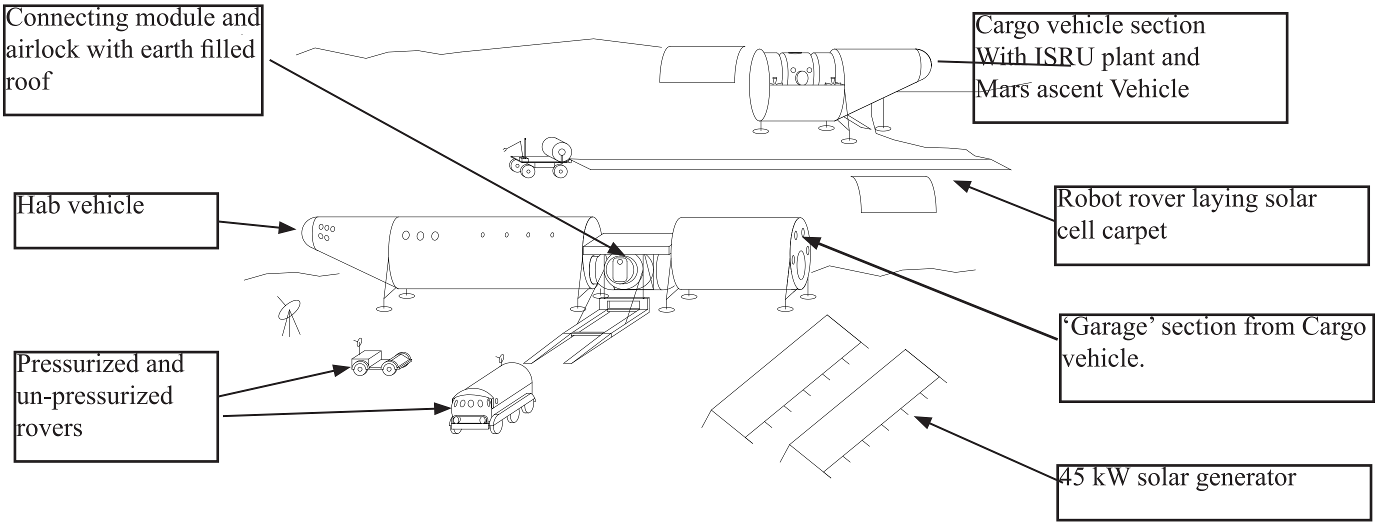
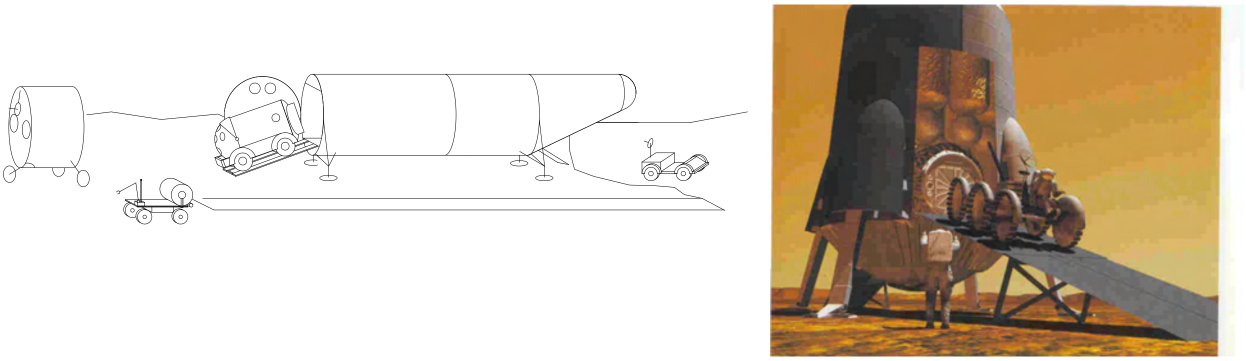


Figure 3: View of the assembled first Mars Station.



Horizontally landed Cargo vehicle
NASA

Tail landed vehicle©

Figure 4: The comparison between unloading cargo from a horizontally landed vehicle to a traditional tail landed vehicle. Note the limitations of cargo length and high unloading ramp on the tail landed vehicle

We can now look at our concept Hab and Cargo vehicle in detail. Figure 5 and 6 show the Hab and Cargo vehicle concept detail. Table 2 and 3 follows listing the equipment and mass take off of each vehicle. Some of the methodology underpinning the listed masses is described in the Appendix.

The Hab and Cargo vehicle masses were restricted to 62 tonne mass as, at the time of developing these concepts, NASA had not announced its plan to develop a shuttle derived heavy launch booster. We assumed a shuttle sized payload booster of 105 tonnes could be placed in orbit and rendezvous with each of the Mars vehicles and propel them to Mars. These masses are best kept low to allow easy towing of the structures on Mars.

Figure 5: The Hab

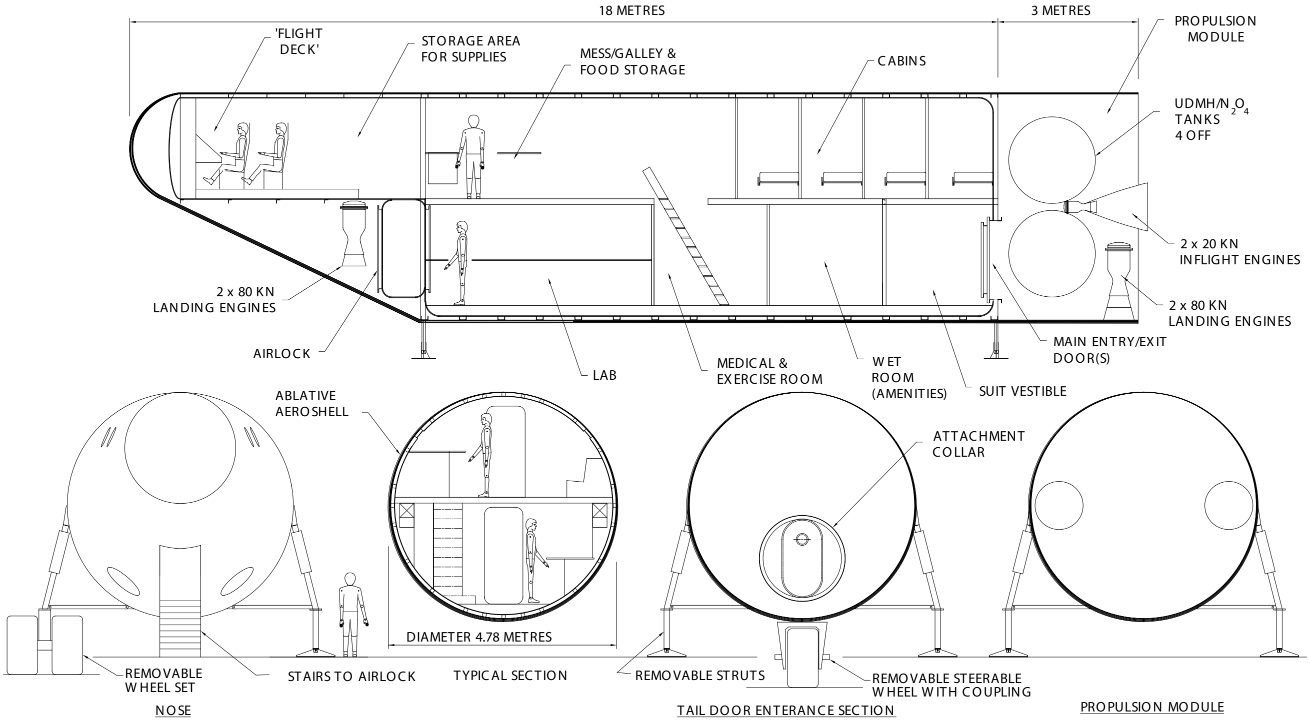


Table 2. The Hab Mass Estimate Breakdown

Item	Mass estimate
Hab	
Main structure, (habitat volume 210m³)	6.8 tonnes
Aeroshell on Hab	5.4 tonnes
Bulkheads, partitions, decks and furnishing.	4.4 tonnes
Electrical control system	0.8 tonne
Life support system	3 tonnes
Power storage – Batteries	1.5 tonnes
Consumables for 600 days (Water and O2 is from the Cargo vehicle ISRU plant) + 200 days food air and water emergency supply	9.97 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
Surface erected 15 kW solar power cells	1.5 tonnes
Lab equipment	1 tonne
Non pressurized rover	0.4
Subtotal	**36.57 tonnes**
Propulsion module	
Propulsion module dry Mass inc aeroshell	3.75 tonnes
Parachutes, 4 x Ø40 m + drogue	1.4 tonnes
4 kW solar Power for flight to Mars	0.16 tonnes
In flight and Landing propellant (1 MPa pressure fed UDMH/N2O4 propellant)	10.64 tonnes
Subtotal	**16.11**
Subtotal	**52.68 tonnes**
Margin 18%	9.32 tonnes
Total Mass at start of trans-Mars injection	**62 tonnes**

Figure 6: The Cargo Vehicle

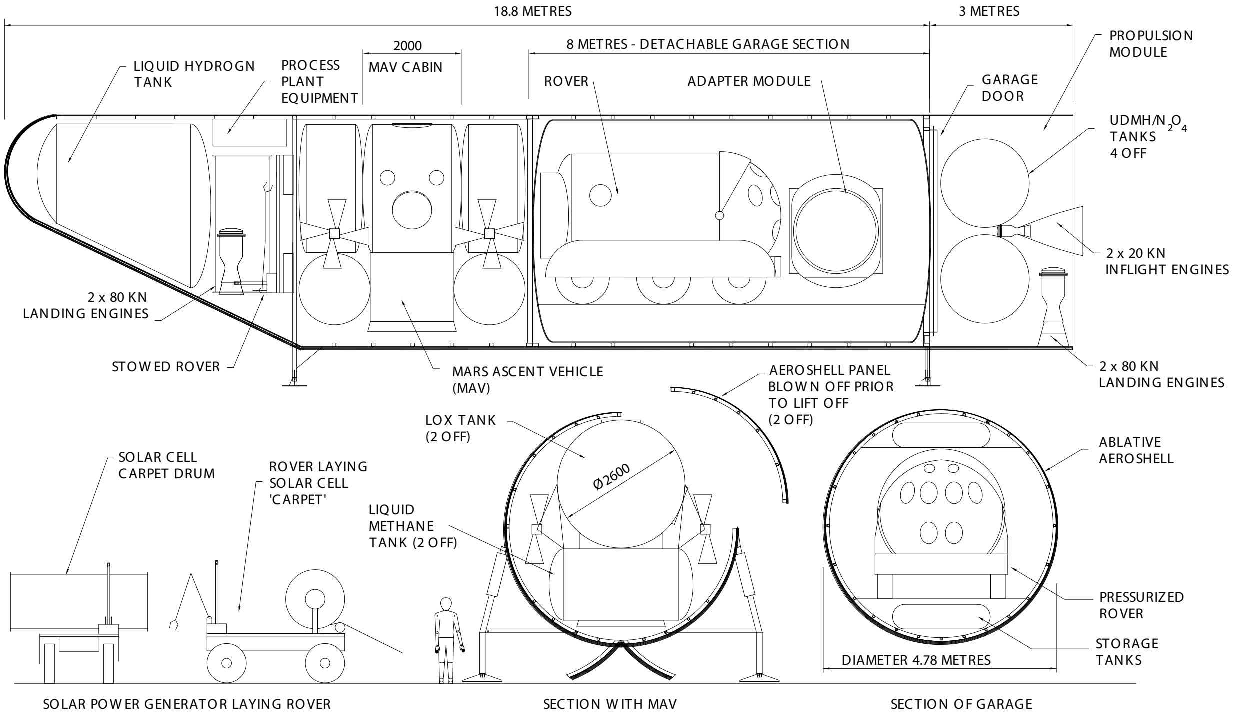


Table 3. The Cargo vehicle Mass Estimate Breakdown

Item	**Mass estimate**
Nose section with ISRU plant and MAV	
Nose section structure, landing engine mass and aeroshell	5 tonnes
Mars Ascent Vehicle (dry mass)	3.9 tonnes
Hydrogen stock in MAV tanks	0.7 tonnes
ISRU Process plant. Manufactures liquid methane, oxygen and carbon monoxide.	0.5 tonnes
Hydrogen Stock + tank in nose	1.3 tonnes
Reaction control system	0.5 tonnes
ISRU power storage – Batteries	0.5 tonnes
25 kW solar cell power for process plant	2.2 tonnes
Solar cell carpet laying rover	0.5 tonnes
Subtotal	**15.1 tonnes**
Detachable Garage section	
Garage structure, furnishing and aeroshell, (habitat volume 100m³)	8.6 tonnes
Garage power storage – Batteries	1.0 tonne
Life support system	0.5 tonnes
Pressurised rover (unfuelled)	3 tonnes
Bogies for moving garage and Hab	1.2 tonnes
Adaptor module and flexible extension airlock	1.5 tonnes
30 kW solar power generator for the mars station.	3 tonnes
Medical Equipment	1.0 tonne
Small ‘Bobcat’ type front end loader	1.0 tonne
Small Jack up roof to be filled with Mars soil	0.5 tonnes
Subtotal	**19.8 tonnes**
Propulsion module	
Propulsion module dry Mass estimate including aeroshell.	3.75 tonnes
Parachutes, 4 x Ø40 m + drogue	1.4 tonnes
4 kW solar Power for flight to Mars	0.16 tonnes
In flight and Landing propellant (1 mPa pressure fed UDMH/N2O4 propellant)	9.92 tonnes
Subtotal	**15.23 tonnes**
Margin 29%	**11.87 tonnes**
Vehicle Mass at start of trans-Mars injection	**62 tonnes**

As stated this description does not show the total workings behind these numbers. However, for comparison, NASA's DMR 3.0 Hab with a 6 person crew has a cited mass of 60.8 tonnes[13]. Our Hab with 4 crew at 62 tonnes compares conservatively with these figures. In addition margin of 20% has been applied.

A major design issue with our Hab was setting the living area dimensions. These were made to an absolute minimum to keep the overall mass down. We expect a more detailed design can improve on this. For example the room heights are 2.1 metres, lower deck width of 1.9 m, upper deck width of 4.5 metres and floor thickness of 125mm. These dimensions were one 'diver' for the overall dimensions of the vehicle. The other 'driver' was Mars Ascent vehicle overall dimensions that fitted into the Cargo Vehicle.

We can now turn to the remaining vehicles the Mars Ascent Vehicle and Mars Transfer Vehicle.

2 The Mars Ascent Vehicle

The Mars Ascent Vehicle (MAV) function is to ferry the crew from the Mars surface to a low 500 km circular orbit and rendezvous with the Mars Transfer Vehicle. We have assumed the spacecraft has two days supply for the crew. The main design challenge was to fit the MAV in the Cargo Vehicle.

To maximize useful space in the Cargo Vehicle, en-route to Mars, we have used the MAV empty liquid oxygen tanks to carry some of the hydrogen stock that is used in the in-situ resource utilization plant. Upon landing the hydrogen is pumped into the plant and combined with carbon dioxide to form water and methane. The methane is liquefied and loaded into the MAV liquid methane tanks. At the same time Oxygen is extracted from the Martian air, liquefied and loaded into the MAV liquid oxygen tanks. This ISRU process and power requirements is discussed in the appendix.

Another approach to make best use of the available space was to make the MAV general shape cylindrical. All up the MAV design is conceptually similar to the ascent stage of the Apollo LM. Indeed, to borrow a phrase, it could be considered a 'LM ascent stage on steroids'. Refer to figure 7.

The cabin OD is a 2.6 diameter cylinder with 10 m^3 volume located between the two LOX tanks. Under these tanks are two methane tanks with one engine located in-between. The vehicle burns methane and oxygen using the high performing RL10 engine or equivalent. We have estimated a 4 tonne dry mass and calculated a fuelled up mass of 18 tonnes to achieve Mars orbit. Mars rock sample boxes are located externally. Retrieving the boxes is discussed in the MTV section. These dimensions and masses are consistent with other studies for 4-person MAVs. In comparison NASA's MAV 6 man vehicle dry mass is 5 tonnes.

Figure 6 shows the MAV fitting into the Cargo Vehicle nose, figure 7 shows the concept MAV with table 4 listing details.

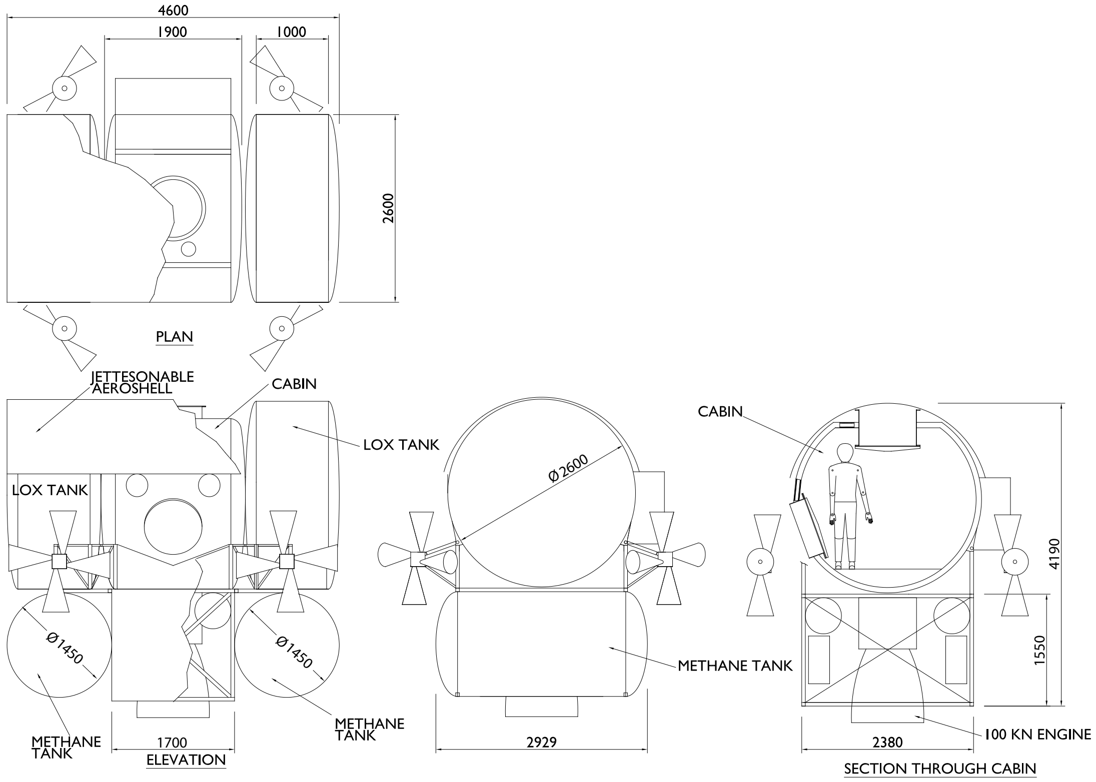


Figure 7: The Mars Ascent Vehicle concept

Table 4. Mars Ascent Vehicle Details

Item	**Details**
Mass	18 tonnes all up mass. 4 tonnes dry mass. Cabin Volume, $10m^3$, 4 crew, 2 days supply.
Engine	1 off 101 kN modified RLa10-4-1 Pratt & Whitney engine or equivalent burning LOX and Liquid methane. Isp = 386 sec[14]
Liquid Methane fuel	3 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	Total 5.7 km/sec required to achieve a low Mars orbit. This can be reduced with a more powerful engine.
Orbit height achieved	500 km height. Circular

3 The Mars Transfer Vehicle

As stated, only enough propellant for a small Mars Ascent Vehicle can by made by an ISRU plant on the Mars surface if powered by solar power generators. This in turn invoked to the need for another vehicle, the MTV, to provide the crew transport to Earth for low Mars orbit.

The question arises: Does the crew travel to Mars in the MTV or alternatively in the Hab? NASA's DRM preferred the crew to travel to Mars in the Hab and return in the MTV (previously sent into Mars orbit).

However, we preferred the crew to travel to Mars in the MTV. The main reasons are as follows:

- The crew could abort and land on Earth in the MTV's Earth Return Capsule if the trans –Mars injection burn failed during the departure from Earth.
- The Hab could be purpose built as a house for living on Mars rather than as a spacecraft for traveling to Mars.
- The solar cell panels could be designed into the MTV to extend for traveling, retract prior to aerobraking into Mars orbit then extending again. This system could not be easily design into the Hab.

In addition, in keeping to the principle that the mission be low cost, we limited the MTV mass to 130 tonnes. This matched the lifting capacity of NASA's planned heavy launch vehicle[15]. This choice implied the need to aerobrake into Mars orbit to keep the fuel mass down. Also we desired a good science return including a brief visit to Phobos during the return journey.

As such the MTV now required a set of minimum characteristics as described below:

- A living module with a radiation shelter and supplies for the 200 day Mars bound journey and the 200 day Earth bound journey;
- An aeroshell for Mars aerobrake that can be jettisoned after aerobraking into Mars orbit;
- Solar panels that can extend/retract beyond the heat shield as required;
- A docking hatch and equipment to rendezvous with the Hab and MAV; and,
- A landing capsule to land on Earth from a hyperbolic trajectory.

Keeping in mind the above characteristics and the 130 tonne mass limitation we derived a concept design geometry as shown in Figure 9. The vehicle concept drawing show the various features including:

- A landing capsule with 12 m^3 habitat volume. The design shown is based on the 1960's'Big Gemini'[16] concept. An Apollo, or Soyuz type capsule could also be used. The capsule has a docking port for the Hab;
- A living module with a spherical radiation shelter located in the supply stores area. The food and water supplies are for the return to Earth voyage and are packed around the shelter. It is possible to make the shelter with an inner and outer shell 200 mm apart filled with in

additional 5 tonnes of water;

- A supply/science module. This module carries the food, water science equipment for the voyage to Mars and. It also has a 'back up' docking port. The supply module is also used as an airlock and carries 2 space suits modified for a space walk on Phobos. The module is jettisoned prior to the leaving Mars via the trans-Earth burn. This is to minimize the return mass;

- Solar panels that can extend and retract and required;

- A primary propulsion module with liquid methane and liquid oxygen propellant;

- A secondary propulsion module with UDMH/N2O4 propellant for maneuvering and minor navigation propulsion; and,

- A three piece heat shield panel that can be opened and closed as required and jettisoned after the aerobrake in Mars orbit process has been completed.

The 130 tonne payload at Earth departure limit resulted in some limitations of the MTV vehicle's capacity. These limitations are:

- The vehicle must rendezvous with the Hab in low Mars orbit. The vehicle only carries supplies for the voyage to and from Mars. It does not have supplies for the 600 day waiting period before the return journey begins if it fails to link with the Hab; and,

- The vehicle cannot undertake an Apollo 13 style Mars flyby and return to Earth on a 1.5 year period orbit if there is a systems failure. It does not carry supplies for this maneuver. We argue, unlike Apollo, the crew would not survive this maneuver over 1.5 year time duration given a major systems failure. A general failure analysis is discussed in section 5

Finally, our design highlighted a number of requirements. These are:

- The recycling system must be very efficient to keep the water mass within workable limits. This invoked the need for a large power supply and hence solar panels. The Mars station, in comparison, does not need efficient recycling as water is manufactured in the ISRU plant from hydrogen stock and the Mars atmosphere.

- The aerobrake maneuver is done in two passes. The first pass reduces the vehicle speed to achieve a rough highly elliptical orbit. A burn at the orbit apogee sets the second pass which achieves a more precise elliptical orbit that achieves 500 km. A second burn establishes a circular orbit.

- The free space Hab volume was set at 60 m^3 or 15 m^3 per person(for 4 people). This volume is between the minimum performance limit of 11 m^3 and the optimal 20 m^{3}volume as suggested by Woolford and Bond[17]. The aim was to keep the Hab size to a minimum. This in turn minimized the Hab mass allowing the overall vehicle to be within the 130 tonne limit. Clearly free space for the crew has been limited to maintain this objective.

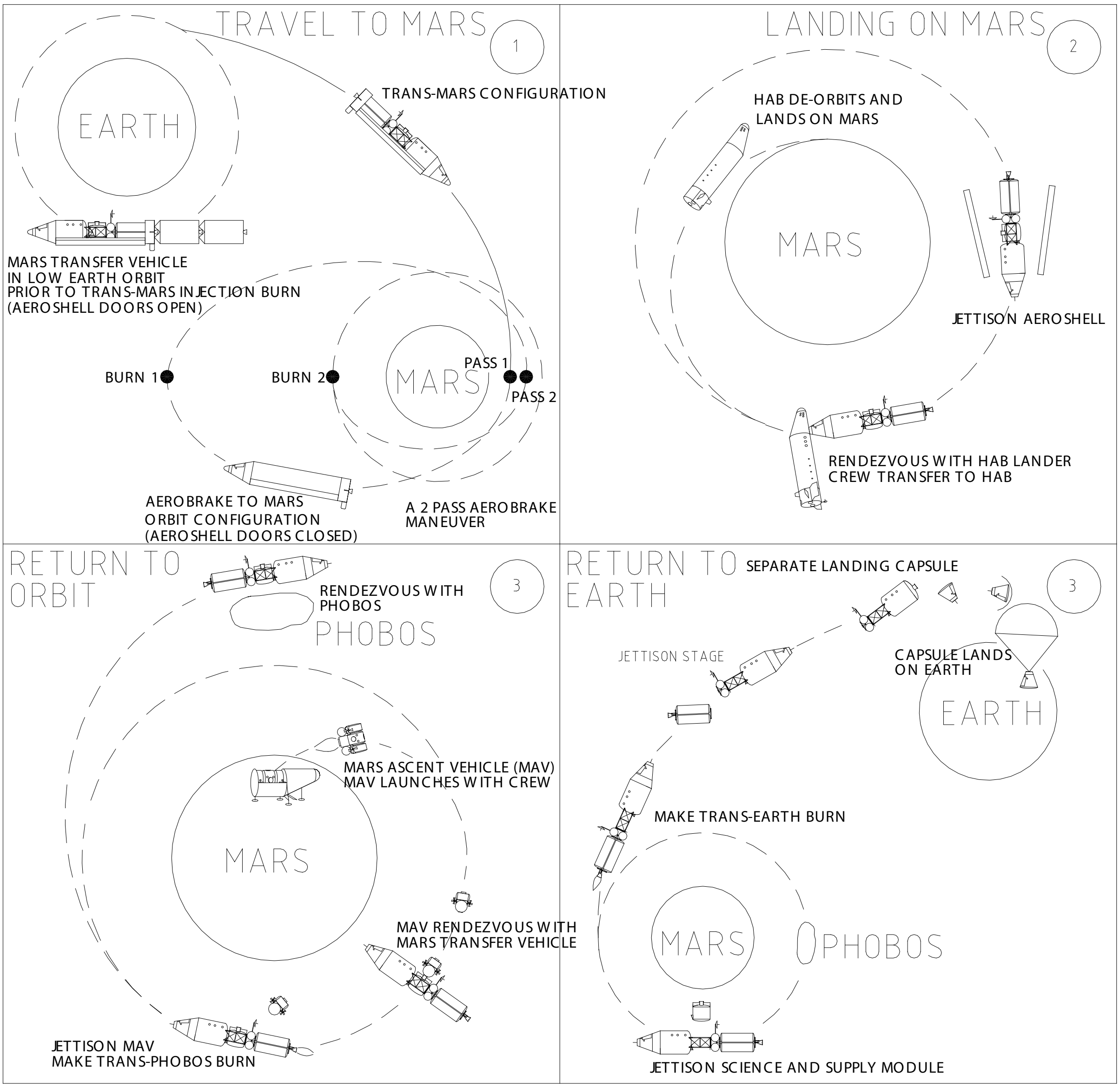


Figure 8: The Mars Transfer Vehicle operation

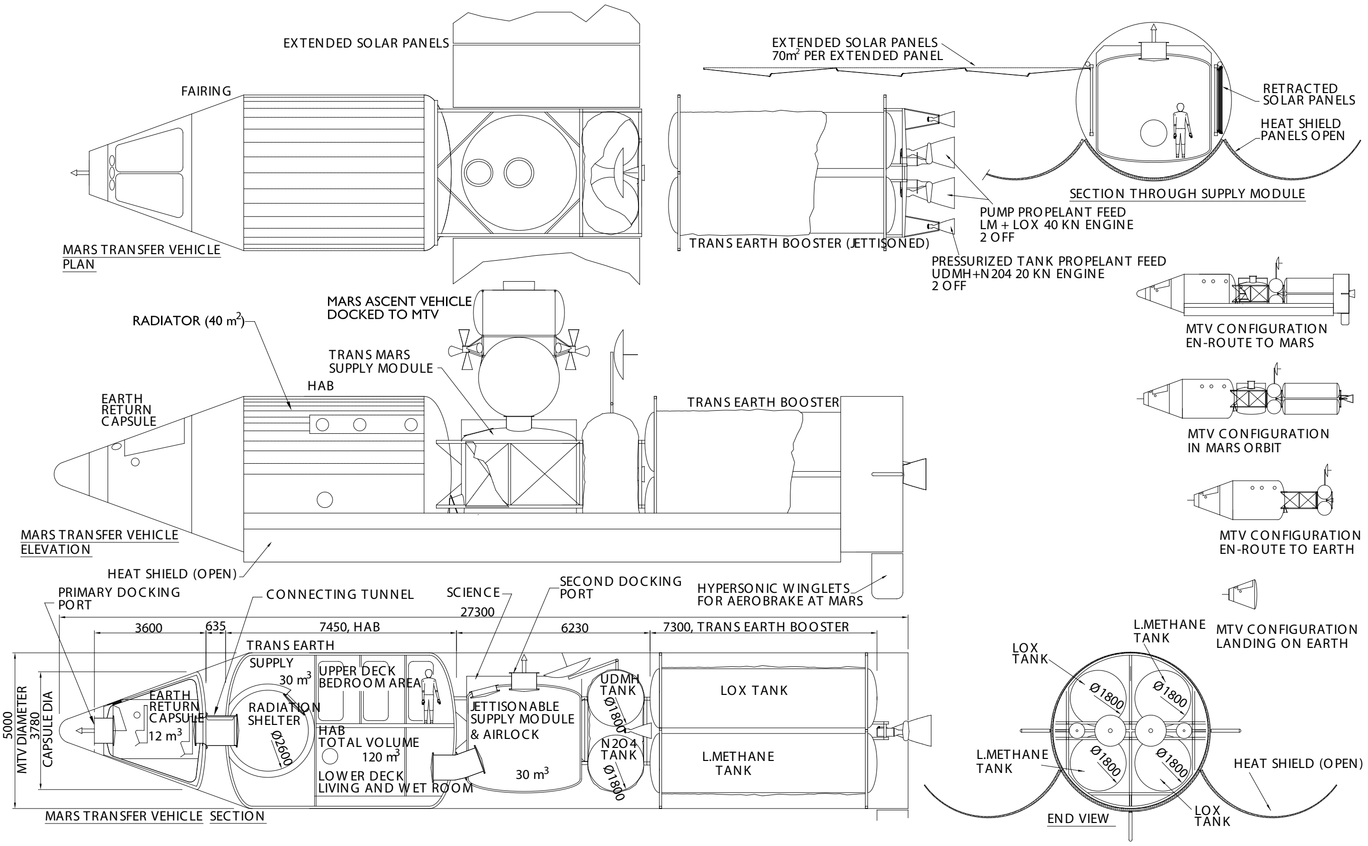


Figure 9: The Mars transfer Vehicle

Table 5. The Mars Transfer vehicle Details

Item	Mass Budget	Item	Mass Budget
Earth return capsule		**Main Propulsion module**	
Total volume 12 m³		Propulsion module dry mass	6.48 tonnes
Earth return capsule. Stripped down capsule with nominally 2 days supply	3.68 tonnes	Propulsion module propellant L methane+L oxygen	44.22 tonnes
Earth return Capsule – Hab fairing	0.4 tonnes	**Subtotal**	**50.7 tonnes**
Subtotal	**4.08 tonnes**		
Hab		Aeroshell (jettisoned after entering Mars orbit)	4.6 tonnes
Free space = 60 m³, Fixed equipment & walls = 50 m³, supplies = 30 m³			
Hab pressure shell, deck, cabin walls and furnishing allowance	5.1 tonnes		
Cabin fixed resources including spares and general house equipment	2.8 tonnes	**Margin: 20%**	**21.4 tonnes**
Environmental system including radiators	3 tonnes	**Total mass at departure from low Earth orbit**	**130 tonnes**
Storm shelter shell excluding water jacket	0.5 tonnes		
Return to Earth consumables	8.04 tonnes		
Crew mass allowance for 4 people	0.8 tonnes		
Science equipment allowance	0.2 tonnes		
Electrical equipment including communications dish	1 tonne		
Connecting truss	0.4 tonnes		
20 kW Solar cell power generator @ 30% efficiency	1.0 tonnes		
Batteries at 100 Whrs/Kg	0.35 tonnes		
Reaction control system	0.7 tonnes		
Secondary propulsion system with hypergolic propellant tanks (dry) mass	1.62 tonnes		
Hypergolic propellant for travel to Mars, Mars orbit and return to Earth	10.62 tonnes		
Subtotal	**36.13 tonnes**		
Supply module (jettisoned before the return to Earth journey)			
Supply module pressure shell 30 m³, shelves, freezer and medical equipment	4.5 tonnes		
Return to Earth consumables	8.04 tonnes		
Orlan Suits (2 off) for Phobos space walk	0.25 tonnes		
Science equipment	0.3 tonnes		
Subtotal	**13.09 tonnes**		

Following from the above concept and mass estimates we have listed in Table 6 our vehicle 'delta V' budgets and the matching propulsion system used in the MTV. The 'delta V' budget is used to calculate the mass of propellant carried in the vehicle.

Table 6: vehicle 'delta V' budgets

Mission Segment	**Delta V Budget**	**Propulsion System and propellant**	**Propulsion Specific Impulse**
Tug requriements			
Trans Mars injection burn at low Earth orbit	3.7 km/sec	2 off stage L hydrogen + LOX Booster	450 sec[18]
Mars Transfer Vehicle Requirements			
Earth to Mars control and navigation budget	0.2 km/sec	Secondary propulsion, Hypergolic	316 sec
Mars aerocapture to a 500 km circular orbit	0.15 km/sec	Main propulsion module, L Methane + LOX	386 sec[19]
Rendezvous with Hab in LMO	0.15 km/sec	Main propulsion module, L Methane + LOX	386 sec
Mars orbit maintenance	0.1 km/sec	Secondary propulsion, Hypergolic	316 sec
Phobos rendezvous	0.15 km/sec	Main propulsion module, L Methane + LOX	386 sec
Trans injection Earth burn at low Mars orbit	2.4 km/sec	Main propulsion module, L Methane + LOX	386 sec
Mars Earth control and navigation budget	0.2 km/sec	Secondary propulsion, Hypergolic	316 sec

The 'delta Vs' in table 6 have been calculated, in the case of planetary transfer orbits. The rendezvous delta Vs are based on the Gemini spacecraft[20] rendezvous allowance. The Mars aerocapture allowance has been based on 2 passes through the atmosphere. The 1st pass results in a 20,000 high elliptical orbit and a burn at the apogee. The 2nd reduces it to a 500 kM high circular orbit with a burn at the apogee as shown in figure 8. This paper will not cover the details of this calculation.

Table 6 shows a delta V allowance to visit Phobos on the return journey. The MTV would go into a low orbit about the moon allowing the crew to land instruments on Phobos. Alternatively the crew could descend to the surface in space suits equipped with a maneuvering units.

Finally we note that the radiation shelter in the Hab suited for solar storms uses for the radiation shielding material the return to Earth water and food supplies. This is stored in detachable containers located around the shelter. This would be OK for the journey to Mars but on the return journey, the radiation shield would be drunk and eaten to depletion. The wastes being dumped overboard.

As such we could risk possible solar flare radiation exposure or we have the option to locate 5 tonnes of water permanently around the shelter walls. This mass budget would be taken from the 'margin' of 21 tonnes listed in table. Overall we would take 12.43 tonnes from this margin including the 5 tonnes of water and 7.43 tonnes of propellant.

The next section, the appendix, covers some of the basic information used to design this family of vehicles.

4. The Trans-Mars Stage

A booster stage place in low Earth Orbit is required to launch the vehicles off to Mars. We have assumed this to be powered with Liquid Hydrogen and Oxygen propellant as currently being developed for NASA's 'back to the moon' program.

We estimate its mass to be 110 tonnes with 10 tonnes dry mass. The minimum manned Mars mission as described in this paper the following payload will be required to lift into Low earth Orbit.

Table 7: Manned Mars Mission Total mass in LEO

Payload Lifted into Low Earth Orbit	**TMS(s) required for the Trans-Mars burn**
Hab, 62 tonnes	1 TMS, 110 tonnes
Cargo vehicle, 62 tonnes	1 TMS, 110 tonnes
MTV, 130 tonnes	2 TMSs 220 tonnes
Total mass in LEO	**694 tonnes**

Table 7 does not include lifting the crew into LEO. This could be done in the MTV capsule equipped with an escape tower or on a separate Soyuz or Crew Exploration Vehicle being developed by NASA.

5. Discussion of Failure and Abort Options

Finally a brief summary of possible mission and vehicle failures and about options is listed in table 8.

Table 8. Table of General Possible Failures and Abort Options

General Possible Failure	Abort Options and Comments
The MTV fails to achieve low Earth orbit after take off with the crew.	**Abort option possible.** The crew can return to earth in the 'Return to Earth' Capsule.
The TMS fails to boost the MTV with crew to Mars	**Abort option possible.** The crew can return to earth using the MTV engines and the 'Return to Earth' Capsule.
The MTV fails to achieve Mars orbit	**Abort option not possible**. The MTV must achieve Low Mars Orbit
The MTV fails to rendezvous with the Hab in low Mars orbit.	**Abort option not possible**. The MTV must rendezvous with the Hab in low Mars orbit.
The Hab fails to achieve a landing or land near the Cargo vehicle	**Abort option possible**. If the Hab remains in LMO. The crew could survive on supplies in the Hab and MTV. **Abort option not possible**. If the Hab crashes during landing. **Abort option not possible** . If the Hab does not land within traveling distance of the Cargo vehicle.
The ISRU fails to operate.	**Abort option possible.** The ISRU plant completes its primary mission before the crew depart from Earth.
The MAV fails to achieve Low Mars orbit or rendezvous with the Hab	**Abort option not possible** .If the MAV crashes. If MAV fails to launch, Crew may not survive unless additional food supplies are provided
The MTV fails to depart from LMO.	**Abort option not possible** The MTV primary engines must operate to return to Earth.
The MTV, Hab and MAV have a major environmental or power failure	**Abort option not possible for MTV & MAV.** MTV and MAV environmental and power systems must be operational. **Abort option possible for Hab.** If the Hab environmental and power systems fail the crew can use the Cargo vehicle and Garage equipment

It is clear from table 8 that there are a number of mission elements that must succeed to achieve a successful mission. Further analysis is required to reveal the overall probability of a mission failure. However, we suggest in principle the elements where abort is not possible can be managed by the crew control and careful design.

As stated the MTV does not have the capacity to bring the crew home on a 'free return' trajectory due to the 130 tonne mass limit capping the crew supplies.

However, we argue if the MTV environmental, power and propulsion systems failed such that it could not achieve Mars orbit and rendezvous with the Hab, it would not be fit to transport the crew back to Earth for 1.5 years on a free return trajectory.

6. Conclusion

We find using a modified Semi-direct architecture offers a number of advantages in safety and design efficiency. These include:

- It allows the three main modules- MTV, Cargo and Hab to be designed specifically for operation in transit and on the Martian surface, respectively.

- It avoids the need for nuclear power generators, requiring a solar-powered ISRU plant to provide propellant for a small Mars Ascent Vehicle to the MTV; and,

- Provides an opportunity to visit Phobos.

In addition we find the the MTV mass can be limited to 130 tonnes (including margins) so that along with all other mission elements, are within the capacity of NASA's Ares V heavy lancher currently being developed.

Also the horizontally-landed surface modules, providing cargo and crew habitation, can be designed as flexible building blocks for a long term Mars station similar to the early Antarctic stations.

Finally the minimum mass required in low Earth orbit for our proposed ‘first' Mars mission is 694 tonnes, and could be achieved by seven Ares class launchers.

Appendix
Supporting Information

This section provides tables of information in the areas of vehicle mass estimation, solar power generation, consumable recycling and in-situ resource utilization plant details. These details were the basis for our concept vehicle designs discussed in this paper.

(1) Vehicle Mass Estimation

Two methods were used to estimate the vehicle masses.

The first method assumed all components were made of high grade aluminum from which we calculated the volume of metal and mass. In all cases the structure had a 1.2 to 1.5 factor added to account for fixings, welds and flanges. The table below summarizes this result.

Table of Hab wall masses

Mass per m^2 of Hab double walled aluminum shell including insulation	30 kg
Mass per m^2 of Hab floors and walls including insulation	15 kg
Mass per m^2 of insulation in walls	3 kg

The second method was used as a check on the first. We used an algorithm, based on the history of manned space vehicles. The algorithm states:

Vehicle mass = 592 x (the number of crew x mission duration in days x pressurized volume)^0.346

This excludes propellant, propulsion, heatshields and any special equipment. In the case of the Earth return capsule extra mass was added including 0.24 tonnes for navigation equipment and 18% for thermal protection and landing equipment.

This method enables us to compare mass estimates built up from basic elements to an overall estimate

In addition the relation shown below was the main method used to calculate the propellant mass.

Mbb/Mab = e^(V/v)
Where
Mbb = Vehicle mass before engine burn
Mab = Vehicle mass after engine burn
V = The velocity required by the space craft in m/sec; and
V = The exhaust velocity of the rocket engine in m/sec ; or,
V = The specific Impulse x 9.81 (m/sec)

Finally mass estimates for equipment such as heatshields, parachutes and electrical harness has been derived from Petro[21].

(2) Solar Power Generation

This section lists in ‘The table of power budgets’ and ‘The solar generator design assumptions’ our basic assumptions to calculate the sizes and masses of the solar power generators.

Table of power Budgets (derived from Landis, McKissock and Baily[22])

Mission phase Power Allowance	Average power budget	Solar generator size provided
The Hab power for the voyage to Mars	4 – 8 kW	4 kW
The Cargo vehicle power for the voyage to Mars	4 kW	4 kW
The in-situ resource processing power	20 kW	25 kW
The Hab in stand alone condition	4 – 8 kW	15 kW
The Mars station consisting of the combined Hab and garage power	4 – 45 kW	45 kW
The Mars transfer vehicle power	15 kW	20 KW

The Solar Generator Design Assumptions

The solar energy flux in Earth orbit	1.37 kW/m^2[23].
The solar energy flux in Mars orbit	0.603 kW/m^2
The solar energy flux on Mars on a clear day	0.301 kW/m^2[24].
The solar energy flux on Mars during a dust storm.	0.089 kW/m^2
The solar cell performance and mass in Mars orbit	120 W/m^2 and 25 Watts/kg
The solar cell performance and mass on Mars	45 W/m^2 and 10 Watts/kg
The ISRU solar cell carpet performance and mass	45 W/m^2 and 11.5 Watts/kg
Additional performance loss due to dust on cells	25%
Assumed overall solar cell efficiency on Mars	15%
Assumed overall solar cell efficiency traveling to Mars	20%
Battery recharging efficiency	60%

We noted from the experience of the recent rovers, Spirit and Opportunity, Mars dust does not adhere to solar panels. The dust can be removed by wind or cleaners attached to the panels.

The solar cell Watts/kg has been derived from general 1990’s satellite solar cell efficiencies[25].

(3) Recycling and General Consumables Assumptions

We considered basic supplies that can be recycled such as oxygen, and water. In addition we considered general consumables and fixed resources.

We start by listing the recycled supplies in the most simplified manner as possible.
The table [26]below shows each person consumes nominally 27.5 kg per day. However most of this is recyclable water. Only nominally 5.62 kg per person per day is unusable lost mass that requires to be replaced.

Table of Minimum Design Consumables per Person Per day (as derived from Guy[27].)

Product provided/person/day	**Mass provided/ person/day**	**Product lost/ person/day**	**Mass lost/ person/day**
Oxygen from stores	0.84 kG	CO2	1 kG
Fresh Drinking water from stores	2.4 kG	Urine	2 kG
Food (2/3 water) from stores	1.8 kG	Faces	0.12 kG
Fresh wash water from stores	0.7 kG	Brine	2.5 kG
Water recycled from air conditioning	1.8 kG		
Water recycled from wash water	22.5 kG		
Total	**27.5 kG**		**5.62 kG**

The table assumes 90% of wash water is recycled and all water from respiration and perspiration can be recovered. A wash water allowance of 25 kg/person/day of has been provided.

This leads to the table below that summarizes the total minimum supplies per 4 people required to be carried in the in the MTV, Hab and Cargo vehicle for a 200 day journey to and from Mars and 600 days on the surface. A 5 kg per day air loss due to cabin leakage is also shown. Minor discrepancies between this table and the above is due to rounding errors.

Table of The Minimum Basic Consumables to be launched form Earth for 4 People for a 2.5 year Mars Mission. (as derived from Guy[28].)

Product	**Supply for 200 days travel to Mars in the MTV**	**Supply for leakage over 200 days**	**600 days on Mars**	**Supply for 200 days travel to Earth in the MTV**	**Supply for leakage over 200 days**	**Total Mass**
Oxygen	640 kG	240 kG	From ISRU plant	640 kG	240 kG	1760 kG
Water	2480 kG	10 kG	From ISRU plant	2480 kG	10 kG	4980 kG
Food (2/3 water)	1440 kG		4320 kG	1440 kG		7200 kG
Nitrogen		750 kG	From ISRU plant		750 kG	1500 kG
Totals	**4560 kG**	**1000 kG**	**4320 kG**	**4560 kG**	**1000 kG**	**15,440 kG**

Water for living on Mars is from the in-situ resource utilization plant in the Cargo vehicle and stored in the Garage section. This is calculated from the above tables as 5.76 tonnes for drinking and up to 1.68 tonnes for washing. Each day on Mars a person is allocated 24.9 kG of fresh and recycled wash water.

Finally other general consumable supplies and fixed resource that were considered is listed below.

Table of General Consumables to be launched from Earth for 4 people for a 2.5 Year Mars Mission. (as derived from Stilwell, Boutros and Connolly[29].)

Consumable resources	**Mass**
kitchen cleaning supplies	250 kg
Contingency faecal & urine collection bags	370 kg
WCS supplies (toilet paper, cleaning, filters etc)	200 kg
Hygiene supplies	350 kg
Disposable wipes	400 kg
Trash bags	200 kg
Operational Supplies (diskettes, zip-locks, velcro, tape)	160 kg
TOTAL mass	**1930 kg**

Table of Fixed Resources to be launched from Earth for 1-4 people for a 2.5 Year Mars Mission. (as derived from Stilwell, Boutros and Connolly[30].)

Fix Resources and Equipment	**location**	**Mass**
Clothing	Hab and MTV	800 kg
Personal hygiene kit	Crew	10 kg
Personal stowage/closet space	Hab and MTV	400 kg
Freezers	Hab and MTV	200 kg
Conventional oven and microwave ovens	Hab and MTV	260 kg
sink, spigot for food hydration and drinking water	Hab and MTV	60 kg
Dishwasher	Hab and MTV	80 kg
cooking utensils	Hab and MTV	40 kg
Waste collection system (toilets)	Hab and MTV	180 kg
Shower and wash basin	Hab and MTV	170 kg
washing machine and dryer	Hab and MTV	320 kg
Restraints and mobility aids	MTV	100 kg
Vacuum (prine + 2 spares)**	Hab and MTV	30 kg
trash compactor/trash lock	Hab and MTV	300 kg
Hand tools and accessories	Hab and MTV	600 kg
Test equipment (oscilloscopes, gauges etc)	Hab and MTV	1300 kg
Fixtures, large machine tools, gloveboxes, etc)	Hab and MTV	1260 kg
Camera equipment (still & video camaras & lenses)	Hab and MTV	240 kg
Exercise equipment	Hab and MTV	300 kg
Medical/surgical/dental suite and consumables	Hab and MTV	2500 kg
TOTAL mass		**9150 kg**

In essence these tables show a person on a 2.5 year Mars mission using ISRU requires for basic supplies and equipment:

- Nominally 1.25 tonnes water, 0.35 tonnes oxygen, 0.75 tonnes of wet food and 100 kg of disposable equipment for travel to and from Mars in the MTV;

- Nominally 1.9 tonnes water, 0.5 tonnes oxygen from the ISRU plant;
- Nominally 1.1 tonnes wet food for surface operations; and

- Nominally 9 tonnes basic equipment for traveling to Mars and surface operations.

(4) <u>The in-situ resource utilization plant details</u>

Lastly we show details of the in-situ resource utilization plant carried in the Cargo vehicle along with hydrogen. This is shown in the process diagram below.

In summary the issues that drive the ISRU plant process are:

- The plant uses the Sabatier reactor with a nickel catalyst and the reverse water gas shift process[31] with a copper catalyst.

- The plant uses 1.6 tonnes of Hydrogen to provide:

    - 3.2 tonnes liquid methane for the MAV;
    - 11 tonnes Liquid oxygen for the MAV;
    - 2 tonnes liquid oxygen for the crew;
    - 7.2 tonnes of water for the crew;
    - Small quantities of nitrogen gas for the crew;
    - 0.8 tonnes liquid oxygen for the rover; and,
    - 1.4 tonnes liquid carbon monoxide for the rover;

- The plant operates in steps to maintain the power consumption below 25-30 kW;

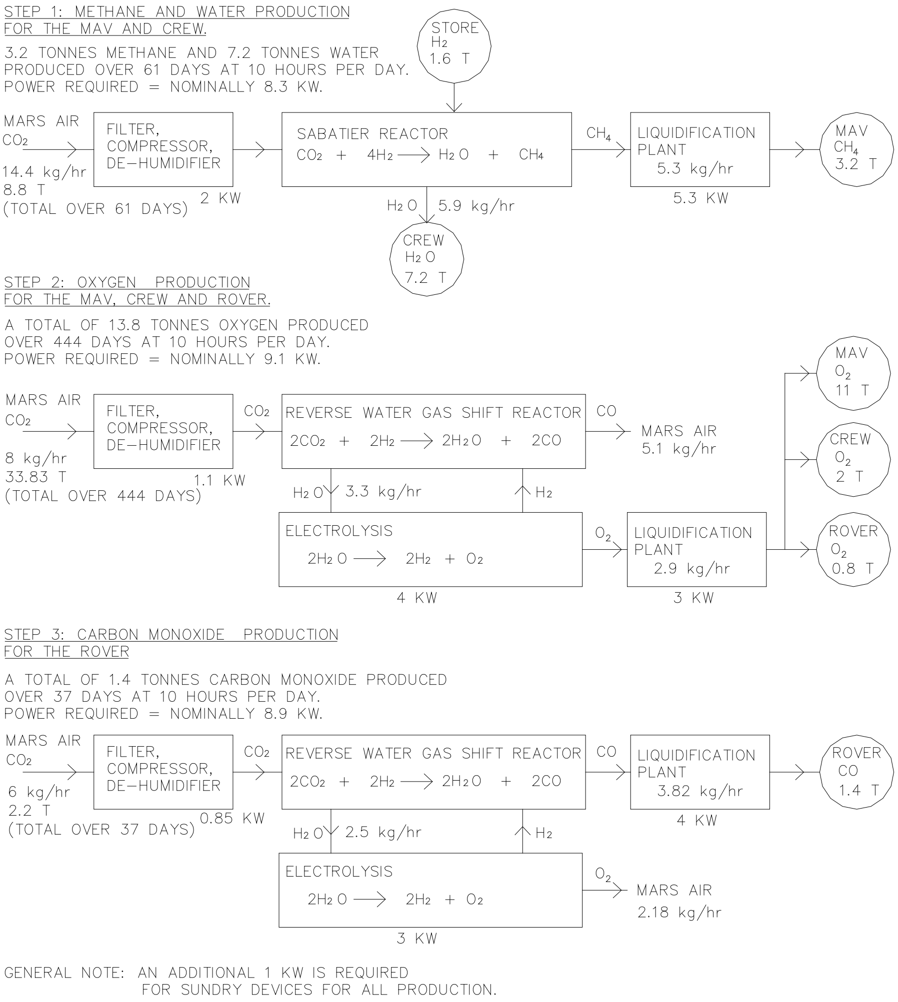
- The bulk of the power consumed is in the electrolysis process for the oxygen production;

- Water is not extracted from the atmosphere (1 kg per 1,000,000 m^3[32]) as large quantities of atmosphere must be process;

- Standard industrial liquefication systems can produce liquid oxygen at 0.86 kW-hr/Kg[33]. 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; and,

- The processing plant completes its processing operation before the crew depart from the Earth. This is a time period of 580 days. During this time 2,625,000 m^3 of Martian air will be processed.

Note that the rover, not discussed in this paper operate on oxygen and carbon monoxide propellant. We chose this compared to using methane/oxygen propellant suggested by others as the water from this process must be extracted. The water extraction would require the need for large radiators located on the rover which effectively limits the rover motor capacity. It is more practical for rover control to use an oxygen/carbon monoxide fuel cell although a combustion engine is also possible.



In-situ Resource Utilization Plant diagram (as derived from Allen and Zubrin[34])

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