A New Plan for Sending Humans to Mars: The Mars Society Mission

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Abstract

Optimal cost and safety will be instrumental not only in sending humans to Mars, but also in achieving the political support and scientific consensus that will allow such an endeavor to begin. The Mars Society Mission (MSM) was created to improve upon the safety, cost, and political viability of previous plans, with emphasis on the NASA Reference Mission 3.0 (RM 3.0). The Mars Society Mission is a complete description of a possible 5-human expedition to the Red Planet targeted at the 2011 (cargo) and 2014 (crew) launch opportunities. All components are capable of performing in any succeeding launch windows. The Mars Society Mission features:

1. **Increased redundancy of design for reduced development**. For instance, the Mars Society Mission's Mars Ascent Vehicle (MAV) and Earth Return Vehicle (ERV) derive from a common Crew Return Vehicle (CRV, distinct from that planned for the International Space Station).
2. **Increased redundancy for maximum safety**. A CRV will accompany the outbound habitat module, and in the event of habitat failure would be able to support the crew until arrival on Mars or Earth. After a 612-day surface stay, both the MAV and ERV will accompany the crew during the return to Earth. If either ERV or MAV fails, or Mars orbital rendezvous does not take place, either component could return the crew.
3. **The Qahira Interplanetary Transportation System** (QITS, pronounced "Keats"). QITS is based on the Qahira launch vehicle, a Delta-IV inspired heavy lifter with only two new components, the Qahira Booster Core (QBC) with 4 RS-68 engines, and the Qahira Upper Stage (QUS), with 1 RD0120 engine. The maximum configuration, the Q3041, is capable of sending 55 MT trans-Mars.
4. **Detailed and improved trajectories**, including a 3/2 Hohmann transfer orbit for the ERV that minimizes propellant boil-off and reduces launch facility strain, as well as optimal trajectories for cargo, free-return, and return from Mars surface.
5. **"Piggyback" payload capabilities** to reduce launch costs and encourage additional planetary science missions.
6. **Minimal assembly in Earth orbit**, specifically no more than one Earth orbit rendezvous.
7. **No nuclear thermal rocketry**, and no activation of nuclear power sources until Mars surface.
8. **A large science payload**, with 13.7 MT available for the 2014 mission.

The 2014 Mars Society Mission will consist of five launches, four of which will use the Q3041 configuration: Payload (A), ERV in June 2011; (B) Cargo including power, hydrogen and science in October 2011; (C) MAV and In-Situ Resource Utilization in November, 2011; and (D) Habitat module in January 2014. A Q1310 configuration will launch Payload (E), Crew in CRV, also in January, 2014. Extensive computer programming and simulation were used to design launch vehicles and trajectories. Comparative risk analysis indicates that the Mars Society Mission has significantly less risk of failure than the Reference Mission 3.0 or Mars Direct.

1. Motivation For Design

Among the requirements listed by Goldin for the commencement of a human Mars mission is "an affordable mission scenario that can be accomplished in about one decade."[1] Recent adoption of in-situ resource utilization (ISRU) and other cost-lowering technologies have come close to achieving this, but a politically and scientifically viable mission with unified support has yet to be realized. The Mars Society Mission resolves this problem by addressing the safety and scientific shortcomings of the Reference Mission 3.0 and Mars Direct.

2. Approach to Mission Design

The Mars Society Mission was designed with the final goal of a complete and workable human Mars mission, with the constraints of: (1) technological simplicity, with few new technologies required; maximization of (2) crew survival options and (3) science return; and minimization of (4) politically sensitive technologies without significant increase in cost. The team achieved this goal through computer simulation, spreadsheet, and in-depth final system selection.

2.1. Computer simulation

Three computer simulations were designed using the C programming language to address trajectory, launch capability, and aerocapture.

2.1.1. Trajectory Program

The trajectory program analyzed mean Keplerian orbital elements of Earth and Mars and assumed a heliocentric conic section transfer orbit. Within these approximations, trajectories were calculated exactly. The program was validated by comparison to previous interplanetary probes.[2,3] Table 2.1.1. displays this validation, using C_3 as the benchmark trajectory feature. After establishing this small absolute error in C_3 for recent Mars trajectories, the program was deemed valid for calculations used in designing the Mars Society Mission.

Table 2.1.1. Validation of Trajectory Program

Probe	Predicted C_3 (km^2/s^2)	Actual C_3 (km^2/s^2)	Absolute Error
Mars Global Surveyor	9.9846	10.0194	0.0348
Mars Climate Orbiter	10.93	11.19	0.26

2.1.2. Launch Vehicle Program

The launch vehicle program assumed a gravity turn trajectory, thrust, and a simple model for air drag. Within these approximations, the payload capacity to low-Earth orbit (LEO) was calculated exactly. The Space Shuttle was used as a test case for the launch vehicle program, which predicted a payload capacity of 28.442 MT to LEO, as opposed to an actual 29.5 MT,[4] an error of 3.59%. Given that the error is expected to be greatest for vehicles where the payload is a small fraction of the mass at burnout (such as the Shuttle, and not the Qahira launch vehicles proposed in Section 3.2.), this program was considered valid for use in designing the mission architecture.

2.1.3. Aerocapture Program

The Mars aerocapture phase of the mission was investigated using a computer model of the habitat module with aeroshell entering the Mars atmosphere at speeds of 8 to 13 km/s. Although it could not produce data on the thermal and aerodynamic issues, as it simply assumed lift and drag coefficients, it was useful in determining the deceleration loads on the crew and lift-to-drag ratio required for a successful aerocapture.

2.2. Spreadsheets

Microsoft Excel was used to create spreadsheets to calculate mass and power budgets, ISRU requirements, health effects, risk, and trans-Earth injection. The trans-Earth injection (TEI) spreadsheet was the most complicated; it accepted data from the trajectory program and returned the parameters of TEI such as the required change in velocity (ΔV) and direction of burns.

3. How the Mars Society Mission Will Send the First Humans to Mars

A step-by-step description of the MSM is provided below. Further details on each system and mission phase are given in the appropriate sub-section.

2011: On July 1, 2011 a Q3041 Launch Vehicle, part of the Qahira Interplanetary Transportation System, will send an Earth Return Vehicle on a 3/2-orbit, low energy trans-Mars trajectory. The Earth Return Vehicle consists of a Crew Return Vehicle and a methane-oxygen rocket stage. A second Q3041 launch on October 27, 2011 sends to Mars a cargo vehicle with surface mobility containing liquid hydrogen feedstock, a 160-kWe nuclear reactor, and science equipment. A third Q3041 launches the Mars Ascent Vehicle (MAV) on November 11, 2011. The MAV consists of a CRV and methane-oxygen rocket stage, identical to that on the ERV, with attached first stage and ISRU unit.

2012: On August 24, 2012, the cargo payload aerobrakes into Mars orbit, then aerobrakes again to reach the Martian surface once satisfactory conditions have been ascertained. After a quick preliminary scout, it will deploy the nuclear reactor, and place a radio beacon at a site appropriate for the landing of the MAV, which will join the landed cargo on September 7, 2012. The ISRU unit aboard the MAV will activate and be connected to the nuclear reactor and hydrogen feedstock, and begin making necessary methane, oxygen, and life support reserves.

2013: The Earth Return Vehicle aerobrakes into a Mars orbit of slightly less than $C_3=0$ and of period 3 sols on July 15, 2013. On November 20, 2013, a second MAV intended for the 2016 mission and including a large science payload departs Earth on a Q3041, followed by a Q3041 cargo launch containing liquid hydrogen for the 2016 mission and the pressurized rover to be used by both the 2014 and 2016 missions.

2014: By early January, the ISRU unit's propellant manufacture is complete and it detaches to be used for other MAV's. Back on Earth, verification that the ISRU has succeeded is followed by the launch to low-Earth orbit of an unmanned habitat module aboard a Q3041. After a final check of the MAV's fitness for their return, the crew launches in a Crew Return Vehicle aboard a Q1310 equipped with a Launch Escape System (LES) capable of accelerating crew and CRV to safety in the event of launch failure. After rendezvous in low-Earth orbit, on January 11 the upper stages of first the Q1310 and then the Q3041 push the crew, CRV, and hab module into a 134 day trajectory trans-Mars. After trans-Mars injection, the CRV separates and from a slight distance accompanies the hab, which deploys a 125-meter truss for artificial gravity at the other end of which lies the burnt out QUS, and at the center of which lie the solar panels that will provide 30 kWe power for the crew until they reach Mars. On May 25, the hab and CRV reach Mars. The CRV will be reused and returns to Earth on a free return trajectory, while the habitat with the crew lands on the Martian surface after aerobraking, several orbits of Mars, and finally descent to the surface. On July 4, the 2016 Mission cargo payload with pressurized rover and hydrogen arrives. The 2016 mission MAV lands on September 15.

2016: In January 2016, the 2014 Mission crew board the MAV, which launches them to rendezvous with the ERV parked in Mars orbit. Then, on January 27, firing first the ERV's and then the MAV's engines, both ERV and MAV accompany the crew back to Earth. On December 25, 2015, the CRV that escorted the 2014 Mission returns on its free return trajectory from Mars and aerobrakes into a C_3=0 parking orbit, where it awaits the launch of the 2016 Mission crew in a stripped down ("ghost") CRV aboard a Q1010. The 2016 Mission crew and hab launch aboard a Q1010 and Q3041, respectively. The crew transfers to the hab after docking, after which the ghost CRV's QUS propels hab and ghost CRV partway to C_3=0 for the rendezvous with the free-returned, fully functional 2014 CRV. After the ghost CRV's QUS burnout, the ghost CRV separates and later falls back to Earth, while the hab's QUS completes the rendezvous with the fully functional 2014 CRV. After docking with the 2014 CRV, the hab's QUS sends the crew, 2014 CRV, and hab module on their way to Mars. On June 4, the first crew returns to Earth, descending to the surface in either their ERV or MAV, while the other component aerobrakes into a C_3=0 orbit, there to await its next task, accompanying the crew of the 2018 mission.

The mass scrub of each of the payloads used for the 2014 mission is shown below.

Table 3.A. Habitat Mass Budget

	Mars Direct	Reference Mission	MSM	Explanation for MSM Figures
Habitat Module structure	5.000	5.500	4.751	Reference Mission figure linearly scaled by surface area ratio (.7511) + margin of 15%.
Life-support system	3.000	4.661	3.796	Figure of current NASA model for crew of six.
Consumables	7.000		3.236	Using 98% closed H_2O/O_2 + Food = .000630 MT per person per day. 900 days total.
Descent Power (fuel cell + radiator)	1.000	2.974	1.292	Adapted from Reference Mission 1.0, p. 3-96.
Reaction control system	0.500		0.500	From Mars Direct—not included in RM.
Comm/info	0.200	0.320	0.320	Exact figure from RM.
Science	1.000			On cargo landers – see Section 3.8.2.
Crew	0.400	0.500	0.417	Crew of 184 lbs each.
EVA suits (4 in Mars Direct, 6 in RM and Mars Society Mission)	0.400	0.969	0.969	Reference Mission figure for six suits, thus including a spare.
Furniture and interior	1.000		1.500	Arbitrary.
Open rovers (2 in MD, 1 in MSM)	0.800	0.500		Mass budgeted with surface power.
Pressurized Rover	1.400			Not included in hab payload.
Hydrogen & LSS ISRU			0.406	(.211 MT H_2 Requirement) x (1.468 Tank) x (1.15 for Boiloff) +.05 MT for micro ISRU unit. To provide additional LSS on Mars surface.
Spares and margin (16%)	3.500	0.000		Included in individual listings.
Health care			1.250	Arbitrary.
Thermal		0.550	0.475	Reference Mission figure linearly scaled by surface area ratio (.7511) + margin of 15%.
Crew Accommodations		11.504		Included elsewhere in habitat mass budget.
Surface Power (RM uses RFCs + "keep alive" solar)		1.700	5.000	At least 25 kWe needed. Reference Mission specifies 5.7 MT for 50 kWe nuclear reactor.
EVA Consumables		2.300		Produced by ISRU on MAV and Hab.
Power Distribution		0.275	0.316	Reference Mission figure scaled up by 15%.
Total Landed	25.200	31.753	24.228	Total of above.
Terminal Propulsion + Propellant			5.330	See section 3.7.4.
Parachutes		.7	0.525	¾ RM's 4 parachutes needed.
Orbital Power (solar)			1.682	Assumes rigid panels from DRMv1.
Aeroshell Structure & TPS			9.530	30% of the above mass
Artificial Gravity Truss (125 m)			1.381	See Section 3.7.2.
Transit Power (solar)			1.682	Assumes rigid panels from DRMv1.
Reaction control propellant	Above		1.666	Calculated in section 3.7.2.2.1.
Total Injected			**46.024**	

Table 3.B. 2014 Cargo Lander Mass Budget

Component	Mass (MT)	Explanation
Nuclear reactor	9.300	Reference Mission 3.0. Uses lander mobility for deployment.
Hydrogen	11.760	Stoichiometry.
Tank	4.704	40% of liquid hydrogen mass.
Power Line from Reactor	0.837	Reference Mission 3.0 Mass Scrub
Science & Exploration	4.692	Based on remaining launch to Mars surface capability.
Fuel cell	0.347	5 kWe power (Reference Mission 1.0.)
Cargo lander mobility	5.544	Assumed 15% of total landed mass.
Descent Propulsion	0.612	Four RL-10M engines.
Descent Propellant	7.170	For 632 m/s Delta V.
Propellant Tanks	0.645	9% of Propellant.
Parachutes	0.700	Reference Mission 3.0
Aeroshell	8.185	18% of Payload.
Transit Power 5 kWe solar	0.480	Reference Mission 1.0
Interplanetary RCS	0.800	Provides 45 m/s Delta V.
Total	54.940	Sum of above.

Table 3.C. Total MAV Payload Mass Budget

Component	Mass/MT	Explanation
MAV	15.042	Table 3.5.1. figure minus mass of crew and Mars rocks
ISRU	9.010	See Table 3.5.2.2.B.
1st Stage	12.380	9% of propellant mass + 14 RL-10M engines.
2nd Stage	2.377	9% of propellant mass + 2 RL-10M engines.
Fuel Cell	0.347	Reference Mission v. 1.0 figure[5]
Landing Propellant	3.670	Enough to provide ΔV 324 m/s (see Section 3.4).
Parachutes	0.700	Reference Mission v. 3.0 figure
Aeroshell	8.372	18% of payload
Interplanetary RCS	0.800	Provides 45 m/s ΔV
Transit Solar Power	0.480	Reference Mission v. 1.0 figure
Total	53.178	Sum of above figures

Table 3.D. Overall ERV Payload Mass Budget

Component	Mass/MT	Explanation
CRV	15.459	See Table 3.5.1.
TEI stage structure	2.377	9% of propellant mass + 2 RL-10M engines
TEI stage propellant	23.025	Propellant needed to return crew to Earth
Power supply	0.827	NASA Reference Mission 1.0
Aerobrake	7.504	18% of Payload mass
Interplanetary RCS	0.800	Provides 45 m/s ΔV.
Total	49.992	Sum of above figures

3.1. Crew Size

A crew of five was determined for the Mars Society Mission based on the minimum of four for adequate science return and system maintenance advocated by Mars Direct,[6] with the addition of a crew member for medical duties as advocated by the Reference Mission.[7] Instead of sending two medical crew members as in the Reference Mission, however, at least one of the science crew will be able to supply medical treatment in the event of the medical officer's illness or injury. Five crew members were thus determined to be sufficient for science return, maintenance of systems, and medical upkeep of the crew, a view supported as plausible by Connolly.[8] The rapid accumulation of habitats and other infrastructure at a single point on the Martian surface and the availability of additional CRV's for later missions (see Section 3.10.3.3.) could allow for greater crew size on succeeding missions.

3.2. Qahira Interplanetary Transportation System

The Qahira Interplanetary Transportation System (QITS) will send all crew and cargo to Mars, using two liquid O_2/H_2 components in two main configurations. The smaller configuration, used for the 2014 Crew/CRV launch, will feature three Castor-120 solid rocket boosters attached to the first stage.

3.2.1. Components

The three components of QITS are the Qahira Booster Core (QBC), the Qahira Upper Stage (QUS), and the currently available Castor-120 solid rocket.

Table 3.2.1. Performance Description of QITS Components

	Wet Mass (MT)	Dry Mass (MT)	Thrust, vac. (Mlbs)	Thrust, Sea level (Mlbs)	I_{sp}, vac. (s)	I_{sp}, Sea level (s)	Burn time (s)
RS-68[9]		6.618	.745	.650	410	365	
QBC	560	65.9	2.98	2.60	410	365	151
RD0120[10]		3.44	.44		455		
QUS	205	18.0	.44		455		425
Castor 120[11]	54.1	5.39	.363	.323*	277.9	247*	82.5

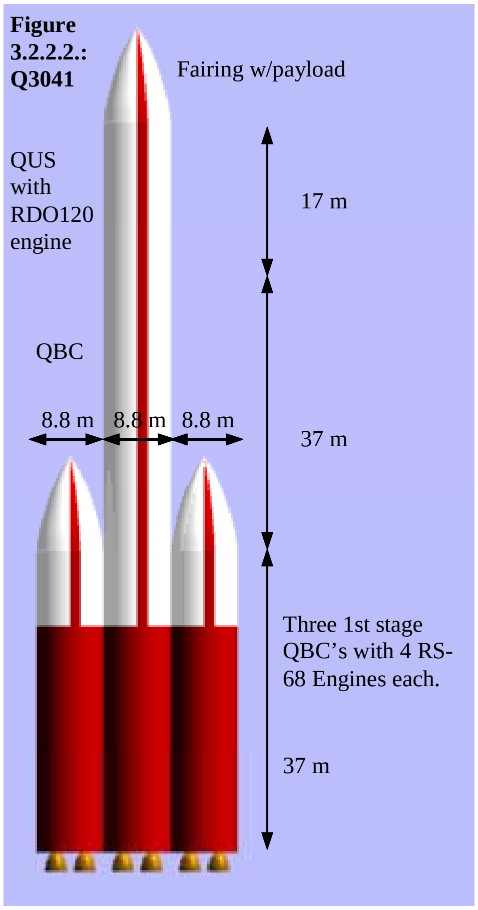
* Estimated from vacuum values

3.2.1.1. Qahira Booster Core

The Qahira Booster Core is powered by four LOX/Hydrogen RS-68 engines. The RS-68 (mixture ratio 6.0) engines were chosen because (1) they are simple; (2) they will have been used and presumably validated many times prior to 2011; and (3) their specifications match those needed for the launch vehicle (moderate to high I_{sp} and high thrust). The QBC has a diameter of 8.8 m and a length of 37 m to provide enough volume for propellant.

3.2.1.2. Qahira Upper Stage

The Qahira Upper Stage serves as a second or third stage for QITS payloads, depending on the configuration. It uses a single RD0120 (mixture ratio 6.0) engine fueled by LOX/Hydrogen. The RDO120 was selected for its high specific impulse and moderately high thrust. The QUS has a diameter of 8.8 m (to match the QBC) and a length of 17 m.



3.2.1.3. Castor-120

The 2014 Crew/CRV launch will use three Castor-120 solid rockets. These rockets were selected because (1) they are inexpensive, (2) simple, and (3) they provide the necessary extra acceleration to allow the QUS of the 2014 Crew/CRV launch to arrive in LEO with sufficient propellant to push the hab and CRV through trans-Mars injection.

3.2.2. Configurations

An advantage of QITS is the ability to mix and match its components to best accommodate a given payload. The two configurations used for the first Mars Society Mission are the Q1310 and Q3041, with the Q1010 and Q3041 used on succeeding missions.

3.2.2.1. Terminology

The terminology for the various QITS configurations is as follows: in the four-digit code, the 1st digit represents the number of QBCs on the 1st stage; the 2nd digit represents the number of solid boosters; the 3rd digit represents the number of engines on the 2nd stage; and the 4th digit represents the number of engines on the 3rd stage. For example, the Q3041 is composed of a 3-QBC 1st stage, 0 solid boosters, a 4-engine 2nd stage, and a 1-engine 3rd stage.

3.2.2.2. Q3041 Configuration

This configuration consists of a three QBC 1st stage, a single QBC 2nd stage, and a single QUS as the 3rd stage. This configuration will be used for all launches except the CRV/Crew payload, because it provides maximum lift capability to Mars, 55 metric tons on a cargo trajectory. The total mass at take-off (including payload) is 2500 MT. Figure 3.2.2.2 depicts the Q3041.

3.2.2.3. Q1310 Configuration

This configuration consists of a single QBC 1st stage and a QUS 2nd stage, with three already-existing Castor-120 solid rocket boosters attached to the 1st stage. Its purpose is to launch payloads which are heavier than what current launch vehicles such as the Proton can handle, but are so light that to place them on a Q3041 would be wasteful. In the MSM, the only use of the Q1310 is to lift the 2014 CRV/Crew payload. A solid-propelled Launch Escape System (LES) similar to that used for the Apollo and Soyuz programs is provided through first stage burnout so that the crew can be recovered in the event of a launch failure. The total mass at take-off is 946 MT.

3.2.2.4. Q1010 Configuration

The Q1010 configuration is simply the Q1310 without the three solid-fueled booster rockets. It is used for the 2016 and succeeding missions.

3.2.3. "Piggyback" payloads

The ERV launch leaves 5 MT of payload capacity unused. Rather than wasting this capacity, the Mars Society Mission uses this space for scientific "piggyback" payloads. These secondary payloads would be released after the upper stage of the Q3041 had burned out. These could include: unmanned spacecraft destined for Mars or its moons (possibly communications or navigation satellites); other planetary science spacecraft, which would be propelled to their destinations by solar-electric propulsion or Mars gravity assist; astronomy satellites that must operate away from Earth, a major infrared source; or space physics satellites to investigate the interplanetary medium. Additional piggyback payloads could be budgeted from within the large science and exploration allotments of the MSM's cargo launches.

3.2.4. Payload packaging

Payload packaging of the MSM differs from the Reference Mission in the orientation of the habitat module. While for the ERV, cargo, and MAV/ISRU launches it is best to have the 9.2-m diameter aeroshell double as a launch shroud as in the NASA Reference Mission, for the human mission this packaging configuration presented difficulties. It prevented the docking port on top of the hab module from easily connecting to the CRV in low-Earth orbit: the hab's aeroshell would be in the way. Therefore, the habitat will launch with the forward part of the aeroshell pointed down into the QUS, with the hab module right-side up and its docking port on top, protected by a light payload fairing. This packaging of the hab module also avoids a sudden reversal of heavy deceleration during Mars entry, as occurs when the Reference Mission hab rotates 180° to fire its retro rockets. Using the MSM launch configuration, the hab module's retro rockets are already properly oriented at this stage of Mars entry. The CRV that will accompany the 2014 Mission outbound crew will launch Apollo-style on the Q1310 with the Launch Escape System on top.

3.2.5. Comparisons with Magnum, NTR, and other Launch Options

The MSM uses the Q3041 heavy lift vehicle, and its smaller siblings, the Q1310 and Q1010, with cryogenic propellants for Trans Mars Injection (TMI), but the decision for this type of launch system came only after consideration of several other launch options. These alternatives for Earth-to-Orbit transportation included a small launch vehicle such as the Proton (20 MT to LEO);[12] a medium launch vehicle in the 40 metric ton range; a Magnum-sized vehicle capable of lifting 80 MT to LEO;[13] and the Q3041 or Saturn-class rocket (151 MT to LEO). The cryogenic propellants for TMI were compared with storable (hydrazine/N_2O_4), nuclear thermal, nuclear electric, and solar electric alternatives.

The use of cryogenic (LOX/hydrogen) propulsion for TMI was decided early in the MSM design process. Nuclear-thermal rocketry (NTR) was rejected for three reasons: (1) NTR presents severe political difficulties; (2) A massive tank is needed to hold the all-hydrogen propellant; and (3) The necessity of reaching a nuclear-safe orbit (at least 407[14]-800 km[15]) before using any NTR stage nearly offset the advantage of its higher specific impulse. Combined with the development costs of the new technology, this argues against nuclear propulsion as an option for human Mars missions possible within a decade.

Ion propulsion was investigated as well, but it was dropped for a multitude of reasons. First, while the exhaust velocities given for ion engines are 5-10 times better than the best cryogenically fueled rockets,[16] ion propulsion requires that the spacecraft slowly spiral away from Earth, then drop back for a chemical rocket stage to provide TMI. The alternative—hundreds or thousands of perigee burns with the ion rocket—would take far too long, and the ion engine would have to provide about 8 km/s of ΔV compared to 3.2 km/s for a LOX/Hydrogen rocket. For solar electric propulsion, the necessary arrays of solar cells would make the reduction in the total mass sent to LEO modest, at best. Finally, for both nuclear and solar electric propulsion, the ion propellant xenon is rare in Earth's atmosphere and therefore costs as much to produce as it does to launch into orbit. The cost savings from ion propulsion may therefore be outweighed by the manufacturing cost of the noble gas.

Finally, storable propellants were found to have too low a specific impulse. Table 3.2.5 summarizes these conclusions; the numbers in each cell of the table indicate the reasons why that possibility was rejected.

Table 3.2.5. Launch Vehicle Rationale

		Launch Vehicle with payload to LEO			
		20 MT Proton	41 MT Q1010	80 MT Magnum	151 MT Q3041
Propulsion Method	Storable (N_2O_4/hydrazine)	7	2	2, 4	2
	Cryogenic (LOX/Hydrogen)	5, 7	6	4	√
	Nuclear Thermal	1, 7	1	1, 4	1
	Ion	3, 7	3	3, 4	3
1. Political difficulties, large tank requirement, reduction in usefulness due to nuclear-safe orbit requirement.					
2. Storable propellants too low in I_{sp} to use unless necessary to prevent boiloff during LEO assembly.					
3. Cost of xenon, offset of I_{sp} by high-ΔV trajectory, requirement of large solar cells for solar electric propulsion.					
4. Liquid Fly-Back Boosters have possible cost, technical issues, and still require QBC and QUS type components.					
5. Boil off of cryogens due to long duration of LEO assembly.					
6. Same development costs for QUS/QBC components as 151 MT vehicle; inefficient to use only smaller configuration.					
7. Long term costs, efficiency, and launch facility strain.					

The launch system that avoids these arguments is the Qahira Interplanetary Transportation System based on the Q3041 with the Q1310 and Q1010 as byproducts, and therefore this system was selected for the Mars Society Mission.

3.2.6. Launch Facilities

The size and placement of QITS' engine and stage components will require either modification of an existing launch pad or construction of a new launch pad. A 90-m high tower was designed for QITS. This tower is high enough to refuel the Q3041's QUS; it is not necessary to have a walkway for crew to Q3041's payload, as only the Q1310 and Q1010 will carry crew, for which a walkway is provided.

3.2.7 Timeline of Earth Ascent

The description of launch events from T+0:00.0 to TMI for the MSM launches is provided in the following sections.

3.2.7.1 Q3041 Earth Ascent Timeline for ERV, MAV/ISRU, and Cargo Launches

Table 3.2.7.1 describes the path of the ERV, MAV/ISRU, and Cargo launches into LEO.

Table 3.2.7.1. Cargo Trajectory-Type Ascent of Q3041

Time	X/km	Y/km	Velocity (km/s)	∠-Vert. (°)	Event
T+0:00.0	0	0	0	0	Liftoff @ 1.4 g
T+0:06.5	0	.09	.028	0	Clear tower
T+0:52.0	1.8	7.1	.331	25	Speed of Sound/Mach 1
T+2:31.0	94	67	2.33	68	Stage 1 separation @ 3.9 g
T+5:02.0	646	163	5.74	86	Stage 2 separation @ 4.1 g
T+8:09.0	1860	199	7.39	90	Stage 3 shut down @ 1.1 g/ enter LEO

The TMI burn is calculated to C_3=15 km^2/s^2, to reach up to 1.77 AU aphelion in the plane of Earth's orbit and sufficient to reach Mars with a wide launch window in any opportunity. TMI for the 2014 Mission launches of 2011 lasts 3 min 57 s for a change in velocity ΔV = 3.91 km/s. Total mass injected is 55 MT.

3.2.7.2. Q3041 Earth Ascent Timeline for Habitat Launch

The habitat launch to LEO differs from the other Q3041 launches because it carries 47 MT of payload for TMI (which will be supplemented by 16 MT carried by the sister Q1310 launch). A dual launch strategy using first the Q3041 to boost the habitat into LEO and then the Q1310 to boost its CRV with the crew was chosen because the Q3041 cannot send the habitat on a fast free-return trajectory to Mars. Upon the Stage 3 QUS shutdown, the Hab gets ready to dock with the CRV containing the crew. Orbit circularization takes place at 360 km for a duration of 6.8 seconds, for a change in velocity ΔV = 0.08 km/s. The 170 MT vehicle is now ready to rendezvous with the crewed CRV. Its mass breaks down into the 47 MT habitat payload and the 18 MT dry QUS with 105 MT propellant. Propellant boiloff is assumed to be kept to 2%, leaving 103 MT.

3.2.7.3. Q1310 Earth Ascent Timeline for 2014 CRV with Crew and LES Launch

Table 3.2.7.3. describes the path of the CRV/crew launch aboard a Q1310 to LEO, for rendezvous with the hab module at 360 km.

Table 3.2.7.3. Ascent of Q1310 with CRV and Crew

Time	X/km	Y/km	Velocity (km/s)	∠-Vert. (°)	Event
T+0:00	0	0	0	0	Liftoff
T+0:05	0	.09	.036	0	Clear tower
T+0:36	1.5	5.3	.331	24	Speed of Sound/Mach 1
T+1:22	21	29	1.12	48	Jettison 3 Castor-120's
T+2:31	133	98	3.00	74	Stage 1 separation @ 4.6 g, jettison LES
T+8:05	1650	296	7.34	89.5	2nd stage shut down @ 2.7 g/ enter transfer

After the initial QUS shutdown, orbit circularization occurs at 360 km and lasts 3.0 seconds, for a change in velocity ΔV = 0.08 km/s. The 73 MT vehicle is now ready to rendezvous with the habitat. Its mass breaks down into the 16 MT CRV and the 18 MT dry QUS with 39 MT propellant.

3.2.7.4. Trans-Mars Injection of 2014 Habitat with Crew and CRV

The smaller vehicle—that is, that launched by the Q1310 consisting of CRV, crew, and QUS—carries out up to 130 m/s of rendezvous maneuvers using 2 MT propellant and leaving 37 MT. The docking occurs in an orbit of 360 km at velocity 7.69 km/s with period 1 hr 32 min. The fully assembled TMI vehicle then has a mass 239 MT, of which 140 MT is propellant.

Of the two QUS stages at each end of the vehicle, with the hab and CRV sandwiched between, the Q1310-launched QUS fires first. It fires for 1 min 24 s, providing 0.75 km/s ΔV and raising the orbit to 360x3830 km with a period of 2 hr 10 min. This QUS is then released. The Q3041-launched QUS fires second, for 3 min 54 s, providing 3.66 km/s Delta V and raising the orbit to C_3=28.1 km^2/s^2.

Rationale for dual launch strategy can be found in Section 3.7.1.

3.3. Trajectories

Exact calculation of trajectories to and from Mars was necessary to determine exact payload capabilities and the time the crew will spend in interplanetary space. Results for outbound flights for all vehicles arriving before the end of 2014 Mission are shown in Table 3.3 in order of arrival.

Table 3.3. Trajectories trans-Mars

		Launch Date	Arrival Date	Transit time/days	C_3 (km^2/s^2)	Perihelion (AU)	Aphelion (AU)	Inclination (degrees)
2014 Mission	Cargo	10/27/2011	8/24/2012	302	10.2	0.98	1.52	0.9
	MAV	11/11/2011	9/7/2012	301	9.0	0.99	1.52	1.7
	ERV	7/1/2011	7/15/2013	731	10.6	1.01	1.52	1.3
	Crew	1/11/2014	5/25/2014	134	26.0	0.98	2.23	0.3
2016 Mission	Cargo	12/8/2013	7/4/2014	208	13.1	0.98	1.60	1.4
	MAV	11/20/2013	9/15/2014	307	13.7	0.96	1.45	1.9

3.3.1. ERV Trajectory

The ERV trajectory from Earth to Mars after launch aboard a Q3041 was calculated as a 3/2-orbit minimum energy trajectory. This decision was made because (1) the same maximum payload capacity is available in both 3/2 and standard Type I & II transfers; (2) the 3/2 trajectory results in a later arrival date around Mars, which means less exposure to the infrared radiation from the Martian surface that is the leading cause of propellant boiloff[17]; and (3) the earlier ERV launch places fewer constraints on launches scheduled for the Type I & II launch windows, and reduces the chance that additional launch facilities would need to be constructed.

3.3.2. MAV/ISRU and Cargo trajectories

The MAV/ISRU cargo payload payloads arrive at Mars using standard Hohmann transfer orbits to maximize their payload capacities, as detailed in Table 3.3.

3.3.3. Free Return Trajectories for Crewed Flights

Evaluation of the Reference Mission and Mars Direct found little detail concerning free return trajectories planned for crewed flights. Mars Direct specifies the same two-year free return trajectory used by the MSM habitat, but gives a transit time to Mars of 180 days,[18] whereas the actual two-year free return trajectory takes a maximum of 154 days. The importance of free return trajectory data for appropriate determination of payload capacity and crew safety called for extensive scrutiny of free return options for the Mars Society Mission. Of the different free return trajectories available, the fastest—lasting two years after Mars flyby—was selected for its hastening of crew return in the event of an emergency. (Actually, faster returns to Earth are possible on trajectories using a Venus flyby on the outbound transit; however, such trajectories are not available in all launch opportunities.) The free return trajectory chosen for the crew launches on January 11, 2014; encounters Mars on May 25, 2014; and returns to Earth on December 25, 2015. Free return trajectories were also important to the MSM for returning to Earth the CRV that escorts the 2014 habitat on the way to Mars. Unless an emergency occurs requiring the use of the CRV beforehand, the CRV will escort the 2016 outbound habitat and crew, as well.

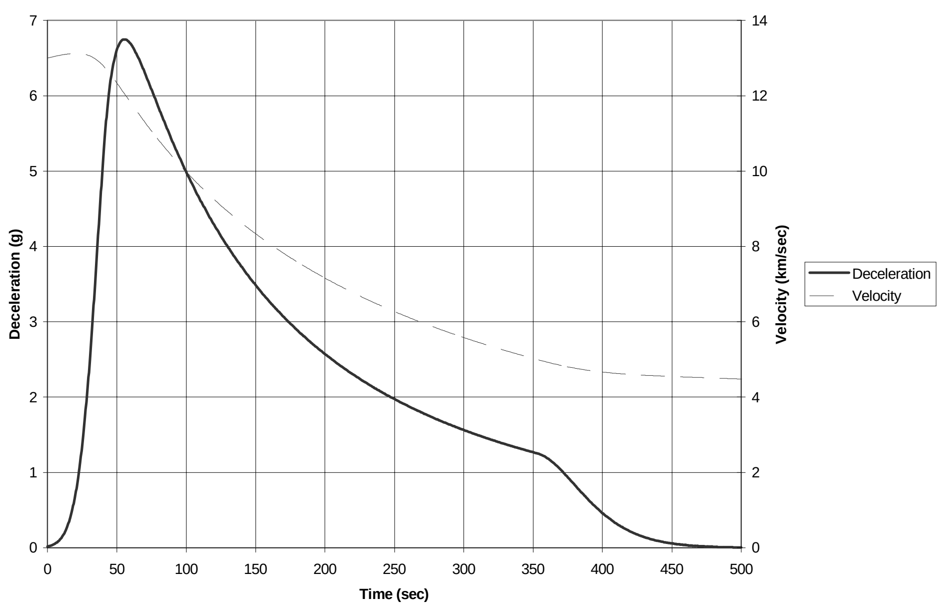
3.3.4. Return trajectories from Mars

The Mars Society Mission's 2014 crew will depart Mars on January 27, 2016. First the ERV's rocket engines fire, putting the crew on a 146-day return trajectory toward Earth with departure C_3=15.7 km^2/s^2. The MAV rocket engine can then fire and provide 0.83 km/sec of ΔV to reduce the transit time to 129 days, returning the crew to Earth on June 4, 2016.

3.4. Aerocapture and Descent

To reduce total mass, aerocapture will be used to insert all vehicles into Mars orbit. The ERV, MAV, and Cargo vehicles use a common biconic aeroshell design that is 13 meters long and 9 meters in diameter at its widest point to capture into Mars orbit. The habitat, being sent on a much faster trajectory and entering the Mars atmosphere at 12.2 km/s, must have a different aeroshell optimized for these higher velocities. Computer simulations of the aerocapture suggested that lift-to-drag ratios of 0.6-0.7 are sufficient for the habitat entry, producing decelerations that peak around 6-7 g. (The deceleration rises quickly at first, going from 1 g to its peak value in ~ 30 seconds. After an additional two minutes, the deceleration has been reduced to 3 g. It is only above 5 g for one minute.)

Figure 3.4. Mars Habitat Aerocapture @ 13 km/sec

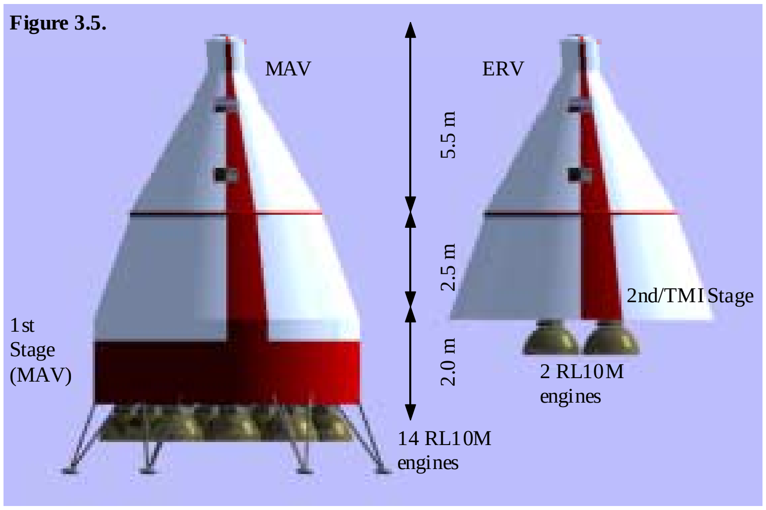


After jettison of the aeroshell, landing is performed using three 50-m diameter parachutes for the hab, four for the MAV and cargo. (The Reference Mission uses four parachutes for every landed payload.[19]) The habitat and Cargo landers burn methane/oxygen bipropellant in four RL-10M engines to provide a final 632 m/s of ΔV and achieve a soft Mars landing,[20] while the MAV lander burns methane and oxygen in its 14 RL-10M engines (see Section 3.5.2.1.). Because of the very high thrust of the MAV lander and its correspondingly greater deceleration, less ΔV is needed on this landing. The 60,000-pound thrust and 40-MT mass figures in Reference Mission 3.0 were used to calculate a terminal descent velocity of 280 m/s with parachutes of the NASA cargo vehicles; for the 240,000-pound thrust used by our MAV lander, we determined that the ΔV needed to land would be only 324 m/s.

3.5. Crew Return Vehicle

The Crew Return Vehicle is the basis for both the Mars Ascent Vehicle and Earth Return Vehicle. Either MAV or ERV can return the crew, the difference being from where: Mars surface for the MAV, low-Mars orbit for the ERV. The generic term "Crew Return Vehicle" is used when the specific designation "ERV" or "MAV" does not matter, such as when discussing the return vehicle's shape, or as during descent to Earth surface, when either MAV or ERV might do the job. Figure 3.5. is a side by side depiction of the CRV's ERV and MAV configurations.

Figure 3.5.



3.5.1. ERV & MAV Mass Budgets

The similarities between the Mars Society Mission ERV and MAV are best illustrated by their mass budgets. Table 3.5.1. itemizes the ERV mass budget of the Reference Mission[21] and the ERV and MAV mass budgets of the Mars Society Mission. The MSM CRV is conical with a base diameter of 6.5 m and a height of 5.5 m. The ratio of the surface area of the Reference Mission ERV to that of the MSM CRV is 0.4295, and this figure was used to linearly scale several mass budget items from the RM to the MSM. Several devices, such as the Reference Mission life-support system, were not scaled down from a RM crew of six to an MSM crew of five, which can be approximated as a 20% margin for the MSM. The "CRV Earth Entry" column describes the mass budget of the CRV immediately prior to re-entering the Earth atmosphere with the crew, the importance of which lay in calculating the aeroshell necessary for returning to Earth. The "CRV Earth Capture" column describes the mass budget of the CRV that will enter a C_3=0 parking orbit immediately after its aerobraking for use in later missions.

Table 3.5.1. ERV/MAV Mass Budgets

	RM ERV	**MSM MAV**	**MSM ERV**	**CRV Earth Entry**	**CRV Earth Capture**	**Comments**
Structure	5.500	2.574	2.574	2.574	2.574	Reference Mission 3.0 figure linearly scaled by surface area ratio (.4295) +15%.
Thermal	0.550	0.257	0.257	0.257	0.257	Scaled from RM 3.0 by S.A., +15%.
Power + dist.	3.249	3.249	3.249	1.292	3.249	Directly from RM 3.0; solar arrays are retractable.
Comm/info	0.320	0.320	0.320	0.320	0.320	Directly from RM 3.0.
Spacesuits	0.243	0.300	0.000	0.300	0.000	MSM figure is for 5 pressure suits.
Crew		0.409	0.000	0.409	0.000	.184 MT each for 5 crew members.
Life support system	3.796	3.796	3.796	2.094	3.796	Exact figure of current NASA model for crew of six.
Food	12.058	0.567	0.000	0.000	0.000	.000630 MT per day per person. RM figure has crew accommodations.
Water & oxygen	0.000	0.095	0.378	0.000	0.095	Assuming 2% open loop for ERV, .5% for MAV (150 day return).
RCS	0.000	0.600	0.600	0.600	0.600	Not listed in Reference Mission.
Mars samples	0.000	0.500	0.000	0.500	0.000	Arbitrary.
Health care	0.000	0.000	1.000	0.000	1.000	Arbitrary.
Science Equipment	0.600	0.000	0.000	0.000	0.000	No need for returning science equipment to Earth.
Spares	1.924	0.000	0.000	0.000	0.000	Accounted for in each item.
Furniture & interior	0.000	0.800	0.800	0.800	0.800	Arbitrary
Subtotal	29.105	13.467	12.975	9.146	12.691	Total excluding Earth landing needs.
Earth Landing Parachute	0.000	0.200	0.200	0.200	0.200	
Aeroshell	0.000	2.284	2.284	2.284	2.284	18% of CRV Earth capture mass
Descent capsule	4.829	0.000	0.000	0.000	0.000	In RM, same unit used for Mars Ascent
Total	33.934	15.951	15.459			

3.5.2. MAV

The Mars Ascent Vehicle is designed to either dock with the ERV in Mars orbit and jointly return the crew to Earth, or to independently return the crew. Its primary difference from the ERV is its second stage.

3.5.2.1. Use of 1st Ascent Stage as Descent Retro-Rocket

The RL-10M engines of the MAV 1st stage will be used to slow the MAV to a gentle touchdown on the Martian surface. This was decided on because (1) the mass of the required propellant (3.67 MT) is far less than a distinct retro-rocket system with or without parachutes and (2) this use allows verification of the MAV 1st stage's functionality all the way to the Mars surface.

3.5.2.2. In-Situ Resource Utilization

The in-situ resource utilization chemical plant is carried aboard the MAV payload attached to the underside of the first stage. Data from TEI calculations were used to find the exact amount of propellant needed. Mass and power needs of the ISRU device for creating life support surpluses was carried over exactly from the Reference Mission, producing an additional 20% margin for the MSM due to the MSM's five member crew size. Since life support figures are unchanged, the mass and power needs of these components was not scaled. Total ISRU output is itemized in Table 3.5.2.2.A.

Table 3.5.2.2.A. Total ISRU Quantities

DRM 3.0	Mass (MT)	MSM	Mass (MT)
O_2	30.33	O_2	106.38
CH_4	8.67	CH_4	30.40
Consumables	23.00	Consumables	23.00
Total	62.00	Total	159.78

The ratio of propellant mass required in the MSM to that required in the RM (3.5385) was used to linearly scale mass and power requirements of propellant-related components for ISRU. The results of this scaling (with comparison to the Reference Mission) are itemized in Table 3.5.2.2.B.

Table 3.5.2.2.B.

	Reference Mission v3.0[22]				**Mars Society Mission**			
	Subsystem Mass (MT)		*Subsystem Power (kWe)*		*Subsystem Mass (MT)*		*Subsystem Power (kWe)*	
Mass Elements	Propellants	Life Support	Propellants	Life Support	Propellants	Life Support	Propellants	Life Support
Compressor	0.496	0.193	5.645	2.893	1.755	0.193	19.975	2.893
Sabatier Reactor	0.060	0.050	0	0	0.212	0.050	0	0
Hydrogen Membrane Separator	0.029	0.023	0.288	0.225	0.103	0.023	1.019	0.225
Methane Water Separator	0.394	0.315		1.69	1.394	0.315	0	1.69
Pyrolysis Unit	0.711	1.172	3.397	3.911	2.516	1.172	12.020	3.911
Electrolysis Unit	0.277		18.734		0.980	0	66.290	0
Oxygen Liquefier	0.043		2.215		0.152	0	7.838	0
Methane Liquefier	0.041		2.093		0.145	0	7.406	0
Subtotal	2.051	1.753	32.372	8.719	7.257	1.753	114.547	8.719
Total	3.804		41.091		9.010		123.266	

After completion of the 2014 mission's MAV fuel production and arrival of the 2014 crew, the ISRU detaches and is moved by the 2014 crew to the 2016 MAV, where propellant production begins again.

3.5.2.3. Two-Stage Mars Ascent System

The MAV uses two stages to either reach the ERV or inject itself trans-Earth. The first stage, which is unique to the MAV, is a cylinder 9 m in diameter and 3 m in height. The MAV 1st stage contains fourteen RL-10M engines arranged in a hexagonal configuration. The MAV 2nd stage is a frustum, going from a 9 m diameter base (to match the 1st stage) to a 6.5 m diameter top (to match the MAV) over a height of 2.5 m. It contains two RL-10M engines.

3.5.2.4. Description of Mars Ascent

The MAV reaches the ERV as described in Table 3.5.2.4.

Table 3.5.2.4. Ascent of MAV

Time	X/km	Y/km	Velocity (km/s)	∠-Vert. (°)	Event
T+0:00	0	0	0	0	Liftoff
T+0:03	0	.013	.009	0	Clear 13 m
T+1:14	2.9	7.6	.238	32	Speed of Sound/Mach 1
T+6:05	370	100	2.99	83	Stage 1 shutdown @ 1.7 g
T+13:01	1580	194	2.88	88.3	Stage 1 restart with 1 engine @ .15g
T+17:20	2340	201	3.24	90	Stage 1 separation @ .16 g/ enter LEO

After a coast period of up to two hours to attain proper orientation relative to the ERV, one RL-10M on 2nd stage of the MAV will ignite for 9 min 33 s and reach the ERV.

3.5.2.5. Back-up Options

The two-stage MAV and adaptability of the ERV provide a number of backup options.

3.5.2.5.1. Failure of First Stage

Immediately prior to T+0:00, the fourteen RL-10M engines can be tested at 30% capacity. If twelve or more are fully functional, the crew can increase the engine performance to 100% and launch; they then have enough thrust to reach Mars orbit, rendezvous with the orbiting ERV, and return home in the event of a docking failure. The crew can still reach the ERV if they have ten of the fourteen engines working by jettisoning the MAV first stage sub-orbital and firing their second stage to reach the ERV orbit, at which point the Mars orbit rendezvous would have to work. If even more engines failed, the crew could still reach low Mars orbit and the ERV could descend to meet them; however, such an event is extremely unlikely – if the probability of an RL-10M engine failing is 2%, then losing five or more engines will occur on 1 in 150,000 missions.

3.5.2.5.2. Failure of Second Stage

If the MAV second stage fails completely, then the crew remains in low Mars orbit while the ERV aerobrakes down to their altitude. Then the crew transfers to the ERV, separates from the MAV, and fires the ERV rocket stage to return to Earth in 148 days.

3.5.2.5.3. Failure of Orbital Rendezvous

In the event of failure of the Mars orbital rendezvous, the MAV has enough propellant to return to Earth by itself on a 146-day return trajectory to Earth.

3.5.2.6. Overall mass budget for MAV/ISRU payload

The mass budget for the MAV and ISRU payload to be launched from Earth on a Qahira 3041 is given in Table 3.C. (Section 3 introduction.)

3.5.3. ERV

The ERV is designed to return the crew from anywhere in Mars orbit. It consists of a CRV-based ERV, and a trans-Earth injection stage that is identical MAV's second stage, the only difference being that the methane/oxygen bipropellant of the ERV will come from Earth.

3.5.3.1. Description of ERV and MAV Combined Trans-Earth Injection

The combined MAV/ERV will inject itself trans-Earth as described in Section 3.3.4.

3.5.3.2. Back-up Options

The presence of both an ERV and MAV capable of returning the crew provides for a number of contingencies.

3.5.3.2.1. Failure of ERV Trans-Earth Injection Stage

If the ERV's trans-Earth injection stage fails, the crew abandon the ERV and continue on to Earth in the MAV alone, using a firing sequence similar to that in Section 3.5.2.5.3.

3.5.3.2.2. Failure of ERV Critical Systems

If the ERV's life support, communications system, or other critical system is disabled and the ERV is rendered unable to support the crew before or after TEI, the ERV will still accompany the crew. This is because (1) a faster trajectory is possible using both ERV and MAV stages, regardless of life support capabilities and (2) the ERV could still provide spare parts to the MAV or be repaired after aerobraking into Earth orbit.

3.5.3.3. Rationale for Freefall During Transit to Earth

Freefall during return from Mars was deemed acceptable because (1) the deceleration upon entering Earth's atmosphere would not be as great as that experienced during Mars entry; (2) full medical support would be available to the crew upon arrival on Earth, with no physical activity immediately required, and (3) the 129 day return trajectory from Mars is comparable to time in freefall experienced by previous astronauts with no long-term ill effects.

3.5.3.4. Overall mass budget for ERV payload

The mass budget for the ERV payload to be launched from Earth on a Qahira 3041 is given in Table 3.D. (Section 3 introduction.)

3.6. Cargo Lander

The Mars Society Mission will launch hydrogen feedstock, a nuclear reactor, and additional science and exploration equipment aboard a Q3041 on October 27, 2011. This cargo lander is mobile to allow easy deployment of the nuclear reactor and transportation of the liquid hydrogen to the MAV.

3.6.1. Power

Power needs were calculated based on the requirements for ISRU, MAV, and habitat module. The power requirement of 123 kWe for ISRU are detailed in Section 3.5.2.2. The hab power requirement of under 25 kWe is justified in section 3.7.2. The MAV will be primarily in utility mode during its stay on the Mars surface, requiring around 5 kWe of power.[23] A SP-100 type nuclear reactor capable of 160 kWe and massing 9.3 MT, is more than able to meet these power needs.[24] With the addition of the hab 30 kWe nuclear reactor, a total of 190 kWe is available, providing a surplus of around 37 kWe to recharge the rover (see Section 3.8) and power science equipment. The nuclear reactor aboard the cargo flight will be deployed using the cargo lander mobility.

3.6.2. Liquid Hydrogen

For an ISRU unit to create 30.67 MT of methane and 23 MT of water, 10.22 MT of feedstock hydrogen are needed. To provide for losses of 15% in the ISRU plant and through boiloff, the MSM sends 11.76 MT of liquid hydrogen in the cargo lander. The hydrogen tank (with mass 40% that of the hydrogen) will be moved to the ISRU unit attached to the MAV using unpressurized rovers.

3.6.3. Cargo Lander Mass Budget

The mass budget for the cargo payload to be launched from Earth on a Qahira 3041 is given in Table 3.B. (Section 3.0).

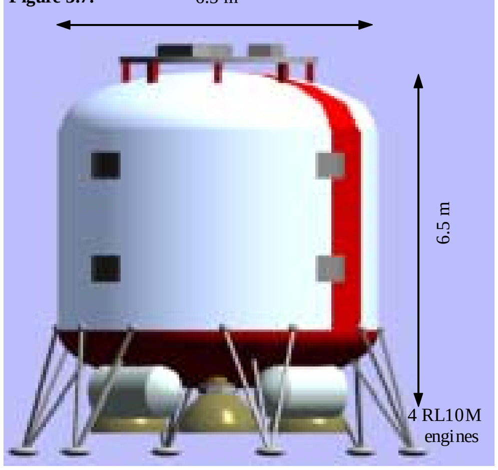
3.6.4. Science and Exploration Equipment

The Mars Society Mission will use 4.692 MT available on the cargo launch for science and exploration equipment, which can also include science support and mobility components such as unpressurized rovers. This space was initially considered for the pressurized rover, but because many rover designs exceed this mass allotment and it is desirable to send the rover to Mars as a single piece, the rover was moved to the cargo launch for the 2016 mission. The mass thus made available to science equipment is 2.6 times the amount available (1.77 MT) in the Reference Mission 3.0 for Mars surface science and exploration.[25] This large amount of science equipment provides a clear indication that science is the mission focus, and will be instrumental in establishing the mission's scientific credibility. Additional science equipment is available to the 2014 Mission crew from the 2016 Mission launches. See Section 3.8.2 for a discussion of exactly which scientific equipment can be sent and what it can do.

3.7. Habitat

The habitat module used in the Mars Society Mission is similar in concept to that of Mars Direct and the Reference Mission. Figure 3.7. depicts the hab module as it would appear landed on Mars.

Figure 3.7.



3.7.1. Dual Launch Strategy

A dual launch strategy was initially decided upon because the desired mass of the hab module to be injected (47 MT) exceeded the capabilities of what Q3041 could send on the 134 day free return trajectory. This was deemed preferable to a larger launch vehicle or additional new components because (1) a smaller Q1310 was a simpler solution and required no development of new components and (2) the secondary Q1310 launch allowed enough additional payload capacity for the inclusion of a 100% redundant backup in the form of a CRV.

3.7.2. Artificial Gravity System

An artificial gravity system was deemed necessary for the MSM's outbound hab flight to (1) minimize bone loss and other effects of freefall; (2) reduce the shock of deceleration during Mars aerobraking; and (3) have optimal crew capabilities immediately upon Mars landing. Experience with astronauts and cosmonauts who spent many months on Mir suggests that if the crew is not provided with artificial gravity on the way to Mars, they will arrive on another planet physically weak. This is obviously not desirable. Countermeasures to freefall are suggested as a means of solving this problem, but are not very effective at present. Unless a set of countermeasures that can reduce physiological degradation in microgravity to acceptable levels is developed, the only real alternatives to a vehicle that spins for artificial gravity are futuristic spacecraft that can accelerate (and then decelerate) fast enough to reach Mars in weeks, not months. To save on mass, the MSM uses an artificial gravity system with the habitat counterbalanced by a burned-out QUS, as in Mars Direct.

3.7.2.1. Rationale For Truss System

If 3 rpm is taken as the maximum rotational rate that we may subject humans to for long-duration missions, and Mars gravity (which is easier to provide than Earth gravity, but will of course condition the crew for the gravitational environment of their destination) is desired, the distance between the spacecraft and its burned-out upper stage is calculated to be 125 meters. The mass of an aluminum truss was calculated according to the equation $M = (6gml\rho)/s_t$, where the number 6 is for margin, deployment mechanism, and cross-struts, g is the desired acceleration, m is the mass at one end of the truss which experiences this acceleration, l is the length of the truss, ρ is the density of the truss material (in this case aluminum, 2,700 kg/m^3), and s_t is the tensile strength of the truss material (for aluminum 220,000 N/m^2).'[26] Oscillation was not deemed problematic because the oscillation frequencies of the truss in all cases were much higher than the frequency of the system's rotation.

A truss connection between the hab and burnt-out QUS was chosen over a tether because the truss had (1) a much lower risk of failure when impacted by a micrometeorite; (2) no risk of snag; (3) less energy stored in the tension of the connecting structure which could be potentially damaging if released. An artificial acceleration due to gravity of 3.7 m/s^2 was chosen as a compromise between desired fitness of the crew and mass and mass budget concerns stemming from a larger truss. The final mass budgeted to the artificial gravity system is enough for a truss system capable of bearing 6 times the expected load.

3.7.2.2. Artificial Gravity, CRV Escort, and Reaction Control

After trans-Mars injection and transfer of the crew from the CRV escort in which they launched to the hab, the hab will separate from the CRV, which will use its reaction control system to move a short distance away from the hab/QUS and out of the system's plane of rotation, to guarantee the CRV's safety in the unlikely event of truss failure. In case of emergency requiring relocation to the CRV, the hab will have to spin down and dock. With modern technology, this process could be automated.

3.7.2.2.1. Reaction Control System (RCS) Propellant Needs

In addition to hydrazine reaction control propellant already needed for guidance and maneuvering, the artificial gravity system introduces the requirement of RCS propellant for spin up, spin down, and turning of the entire system to allow the solar panels to face the sun continuously. The figure for necessary RCS propellant produced by this reasoning was increased by 20% so that the mission could still be carried out if one of the six RCS tanks was destroyed. The total propellant need for a normal mission was 1282 kg (646 kg for the artificial gravity system), so 1666 kg was budgeted for reaction control. In the case of the free return trajectory, the habitat's RCS propellant budget is pushed closer to the total amount available. However, in this case the CRV used to escort the hab to Mars could provide some of the reaction control needs.

3.7.2.2.2. CRV Escort

The CRV is tagging along with the habitat on the trip to Mars to provide the crew with a backup spacecraft which can keep them alive in the event a critical system on the habitat fails. One instance in which the CRV would be used is failure of the habitat life support. The hab life support system was designed with surpluses for 98% closed loop operation. This means that for up to 2% of the 900-day potential operational lifetime—18 days total—the hab life support system can malfunction without endangering the crew. If the malfunction cannot be repaired, the 18 day allowance grants ample time to spin down the hab, dock with the CRV, and transfer the crew.

In the unlikely event of unrepairable habitat breach, the critical factor is the length of time it takes the crew to don their spacesuits. Even if no artificial gravity were present and the CRV and hab had remained docked, the port between the two would be closed to prevent a single breach from robbing air from both components. Continuing the explanation of why the freefall situation is not necessarily safer than the artificial gravity situation, the crew in both cases would perform a brief EVA traveling between the airlocks of each vehicle in order to minimize further air loss (the docking port is not an airlock; it is meant to contain the air pressure of its respective vehicle while closed, and allow travel between two pressurized vehicles when open). True, the crew of the hab with artificial gravity would have the added complication of de-spinning and docking with the CRV, but once in spacesuits the operational lifetimes of the suits would provide more than ample time for the automated despinning and docking procedure. Finally, the likeliest form of hab breach is one that is small and repairable, and if the breach is not repairable, it is likely to be at least slow enough to allow adequate time for spacesuits, despin, and docking.

3.7.3. Hab power systems

The habitat module will use solar panels during its transit to Mars, regenerative fuel cells during power disruptions due to events such as aerobraking , and nuclear power during the Mars surface mission. The NASA Reference Mission version 1.0 specified a 29.4 kWe power need for the habitat[27]; however, the life support power requirements have been reduced from 12 kW to 5831 watts.[28] This reduces the total power requirement to below the 25 kWe level assumed for normal habitat operation.

3.7.3.1. En route power

The Habitat module has two identical sets of solar panels, which are identical to those of RM 3.0 including their power output of 30kWe. The first is deployed at as an attachment to the center of the artificial gravity truss between the hab and QUS. It was decided to abandon this power along with the truss prior to Mars aerobraking because (1) the mass of an additional set of solar panels should the hab need to remain in orbit was considered negligible, (2) a system to retrieve the first solar array would be complex, and (3) the mass of the retrieval system would cancel any mass benefit from not needing a second solar array. After detachment of the truss and its solar array, the hab will most likely aerocapture directly to Mars surface. However, if a dust storm or other complication precludes direct aerocapture, the hab will deploy its second set of solar panels upon leaving the atmosphere and attaining parking orbit, subsisting on its regenerative fuel cells during aerobraking and passage over the nighttime hemisphere of Mars.

3.7.3.2. Surface power and deployment

Upon reaching the Mars surface, the habitat will deploy a 30 kWe nuclear reactor which will be deposited by a robotic rover in a crater or similar shielded area. A nuclear power source was chosen as superior to solar panels or RFC's on the Martian surface. Solar arrays are not efficient on the Mars surface where full sunlight is 485 W/m^2 at aphelion, and low angles of the sun, night, and atmospheric dust reduce the amount of light reaching solar arrays even further, causing the mass of the surface solar power system to become prohibitive.[29] RFC's were rejected for hab contingency power because the lifetime of the mass of RFC's budgeted for the Reference Mission is less than 24 hours, which requires that the crew tap into the existing Martian power grid in an unreasonably short amount of time. This would be problematic in the event of hab landing farther than 1 km from the target. Furthermore, longer lasting RFC's would have too large a mass penalty. Use of a small nuclear reactor as in the Mars Society Mission provides virtually unlimited time to complete surface rendezvous. If future development of solar arrays allows the substitution of solar for nuclear power on the surface, then such a substitution should be made.

3.7.4. Habitat descent system

The habitat will decelerate to a soft landing on the Martian surface by (1) aerobraking with its aeroshell, (2) deploying three 50-m diameter parachutes, and (3) firing its four RL-10M engines to produce 80,000 pounds of thrust during the landing. The propellant masses were calculated to produce 632 meters per second of ΔV required during the landing.[30] The habitat is designed with six landing legs (as are all landed components) rather than three or four so that it can still land if one of the legs fails to deploy. This would prevent it from suffering the fate of the DC-XA experimental single stage rocket, which tipped over in 1996 and was destroyed during a vertical-landing attempt when one of its four legs did not deploy properly.[31]

3.7.5. Habitat in-situ resource utilization

The habitat carries 211 kg of liquid hydrogen to the Mars surface for use in life support in-situ resource utilization. Although it is not essential for the mission, inclusion of this hydrogen and a small ISRU plant for generating oxygen and water is an important safety feature, as it allows the crew to produce 1.9 MT of water and 0.1 MT of oxygen, sufficient for the crew to survive for 19 days on the surface of Mars running on open-loop life support, even if they do not land next to their MAV and cargo lander. The water and oxygen produced could also be used to support the crew on the Mars surface for 630 days in the event that the life support system loses efficiency and can only achieve 97% closure for water and oxygen loops.

3.7.6. Habitat mass budget

The MSM habitat module launched in 2014 and its successors consist of a 4.1 m tall cylinder 6.5 m in diameter capped on top and bottom by hemi-ellipsoids that increase the total height to 6.5 m. The ratio of the surface area of the MSM hab to that of the Reference Mission is .7511, and this figure was used to linearly scale several mass budget items from RM to MSM. Several devices, such as the Reference Mission life-support system, were not scaled down from a RM crew of six to an MSM crew of five, which can be approximated as a 20% margin for the MSM. Table 3.A (Section 3.0) itemizes the habitat mass budgets of Mars Direct[32], the Reference Mission[33], and the Mars Society Mission.

3.8. Resources Available from the 2016 Mission Launches

The 2016 Mission launches to the Mars surface include MAV and Cargo payloads, both of which are launched in December 2013, and arrive on Mars in July 2014, within 40 days of the 2014 Mission's May 25, 2014 crew arrival date. As both vehicles land at the 2014 Mission landing site, additional equipment is available to the crew.

3.8.1. CRV-Derived Pressurized Rover

The Mars Society Mission lands a CRV-derived pressurized rover in July 2014, as part of the cargo payload for the 2016 mission. Table 3.8.1. illustrates mass available on this cargo payload.

Table 3.8.1. 2016 Cargo Payload Mass Budget

Component	Mass (MT)	Explanation
Hydrogen	11.760	Stoichiometry
Tank	4.704	40% of liquid hydrogen mass
Descent power (fuel cell)	0.000	Replaced by Rover RFC's
Rover	**19.536**	**Based on remaining launch to Mars surface capability**
Descent Propulsion	0.612	4x RL-10M
Descent Propellant	7.103	For 632 m/s Delta V
Propellant Tanks	0.639	9% of Propellant
Parachutes	0.700	RM 3.0
Aeroshell	8.110	18% of Payload
Transit Power 5 kWe solar	0.480	RM 1.0
Interplanetary RCS	0.800	Provides 45 m/s Delta V
Total	**54.444**	

The essential component of the 2016 Mission cargo flight, the 17 MT of feedstock hydrogen with tank for the 2016 MAV, leaves 19 MT for a rover's structure and power. The Mars Society Mission's considerations for the rover were (1) minimizing radiation on the launchpad on Earth and (2) minimizing rover mass while (3) maximizing range and carrying capacity. Minimizing radiation was decided upon as the most important factor to avoid the political issues that might prevent a human Mars mission from happening at all.

3.8.1.1. Rover Power

The Mars Society Mission recommends a rover powered by regenerative fuel cells (RFC's). The decision for the RFC system over a Dynamic Isotope Power System (DIPS) was made for political expediency, as the low mass and theoretically infinite range of a DIPS system make it the undisputed choice from a scientific standpoint. A 10 kWe DIPS system converting heat to electricity at 25% efficiency has an activity of 870 kCi; this amount of radiation on the launch pad would reduce the political viability of initiating a human Mars mission. The DIPS radiation level compares poorly to the combined launch pad radiation levels of the 30 and 160 kWe nuclear reactors; even though the SP-100 type reactors generate substantial penetrating β- and γ-particle radiation upon activation on the Mars surface, their launch pad levels of < 1 Ci make them less threatening to the public. The α-particles emitted by the DIPS ^{238}Pu are easy to shield, but given the recent experience of Cassini, the 71 kg of ^{238}Pu required for a DIPS rover should not be made a prerequisite to human exploration of Mars.

Unfortunately, the RFC-powered rover has a limited range because it must return to the nuclear reactor for recharging. The mass available for RFCs on our rover is 7.387 MT, greater than the 6.5 MT[34] estimated to be necessary for the rover to travel 500 km from its base and return. Therefore, the MSM rover is suitable for use in regional exploration.

3.8.1.2. Rover Mass Budget

The Reference Mission 1.0 assigns 16.5 MT rover to the pressurized rover, with 1.1 MT for DIPS.[35] The Mars Society Mission's CRV-derived rover improves upon the structural mass of the rover by using a modified CRV, but the use of a heavier power system, RFC's, raises the total rover mass to 19.536 MT. The CRV's mass budget is available in Section 3.5. The rover's mass budget is itemized in Table 3.8.1.2.

Table 3.8.1.2. CRV-Derived Rover Mass Budget

Component	**CRV-Based Rover**	**Explanation**
Structure	2.574	CRV figure
Thermal	0.257	CRV figure
Power + dist.	7.387	Remaining available for RFC's
Comm/info	0.320	CRV figure
Life support system	3.796	CRV figure
Food	0.095	.000630 MT for 5 people for 30 days
Water & oxygen	1.051	Enough for 10 days of open loop operation
Furniture & interior	0.800	CRV figure
Subtotal	16.280	Sum of the above
Wheels & Mobility	3.256	20% of subtotal
Total	19.536	Total rover mass

The MSM rover lands with water and oxygen for 10 days, in case it has to be used as an emergency vehicle immediately. This water and oxygen allowance, supplemented from ISRU-created stores after losses from EVA and other leakage, means that all five crew members can be 10 days away from base camp when life support fails and successfully return with a 20% margin. The mass of the wheels, carriage, and other mobility requirements was taken as 20% of the landed mass.

3.8.2. Science and Exploration Equipment

The crew of the first human Mars mission will be on Mars for 612 days. During this time, they will conduct scientific investigations of Mars and perform experiments that pave the way for the construction of a Mars base. To do so, they will make use of the 13.7 MT of science equipment sent to Mars on the 2014 cargo and 2016 MAV flights. The 13.7 MT figure is dictated by the amount of space that arises naturally since the MSM vehicles are not all the same size and the launch system is designed to deliver the largest one. It was not chosen due to a desire to include that much payload.

Nevertheless, this payload space is there and it would be foolish to waste it. Therefore, it was devoted to science equipment. The NASA Reference Mission version 3.0 budgets 1.77 MT for scientific equipment including a field geology package, geoscience laboratory, exobiology laboratory, traverse geophysical instruments, geophysical/meteorology instruments, a 10-meter drill, meterology balloons, and a biomedical/biosciences lab. In addition it allots 600 kg of instrumentation for cruise science (space physics, solar studies, and astronomy). Such instrumentation could be included on the ERV, which weighs 5 MT less than the Q3041 payload capacity; however, it should be noted that sending such instruments into Mars orbit and then bringing them back onto a trans-Earth trajectory is wasteful of propellant. It might be better to piggyback a robotic vehicle with this equipment on the ERV flight. This is especially true since, unlike geological investigations on Mars, cruise science can be automated.

For the MSM, the 13.7 MT of surface science equipment can include a 9 MT drill (capable of reaching hundreds of meters depth), and 4.7 MT of other equipment. This can include the 1114 kg of exobiological, geological, and meteorological equipment specified by the MERLIN study[36]; the 1770 kg science package in the NASA Reference Mission (which provides some overlap with the MERLIN equipment)[37]; and the 1000 kg advanced meteorology laboratory planned for the Reference Mission's third crew.[38] After this, there are still 800 kg left over for discretionary science.

3.9. Risk analysis

When sending humans to Mars, it is desirable to know the level of risk to human life in each plan. In this case, risk estimation is an inexact science that is made even more rough by the fact that many of the relevant systems do not yet exist. What is needed is a means of comparing mission architectures. The best means of doing this are different for the outbound, surface, and return phases.

Since the outbound and surface phases of the mission are similar among the Mars Direct, Reference Mission, and MSM proposals, we did not study them extensively. However, there is good reason to believe that the MSM is the safest during these phases. The CRV escort provides backup to the habitat in many critical functions during the outbound transit, and can completely replace the hab in the event of hab failure; also, the launch vehicle is equipped with an Apollo-style Launch Escape System, which is not the case in either Mars Direct or the Reference Mission. Finally, a serious question about the Reference Mission's safety is surface power, which the habitat cannot provide. If the Mars surface rendezvous fails, even by a few kilometers, the habitat would be stuck on another planet without power. The crew, incapacitated by months of microgravity, would likely perish.

The main safety drawbacks of the MSM are that the crew is placed on a new launch vehicle, and that the Mars aerocapture is performed at high speed. Unfortunately, at the present time, we can say very little about the reliability of planetary aerocapture fifteen years in the future; any numerical estimates would be very speculative. Partial answers to these issues are that the presence of an escape tower and the use of all-proven engines on the Q1310 might outweigh the "new launch vehicle" issue, and that a free return trajectory and fast transit time are worth the slightly riskier aerocapture.

It should be emphasized that the risk analysis shown below was comparative. An absolute estimation would require knowledge of the exact systems to be used; since a mission architecture does not include such specific components, a bottoms-up risk analysis of this kind was impossible. Absolute risk estimation would also require analysis of factors such as radiation, which do not vary appreciably between the three architectures evaluated here, although it should be noted, the MSM CRV provides approximately 13 g/cm^2 of shielding, the hab, 17 g/cm^2. To compare mission architectures, it is appropriate to model the risk instead based on failures at the level of spacecraft, rocket engines, and the tasks which these are expected to perform.

It was decided to estimate the probability of losing the crew during Earth return (that is, the inbound phase) as a function of six parameters: the probability per engine of a rocket engine having to be shut down, r; the probability per engine of a rocket stage exploding when fired, R; the probability of a Mars orbit rendezvous failing, f; the probability of a CRV or CRV-type capsule failing, p; the probability of a habitat failing, q; and the probability of losing the crew during Earth aeroentry, K. To lowest order, the resulting equations were:

Table 3.9.A. Methods for Calculating Risk

Plan	**Probability of Not Returning the Crew from Mars Surface**
Mars Direct*	$7R+r+15r^2+p+K$
Reference Mission	$4R+2r+r^2+f+q+K$
Mars Society Mission	$18R+r^2f+2r^2p+p^2-fp^2+fp+K$
MSM minus ERV	$16R+r^2+364r^3+p+K$
*Requiring 5 of 6 engines on first stage, 1 of 1 on second.	

The starting assumption was for r=0.002, R=0.0005, f=0.01, p=0.02, q=0.01, and K=0.005, yielding risks of 3.1% each for Mars Direct and the Reference Mission and 1.5% for the MSM. However, a variety of other possibilities were examined, as seen in Table 3.9.B.

Table 3.9.B. Effect of Different Risk Assumptions on Total Mission Risk

Possibility	**Assumption(s)**	**Risk of Mission:**			
		Mars Direct	NASA DRM	MSM minus ERV	**Mars Society**
Starting assumptions		3.1%	3.1%	3.3%	**1.5%**
Mass budget forces less redundant CRV*	p=0.08	9.1%	3.1%	9.3%	**2.1%**
Mars orbit rendezvous considered risky	f=0.05	3.1%	7.1%	3.3%	**1.5%**
Mars orbit rendezvous nearly guaranteed	f=0.0005	3.1%	2.2%	3.3%	**1.4%**
Unreliable engines	r=0.005, R=0.001	3.7%	3.9%	4.1%	**2.4%**
CRV almost as good as habitat	p=0.0133	2.4%	3.1%	2.6%	**1.4%**
*A concern that was raised about Mars Direct					

As can be seen, the MSM is the safest mission in all of these scenarios - as long as the ERV is included. It is because of this risk reduction and the comparatively low development costs that the ERV was included in the Mars Society Mission in the first place. Several times, our team considered removing it from the plan. However, since it cuts the return risk by approximately half, and also provides a CRV to accompany the next outbound crew, the ERV was left in the mission plan.

3.10. Beyond the First Mission

The flexibility of many Mars Society Mission aspects allows for a number of options for the 2016 and later missions.

3.10.1. Incorporation of Future Technologies into QITS

While the LOX/Hydrogen based QITS is all that is needed for the Mars Society Mission plan, and is the MSM's recommended launch system, it would be fully compatible with upgrades such as Magnum-style liquid flyback boosters (LFBB's), which in any case require a core stage such as the QBC and QUS. One such configuration, playfully dubbed the FatCat, could use two pairs of LFBB's arranged in two catamarans on both sides of a QBC as its 1st stage, a second QBC as its 2nd stage, and a single QUS as its 3rd stage to send 73 MT trans-Mars on a single launch. However, it should be emphasized that upgrades such as the FatCat's LFBB's are neither necessary nor directly planned for by MSM, and thus should not be included in calculating the MSM's development cost. A nuclear thermal rocket (NTR) as a fourth stage could increase the Q3041 lift capability to Mars to approximately 70 MT.

3.10.2. Crewed Launches of 2016 and Later

This section is designed to explore additional possibilities for later crewed launches using QITS.

While it is possible to launch the crews of succeeding missions in the same manner as the 2014 Mission, a more economical option is to launch crews aboard a lightweight, "ghost" CRV stripped of life support and food, all of which will not be necessary during the brief transit from Earth to the orbiting hab. Instead, the same reserves that allow 3.8 days of open loop operation during a CRV's return from Mars provide ample life support ascent to the hab. This lighter vehicle allows for the use of a Q1010 and elimination of the Castor-120 solid rocket boosters.

3.10.2.1. Ghost CRV
The ghost CRV is identical to the fully functional CRV's used elsewhere in the Mars Society Mission (see Section 3.5.) but without food or a recycling life support system, giving it a mass of 11.088 MT as opposed to 15.951 MT for a fully functional CRV.

3.10.2.2. Q1010 Earth Ascent Timeline for 2016 Ghost CRV with Crew and LES Launch
The 2016 crew launch involves first a Q3041 launch with a habitat, as in the 2014 crew launch. However, the crew launches in an 11.088 MT ghost CRV that is light enough to be launched by a Q1010 - that is, a Q1310 without the solid boosters. After the initial QUS shutdown, orbit circularization occurs at 360 km and lasts 1.3 seconds, for a change in velocity ΔV = 0.04 km/s. The 63.6 MT vehicle is now ready to rendezvous with the habitat. Its mass breaks down into the 11.1 MT CRV and the 18.0 MT dry QUS with 34.5 MT propellant.

The smaller vehicle—that is, that launched by the Q1010 consisting of ghost CRV, crew, and QUS—carries out up to 130 m/s of rendezvous maneuvers using 2 MT propellant and leaving 32.5 MT. The docking occurs in an orbit of 360 km at velocity 7.69 km/s with period 1 hr 32 min. The fully assembled TMI vehicle then has mass 229.6 MT, of which 135.5 MT is propellant.

3.10.2.3. Trans-Mars Injection of 2016 Habitat with Crew and 2014 CRV
Of the two QUS stages at each end of the vehicle, with the hab and ghost CRV sandwiched between, the Q1010-launched QUS fires first. It fires for 1 min 14 s, providing 0.68 km/s ΔV and raising the orbit to 360x3410 km with a period of 2 hr 5 min. The crew transfers to the hab and the QUS and its ghost CRV are then released. The Q3041-launched payload (QUS and hab) is then accelerated by the QUS's single RD0120 engine. This fires for 2 min 44 s, providing 2.51 km/s Delta V and raising the orbit to C_3=0. Here the crew can dock with the CRV left behind at that energy by a previous mission, using up to 130 m/s of ΔV for rendezvous maneuvers. After docking, the vehicle consists of a QUS (18 MT dry with 28 MT propellant), 47 MT hab, and 16 MT full CRV. The QUS then fires its engine again for 1 min 4 sec, burning all its remaining propellant to provide ΔV=1.32 km/sec. As the ghost CRV is designed to carry the crew back to the Earth's surface intact, there is no reason not to land the ghost CRV intact even without crew. When the ghost CRV's QUS burns out and the CRV jettisoned, the perigee of its orbit is only 360 km. If the ghost CRV's orbit is allowed to decay in a controlled manner, it can be recovered, refurbished (necessary only for the aeroshell), and reused to launch the 2018 and succeeding crews.

3.10.3. Additional Applications of the CRV
The redundancy of the CRV used by the Mars Society Mission is the basis for additional applications unrelated or merely incidental to sending humans to Mars.

3.10.3.1. Lifetime of a Typical CRV
The availability of CRV's for additional applications is exemplified by the CRV that accompanies the crew on the 1st mission in 2014. On December 25, 2015, the CRV returns on a free return trajectory from its mission as an escort to the outbound 2014 crew. It is then available to act as escort again for the 2016 crew. After free-returning to Earth and aerobraking a second time, its aeroshell is likely to have ablated to where it cannot aerobrake again. Two such CRV's will be produced by the 1st mission: the aforementioned outbound escort to be used by the 2014 and 2016 outbound crews, and the inbound escort from the 2014 mission (of the ERV and MAV, whichever is not used to land the crew on Earth), which will be used as an outbound escort by the 2018 mission. Starting with the 2016 mission, one re-usable CRV will be produced per mission, each to be used by the mission four years later. After the second aerobraking at Earth, the CRV can be used for other purposes.

3.10.3.2. Space Station
CRV's retired from interplanetary space could augment the International Space Station. For every CRV added, the ISS benefits from increased (1) crew capacity by five, (2) power by 81 kWe (the same array that produces 30 kWe at Mars aphelion produced 81 kWe at Earth aphelion), and (3) volume by 55 m^3 minus space already taken up by equipment. Compared to the planned capabilities of the ISS, a single CRV would increase the crew capacity, power, and volume of the ISS by 71%, 88%, and 5% respectively.[39]

3.10.3.3. Increased crew capacity
The aeroshells of twice-aerobraked CRV's could be refurbished for additional Earth aerobraking. The CRV's could then be used to expand future Mars missions by sending additional crew, possibly by launching crew in fully functional (instead of ghost) CRV's aboard Q1310's. As only the hab is equipped to land on Mars with people, the crew would spend the time in transit in the CRV, then transfer to the hab briefly to aerobrake to Mars surface while the CRV free-returns to Earth. The hab would carry all 10 astronauts to the Martian surface, where the extra five could occupy habs from previous missions, inflatable structures, or structures created on the Martian surface as part of an expanding Mars base.

3.10.3.4. Lunar missions
CRV's could also be sent to Luna. They are potentially useful as return vehicles from the lunar surface, as they could keep their crew alive for months in lunar orbit (i.e., until a rescue mission could arrive) in the event that Trans Earth Injection from lunar orbit were a failure. A Q3041 equipped with a LOX/hydrogen upper stage (for lunar landing) could deliver a CRV with a storable propellant (N_2O_4/hydrazine) trans-Earth/ascent stage to the lunar surface. A ghost CRV also has sufficient open-loop life support (3.8 days) to be used as a lunar return module.

4. Conclusions

The Mars Society Mission has the potential to send humans to Mars with reduced risk using fewer components and requiring less development than the NASA Reference Mission 3.0. NASA should evaluate the Mars Society Mission and consider it for adoption as the basis for the Design Reference Mission 4.0.

5. Future Studies and Lessons Learned

In relation to the Mars Society Mission, a number of paths are still to be explored. As our goal was not to create a project for a class, but to develop a comprehensive infrastructure and strategy for human interplanetary exploration, we are striving to improve the existing MSM. As with any humans-to-Mars mission design, the specifics of all components are being continuously improved upon, for instance, we are designing the exact fuel tank configuration of the QBC, QUS, and MAV stages, and considering new launch vehicle and Mars ascent ideas. We are also determining the applicability of MSM components to human and robotic missions to Luna, Saturn, and the asteroids, and will plan new components.

6. Outreach Efforts

As members of an organization dedicated to furthering the robotic and human exploration of Mars, our team has done considerable public outreach, and will continue these in the future. Efforts specific to the Mars Society Mission have included:

- Presentations of the Mars Society Mission to the public at Caltech on May 2nd and May 4th, with a total of about 150 attendees.
- A comprehensive web site explaining the details of both the Mars Society Mission and the general aspects of Mars exploration, including computer-generated movies and a comprehensive resource area with fliers, banners, and other downloads that everyone can use to rally support for Mars exploration. The site has been uniquely accessed over 5500 times since it was created on September 1, 1998. See http://www.cco.caltech.edu/~mars.

Our four person team also has several additional activities scheduled for the coming year, with several events which we will be personally organizing:

- June 11-13, 1999: **Booth and Presentation at AgamemCon Sci-Fi convention** in Anaheim, CA, featuring a large amount of literature distribution, Mars Society membership drive, and a talk on behalf of future Mars exploration.
- July 20th, 1999: **30th Anniversary of the Apollo 11 Lunar Landing**. We are planning an event to attract media attention to the fact that, 30 years after Apollo, we have yet to reach Mars. We will be collaborating with the Fifth International Conference on Mars, which will be held at Caltech during the weekend of the Anniversary.
- August 12th - 15th, 1999. **Presentation of the MSM at the National Convention of the Mars Society.**
- December 3rd, 1999: **Mars Polar Lander in the Southern Layered Terrain**. This event will be a celebration of the (hopefully!) successful arrival on Mars of the Mars Polar Lander. The Mars Society will use the interest generated by this 1999 landing to increase membership and awareness.
- April, 2000: **Membership Drives and Public Awareness Campaign** in conjunction with the release of the major motion picture *Mars*.
- May 25, 2000: **The Next First Step T-14 Years**. According to the Mars Society Mission trajectories, the first human landing on Mars will take place on May of the year 2014. This event will call attention to the effort to make sure the scheduled date is achieved.

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