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KEPLER PRIZE ENTRY: TEAM DAEDALIA DESIGN FOR EARTH RETURN VEHICLE

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ABSTRACT

The Kepler Prize was a contest held this past year by The Mars Society to design the Mars Direct Earth Return Vehicle (ERV) in as great a detail as possible. This is the summary report of Team Daedalia, which won this international competition in the summer of 2004.

SYSTEM OVERVIEW

Before Project Constellation was announced, our design was made as modular as possible to allow for rapid construction, field serviceability, interchangeable part swapping for both repair of planned systems and, for future explorers, adaptation to unanticipated systems, and phased technology changes over the development of the ERV fleet. Nothing is done without reference to both pre-ERV needs and post-ERV re-use of system components on Mars.

While the craft is divided into many sections, the design is somewhat unique in that a single passageway runs almost the entire length of the vehicle, from the base of the reentry capsule to the engine compartment in the back. This passageway, with rectangular doors at each break, allows suited crew members to switch to a pressurized environment the minute they arrive at the vehicle's base. In an emergency, this could be critical. In addition to the internal ladder, a hoist assembly can lift large objects and crew members from the surface to the Mission Module. A small block and tackle can even finish the job of loading surface samples into the Command Module. The second major advantage of this feature is that the passage contains multiple access doors all the way to the surface. Any section can be closed off, depressurized (if appropriate) and access doors opened to allow repair at any point from the first stage engines to the Command Module. Finally, the pressurized tube down the middle of the entire vehicle acts as a backbone for structural purposes. The vehicle starts out very top-heavy on landing, and a separate structural component to take some of the weight away from the now-empty tanks is desirable. While other structural frameworks are used throughout the vehicle, having a core simplifies the compression element of the design.

The craft is assembled from the following sections:

Command Module

This is nearly identical to the Apollo Command module, except that it contains a crew of four during entry. It also has a hatch at the back that interfaces with the rest of the craft.

Service Module

This provides the parachutes for Mars landing, cameras for viewing the exterior of the craft, RCS pods on four sides, solar power for the cruise both to and from Mars, radiator capacity, and communications. It also provides additional water and waste storage so that it can be disposed of in Earth's atmosphere after return. After separation of the mission module, it can also provide enough delta-V for the basic command module/service module block to aerobrake to Earth orbit, then de-orbit.

Mission Module

This has two levels, and is largely inspired by a 1960's NASA Mars flyby design [3]. A main level contains the crew, staterooms, dining area, restroom, kitchenette, exercise area, and meeting/dining table. The unique feature of this level is that all fixtures and furniture can be flipped from the "floor" at landing to the "ceiling" when the vehicle is spun for artificial gravity. This is a safer and less extreme way to deal with orientation than to move the second stage to the front of the stack, dock each centrifugal cable, and back away.

This is a quick summary of the unique design elements of the crew area. Showers, sinks, and the laundry have drains at the top and bottom, and are enclosed to allow use in either orientation or microgravity. Sinks have sleeves to allow the user's hands in; the cover is removed when not in microgravity. The toilet is flipped from plumbing on the floor to plumbing on the ceiling, and a cover plate makes the reverse trip. The table is also manually flipped. Most other elements use hinges to be reversed. The state rooms have a bed space that is vertically divided like triple bunk beds, but with storage in the top and bottom slots. To flip the middle, simply flip the mattress to the other side. The foot of the bed flips down at the bottom and up at the top. Depending on which end is up, one "foot" is left up as a seat for the desk, and the other is folded away against the storage unit to allow headroom at the desk.

Above this area (as seen when the vehicle is on the ground), the Mission Module has a small "attic" logistics section that contains life support, water storage and treatment, food supplies, medical supplies, and the hoist for moving objects up the core passage. Areas around life support equipment are kept clear for repair access.

Second Stage

This section has its own RCS pods which, when used in concert with the Service Module, allow the vehicle to separate, spin and despin. The stage has two tanks for fuel and oxygen, and two main engines on either side of the passage. These fuel tanks are ellipsoid in cross section to make the best use of the space allowed. The RCS pods also are sufficiently powerful to settle the tanks for the main engine when re-ignited for Trans-Earth Injection. For the two main second stage engines, we calculated 18,306 kg of thrust, spread across two engines. This gives engines of 10,000 kg each, with a buffer of 1752 kg over the minimum, or roughly 9 percent.

First Stage

Because hydrogen, liquid oxygen, and fuel are all needed on landing, three ellipsoid tanks are arranged symmetrically around the core passage. The tanks vary in length, and the gaps at the base of each tank allow more or less room for different base components. Three engines are mounted to a truss structure that provides support for the tanks above and the engines below. This is also where the airlock and suit storage units are placed. Internally, the vehicle looses its cylindrical cross section as the shell wraps more closely around the engines and the remaining space is taken up by the base structure. These voids allow room for equipment in the base, below and outside the first stage housing. Externally, the vehicle and the base still have a cylindrical profile. The first stage is nested within the base at this point.

We took the thrust to weight ratio of the original Mars Direct ERV design and scaled it up, crosschecking it against relative G forces for Mars and Earth. This resulted in a thrust to mass ratio of .766 for the first stage and .268 for the second stage. Relative to the weak gravity of Mars, this first stage lifts off with a thrust to weight ratio of 1.96.

For the first stage, this resulted in a thrust of 179,859 kg, spread across three engines. Each engine, therefore, is designed at 62,000 kg of thrust, giving a margin of 6141 kg, or roughly 3.6 percent. We set our engine envelopes at 3 meters long by 1.5 meters in diameter. We set it at 2000 kg for all three engines, the associated thrust vectoring actuators, and pumps.

Base

The base contains the landing gear, retractable dust covers for the three first stage engines, the rear "beaver tail" control surfaces for entry, and the three main surface equipment bays. The tallest bay, located under the shortest First Stage tank, contains the truck and flips out in a way analogous to the Mars Pathfinder petal containing the Sojourner rover. The second bay contains the reactor and related equipment, which are accessible on ramps that flip out from the side. The last bay contains modular In Situ Resource Utilization (ISRU) pods, which produce fuel, water, and oxygen for the craft. The ISRU pods can be removed for use at a future base.

Dimensions

The original Kepler Prize RFP called for a Magnum launch vehicle with a 28 by 7.6 meter payload. Our design relies on its own shape for aerodynamics. The vehicle is 27.6 meters in length including the aft aerodynamic skirt. Structurally, the vehicle is 27.1 meters long. The magnum upper limit is 28 meters. The magnum limit for diameter is 7.6 meters, and our design is 7.5 meters across at the base. The second stage and mission module narrow to seven meters, plus RCS pods that project 20 centimeters from four sides, for a total of 7.4 meters. The service module narrows again from seven meters at its base to four meters at the top, and the command module caps the vehicle with a base of four meters and a conic shape.

Propulsion

Fuel Requirements

First stage fuel tanks are split between one for liquid oxygen, one for liquid hydrogen, and one for ethylene. On landing, the hydrogen tank is filled to capacity and the other two tanks are partially filled with enough propellant to aerocapture, deorbit, and land safely. Any remainder is used to fuel the APU and truck from the time of landing until the reactor is set up.

This plan uses ethylene and oxygen. For the RCS pods on the service module, methane is produced anyway from the life support system, so methane will subsidize the RCS system on the return flight to Earth. The production methods are detailed in source [2], but in summary use Reverse Water Gas Shift combined with an ethylene reactor. Ethylene burns at a ratio of 2.6 units of oxygen to 1 unit of ethylene. The ERV must carry 6849 kg of hydrogen from Earth to make enough fuel to get back.

The first stage requires 158,381 kg of propellant, which at the fuel ratio needed, breaks down to 114,861.6 kg of oxygen and 43,994.7 kg of ethylene. The second stage requires 44,116 kg of propellant, broken down to 31,861.6 kg of oxygen and 12,254.4 kg of ethylene. With RCS pods and the vehicles calculated into the system, the final amount is 155,781 of ethylene and 59,916 of oxygen.

Survivability Summary

The following issues are covered on the long version on the CD:

For Category I (Loss of crew or mission) – Issues with Earth entry, aerocapture, cruise phase, launch from Mars, surface operations, and life support failure on the surface are covered. Of note is the discovery that after launch to orbit but before injection to Earth, the ship has enough fuel and power to return to the surface safely if it is designed to do so. This same capacity could be used if the first stage fails prematurely, allowing the crew to use the second stage to re-land downrange. Structural elements between the first and second stage allow the vehicle to land safely, and the parachutes normally used by the command module on Earth landing are used to help slow the craft. Details are in the full report.

For Category II (Delay of mission/ Possible crew loss), pressurized space is compartmentalized for escape and repair of compromised sections, the core tunnel allows inspection and repair of interior components via a “microrover” that would crawl from the main tunnel to the appropriate components, RCS pods can be swapped, the thermal protection system can be patched, and theoretically main engines can be swapped with the landing engines from the Hab. If an experimental water collection system is carried on either craft, shortfalls on water or hydrogen can be covered.

Category III (long lead time and nuisance issues) – Using the ERV in place of a damaged Hab, Truck having insufficient fuel, and hygiene facility failure.

OPERATIONS OVERVIEW

Cruise to Mars

After launch, the cameras are deployed to assist in ship inspection and navigation. Also, the smaller high-gain dish is deployed and relays data via the TDRSS communications satellite constellation. Cameras onboard the craft are also used for system inspection. Interior diagnostics and tests are preformed.

Within one week, a second magnum launches a third stage booster for the ERV. Using the docking radar, lidar, cameras, and the four external camera pods, the two ships are docked in orbit. The cameras are retracted, and the third stage fires for Trans-Mars Injection. If sufficient room is allowed in the mass of the third stage, it may carry a navigational surface probe bus to assist the ERV, but this is optional. The third stage would be redirected to avoid Mars after releasing the ERV. The ERV would then fire the RCS pods to direct it towards the aerocapture point.

Once separated from the third stage, the smaller high gain dish, solar panels, and radiators come on line. Automated navigation systems simplify communications.

Mars Approach/Entry/Decent/Landing

On approach, the batteries are fully charged and all zones are cold soaked before the radiators are retracted. The solar panels, radiators and antennas are all retracted and inspected by the camera pods. Once all systems check out, the camera pods retract and the craft prepares for entry. The ERV is weighted more heavily on the side opposite the truck door, and two control surfaces fine-tune that balance on entry. After the control surfaces are no longer useful, the craft reverses attitude and fires first high speed and then low speed parachutes. The ERV uses the RCS pods at this point to help guide and stabilize the approach. After slowing to roughly 300 KPH and descending closer to the surface, the vehicle cuts the parachutes and fires the main engines. The engines land the craft and the landing gear pop out seconds before touchdown. As the craft settles onto the gear, lateral "feet" flip out of each gear assembly to help stabilize the craft. The gear also attempt to level the craft as the engines drop to zero thrust. Finally, the engines cool and the dust protection doors cover them until launch. These covers are actually part of the base, not the first stage. They deploy from rollers and are magnetically sealed to prevent dust from entering the engine compartment. The landing legs then retract as much as is allowed by terrain to keep the center of gravity low and allow egress of the truck.

Propellant Production

The cameras deploy and survey the location with instruments similar to those on the Mars Exploration Rover scan platforms, but mainly look for rocks or other obstacles that may block the truck door. The truck door extends like a petal, with the truck mounted on top of it at the base. This is similar to the Sojourner probe on Pathfinder, except that the truck is roughly 3 meters long and two meters wide. Flexible ramps deploy from the front, back, and outside of the petal, allowing the truck to drive off in any direction. If rocks are at the surface and the petal has to come in contact with rocks instead of the ground, the rocks can be up to two meters tall without causing problems with the truck deployment.

Fuel and oxygen left in the tanks is transferred to the truck for use in setting up the reactor. The truck is a low, twelve-wheeled platform with a backhoe arrangement on one end and either a camera platform or a complete “robonaut” interface at the other equipped with a stereoscopic camera head and two manipulator arms. It basically resembles the Mars Science Laboratory with several major exceptions. First, instead of one wheel per axle, the truck has one on each side to increase traction and weight distribution, and also to counterbalance the load on each axle. Secondly, the rocker-bogie arrangement is much heavier and not designed to rotate the front wheel suspensions into place. All hinges are deployed for use with electric motors, and locked or bolted into place permanently. Each of these bolts is connected to an individual electric motor. When the parts are lined up properly, the motors crank the bolts into place and lock the components together.

The body of the truck contains a large loading bed for the reactor. At this point, the bed only contains a base for the reactor since the reactor itself isn’t loaded on the truck yet. The engine and tanks of the truck are built low in the frame, and the generator is used to drive a large battery. For heavy operations, as with any hybrid electric, power from both the battery and generator is used concurrently. These would include moving the reactor, using the backhoe to clear a path or build up a sheltering crater wall, and so on. Electric motors drive both the backhoe and the wheels. Two stabilizing feet can be deployed on the backhoe side of the vehicle to stabilize the truck during digging operations and while loading and unloading the reactor. Using the cameras on the ERV and some exploration by the truck, a reactor site is determined. The truck has three options: find a naturally shielded location for the reactor, carve one with the backhoe, or improve a natural one in the same fashion. It then levels the ground for the reactor and puts down a base-plate that will be the reactor’s foundation once deployed. After clearing and leveling the path between the ERV and the reactor site, it loads the reactor by rolling it from a ramp on the ERV to a mount on the truck bed. The base of the reactor has a series of rollers that can be locked in place on command. After rolling alongside the reactor baseplate, a lateral ramp locks into the baseplate and the reactor is rolled off the truck using the backhoe arm and an eyelet at the top of the reactor. This seems elaborate until you remember the reactor weighs nearly five times more than the truck, and minor mistakes could upset both. After the truck leaves the reactor area, the reactor is activated and the power leads reeled out behind the truck can be anchored or elevated as needed. If there is not sufficient fuel for the truck to do all the required reactor deployment maneuvers, a solar panel is deployed to make fuel before the reactor comes on line. Up to 31 days can pass between the landing and reactor deployment and ISRU pod activation. These pods will take the vast majority of electrical power during the next 517 days.

Surface Operations

Once the reactor is deployed, the ramp and landing legs are reinforced with loose guy wires and drilled pegs. The landing radar surveys the soil and rock below the ground to ensure there are no surprises that may topple the craft as the fuel tanks slowly fill and make the craft more than quadruple in weight. While the craft is still light, the ERV is raised as much as possible on the landing gear struts. Then the truck’s backhoe clears an exhaust ramp beneath each engine and

radiating out, being careful not to undermine the landing gear. Once this is complete, a large blanket is placed under the engines to reduce damage from sand and rocks on takeoff. Once the vehicle is lowered again, guy wires and other stabilization methods are used to lock the landing gear and the base in place as much as possible. These wires are anchored using the surface sample drill and appropriate "tent peg" anchors placed in soil or rock.
During the fuel production phase, weather data and basic scientific work is collected from the ERV sensors. The truck now levels a landing zone for the hab and deploys beacons around the proposed landing site. Spots are also cleared for the pressurized rover egress and high-gain antenna. If the hab carries its own reactor, a site is prepared for that as well.

After the Hab arrives, the ERV and robonaut are under close remote control by the crew. The truck and power reserves from the reactor will expand the ability of the crew to do construction work and site improvements as needed.

Departure Preparations

The crew removes any important tools, medical equipment, and spare parts from the Hab. Before departure, the crew and truck begin removing equipment from the landing base. The ISRU pods are modular and can be moved to a shelter by the Hab. In fact, the entire base, except for the landing gear and any critical systems, is designed to be stripped this way. Even the skin is removed to allow the engines to avoid damaging the base on takeoff. What is left is a hollow frame with the dust shielding plate and doors below the engines. These panels are not retracted until inspection and then takeoff.

Launch/Trans-Earth Injection

After launch, the crew inspect the craft and report home at low bandwidth. They then prepare for second stage firing. After the RCS pods settle the tanks, the second stage fires and sends the crew home.

Cruise to Earth

Once systems check out, the second stage is separated and plays out four long cables about 140 meters between itself and the mission module. The RCS pods on both vehicles now spin the complex at 4 RPM. Once the spin is stabilized, the solar panels and high gain dishes are deployed. The craft spins with the axis pointing towards Earth, so the antennas will not have to swivel four times a minute to track. Since earth is roughly sunward at this point, the solar panels will not need to track either. If the angle becomes too great between the two, the solar panels are locked on the sun by the spin axis and the communications is done by the omni antennas.

Earth Approach/Entry/Decent/Orbit or Landing

Depending on the possibility of life on Mars, the entire ERV craft may either enter the atmosphere or be targeted initially for an Earth flyby. On approach, the craft is de-spun and the second stage is either reeled in and docked or cut away. The crew move any personal items, spacesuits, and themselves to the command module after microgravity is established and any motion sickness issues are resolved. At the appropriate time, the command and service modules separate from the mission module and they use the RCS pods to redirect it into an aerocapture or landing path, depending on the requirement for that mission.

CONCLUSIONS

Our design ended up encountering many issues with mass. The design was to take advantage of the higher weight restriction of the double launch, and ended up barely clearing the mass allowance of the booster. Care must be taken to optimize the cabin in a real vehicle. Ultimately, no ERV design from this contest will be adopted on an equation-by-equation basis by those who would actually build it. It is not our math that will carry forward into the real thing, but perhaps our ideas will. There is a good chance that something in this paper, we know not what, could be adopted in some small way in an actual spacecraft. In that sense, it stands on the shoulders of giants from bygone paper projects now distributed on the web or in print [3, 12], with ideas that never really die but come back in future designs. Ultimately, this is why anything is written down – to carry ideas and knowledge forward in time to those who gain from them.

REFERENCES

1. Zubrin, R and Wagner, R The Case For Mars, 1996, The Free Press
2. Zubrin, R, Frankie, B and Kito, T Mars In-Situ Resource Utilization Based on the Reverse Water Gas Shift: Experiments and Mission Applications, 1997, AIAA 97-2767, http://www.nw.net/mars/docs/in-situ.doc, last viewed 5/29/2004.
3. NASA Manned Spacecraft Center Planetary Missions Study Task T2A600, 1967. Published in Mars: The NASA Mission Reports Volume 2, 2004, Apogee Books
4. Deep Space 1: Advanced Technologies: Autonomous Navigation, http://nmp.jpl.nasa.gov/ds1/tech/autonav.html, last viewed 5/29/2004.
5. Zubrin, R Mars on Earth: Adventures of Space Pioneers in the High Arctic, 2003, J. P. Tarcher
6. Mars Exploration Rover: Entry, Descent, and Landing. http://athena.cornell.edu/mars_facts/sb_punch.html. Last viewed 5/29/2004.
7. Heninger, R Mars Science Laboratory Mission 2009 Landed Science Payload, Draft Proposal Information Package (D-27202), 2004, Jet Propulsion Laboratory. http://centauri.larc.nasa.gov/msl/PIP-FINAL-14Apr04.pdf. Last viewed May 30, 2004.
8. Larson, Wiley J. and Pranke, Linda K. (Editors) Human Spaceflight: Mission Analysis and Design, Space Technology Series, McGraw-Hill Publishing
9. Radar Mapping Crew Charts Mission for Fans, http://www.space.com/news/spaceshuttles/endeavour_crew_000324.html, last viewed 5/29/2004.
10. Third Stage, http://www.apollosaturn.com/s5news/p51-13.htm . Last viewed 5/30/2004.
11. LOX/LCH4 http://www.astronautix.com/props/loxlch4.htm. Last viewed 5/30/2004.
12. The Spacemodeler's List Gallery: McDonnell Douglass Two Man Apollo Study http://www.apollosaturn.com/twoapollo/twoapollo.htm. Illustrations dated 1962. last viewed 5/30/2004.
13. Jenkins, Dennis and Landis, Tony Hypersonic: The Story of the North American X-15, 2003, Specialty Press.

TABLES

Table 1: Fuel Estimates, Landing

Maneuver	Delta-V (meters/sec.)	Mass Before	Mass After	Fuel Used
Aerocapture, Orbit Insertion	111	52,965	51,394	1,571
Deorbit, Mars	111	51,394	49,870	1,524
Landing, Mars	630	49,870	42,036	7,834

Table 2: Fuel Estimates, Earth Return

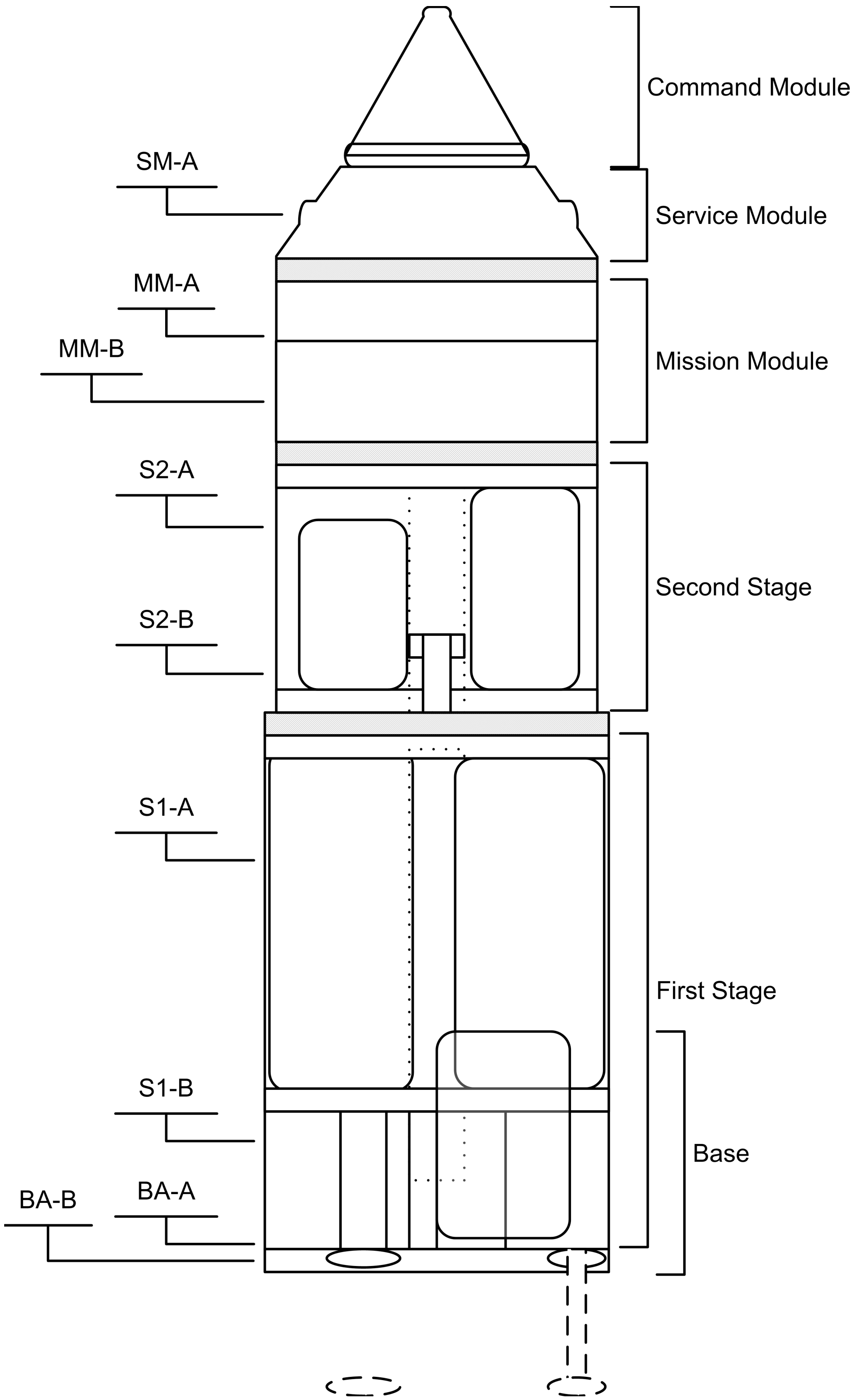
Maneuver	Delta V [8] (meters/sec.)	Mass Before	Mass After	Fuel Used
Launch From Mars (Mass after includes stage 1)	4,140	234,748	76,367	158,381
Trans Earth Injection	3,821	68,367	24,251	44,116
Aerocapture, Earth	39	9,161	9,065	96
Deorbit, Earth	39	9,064	8,969	95

Table 3: Mass Breakdown Summary

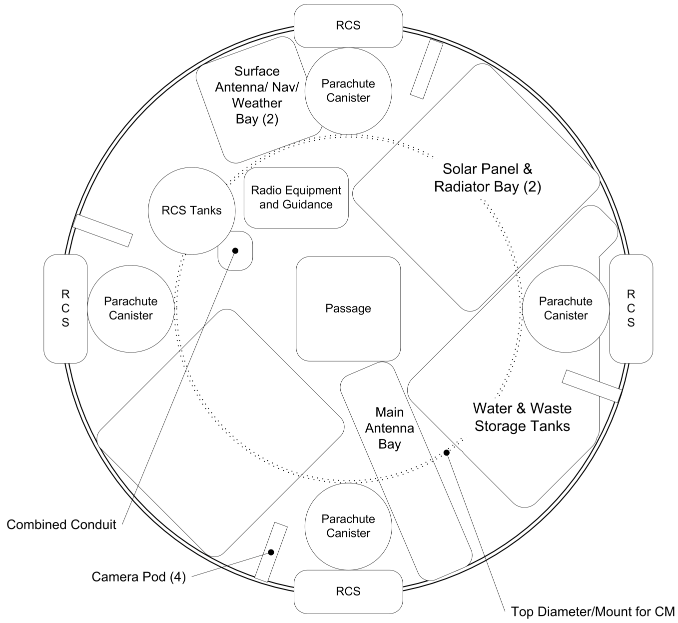
Component	Mars Landing (kg)	Mars Launch (kg)
Command Module	4,525	5,345
Service Module	3,620	3,820
Mission Module	8,406	12,086
Stage 2	3,000	47,116
Stage 1	26,252	166,381
Base (left on surface)	7,100	0

SCHEMATICS AND VEHICLE MASS BREAKDOWN

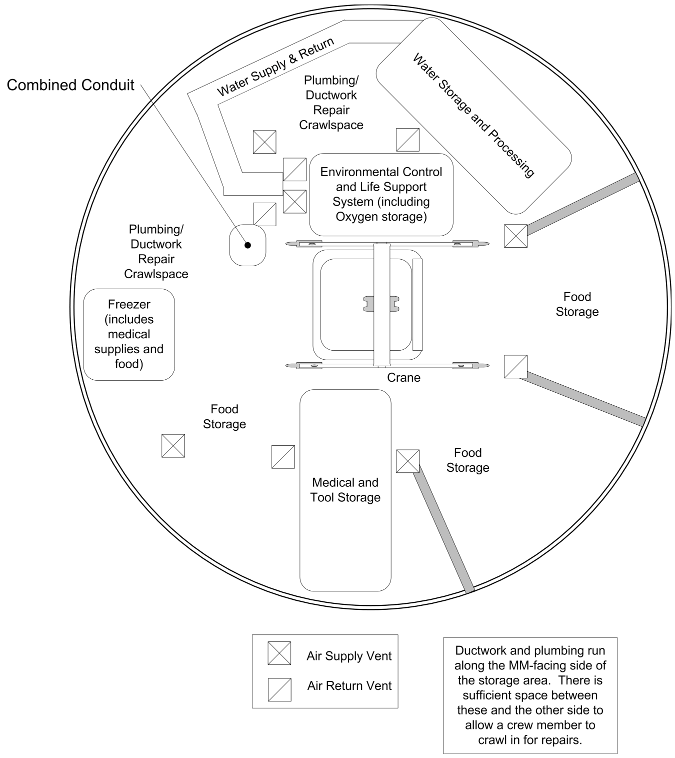
The sections that follow this will use horizontal slices from this cross section.



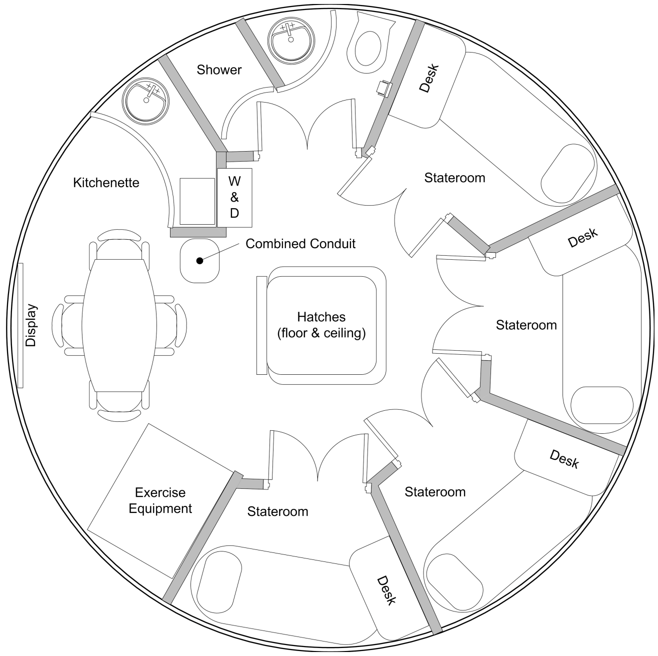
SM-A: Service Module



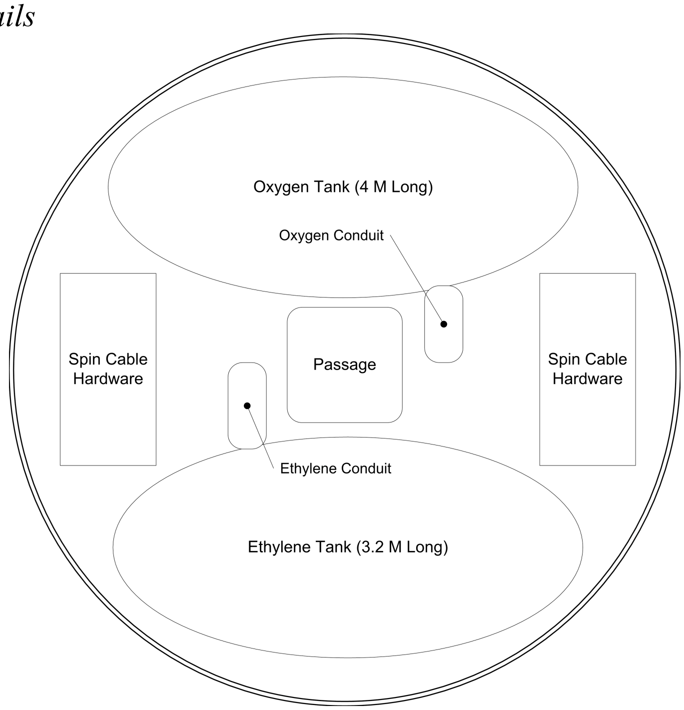
MM-A: Logistics Level



MM-B: Crew Level



S2-A: Tank level details



S2-B: Engine level details

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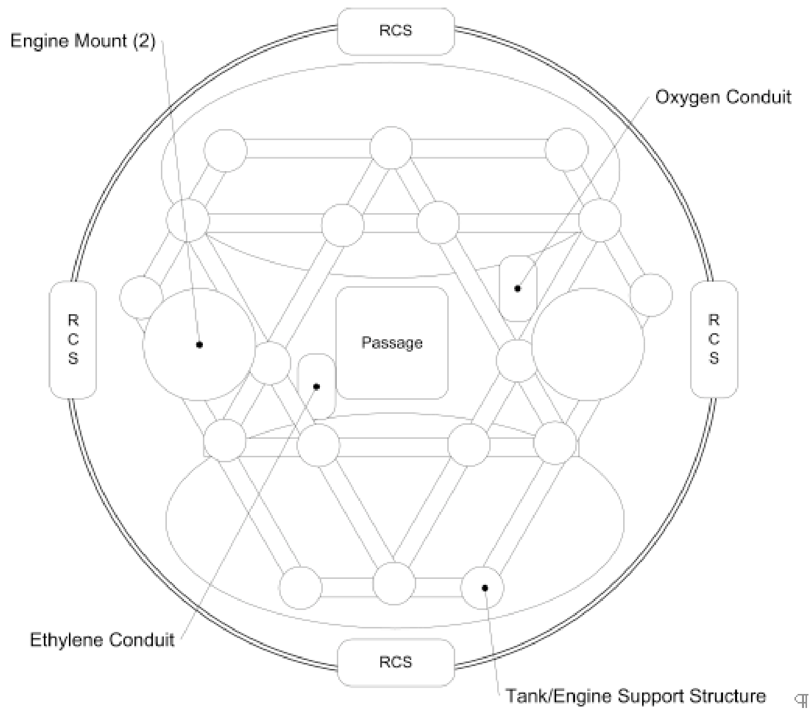

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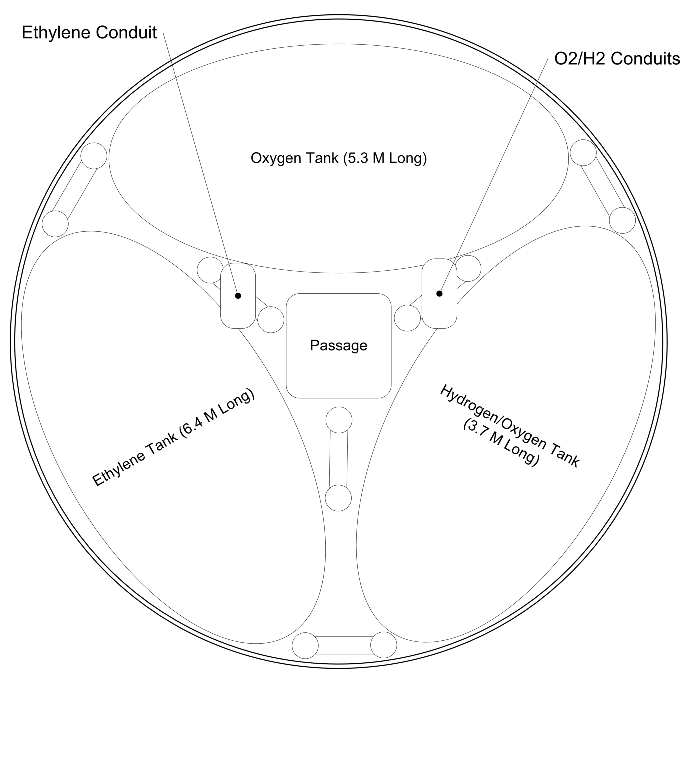
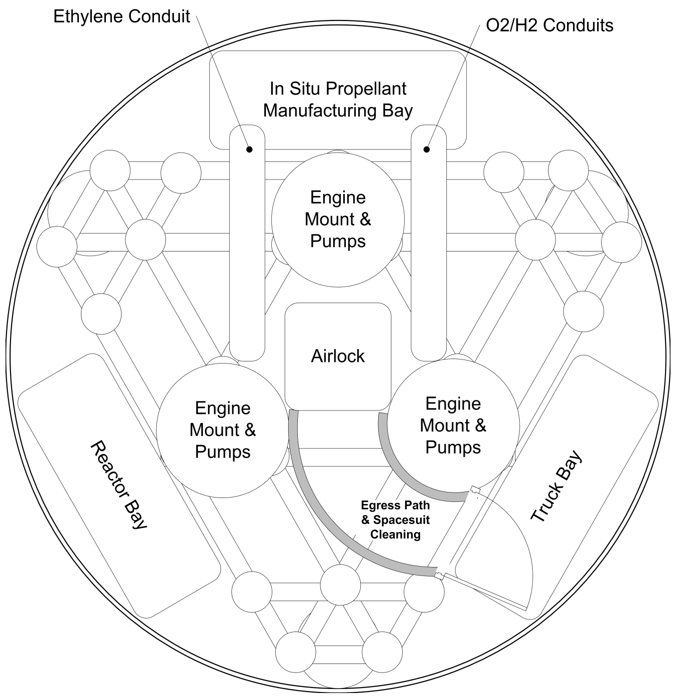
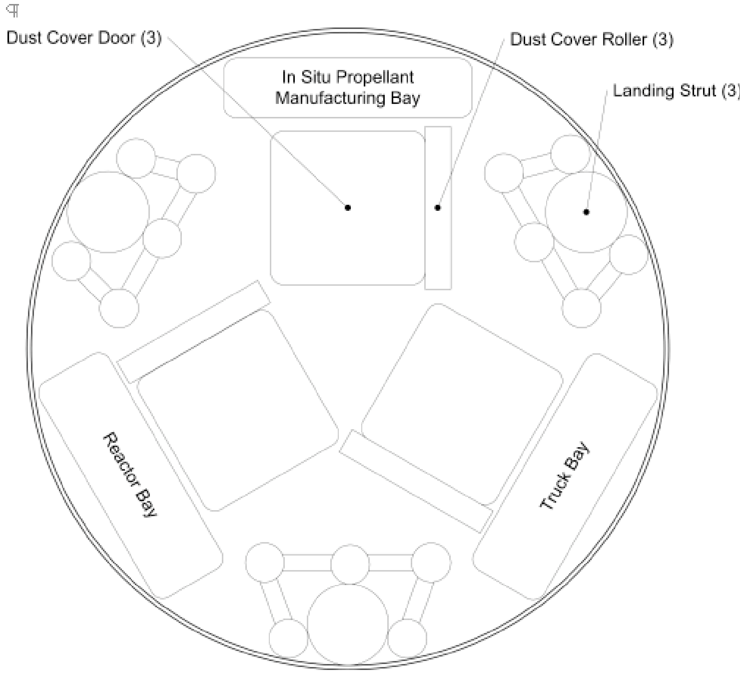
S1-A: Tank level details



S2-B: Engine level details



BA-A: Engine Doors



BA-B: Aft Fairing

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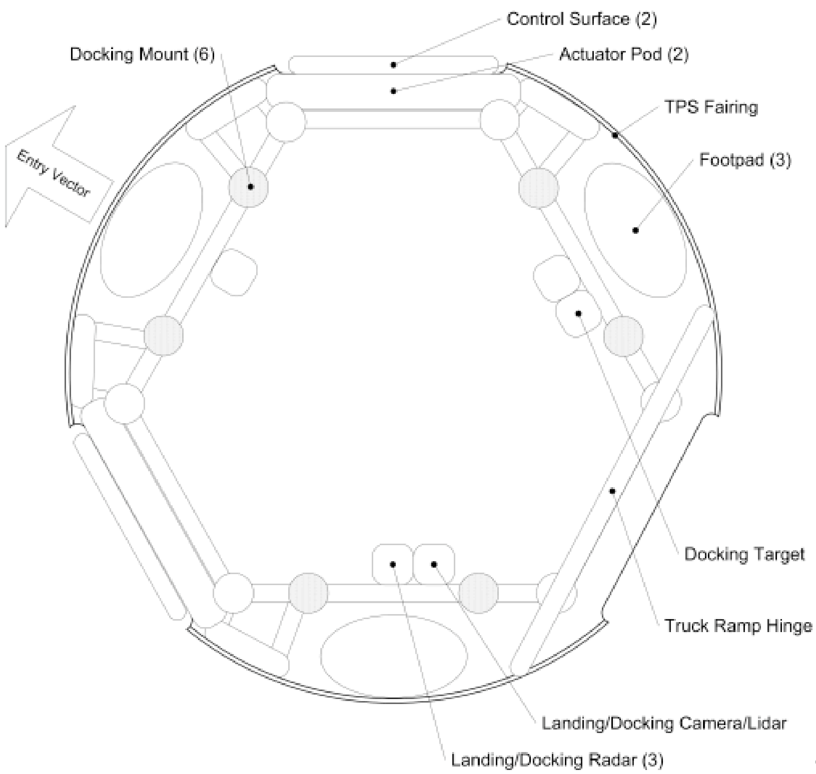

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