Proposal for Next Generation Mars Lander and Return Vehicle

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What are we trying to do?

Complete feasibility and preliminary design for a new model of spacecraft capable of landing on the surface of Mars and eventually returning to Earth in essentially complete form. This spacecraft, the Wide lifting bodY Vehicle for Earth ReturN or WYVERN, is envisioned as a versatile chassis capable of a wide variety of missions with minimal changes. More specifically, such a spacecraft must meet (and our proposal does meet) the following requirements:

- Low ballistic coefficient. Mass/heat shield area <250kg/m^2 during Mars atmosphere entry phase.
- Rocket powered soft landing without parachutes or inflatable components, for reliability.
- A stable, low form factor on the surface, even on sloped ground.
- Capability to be launched from Earth in one piece, without assembly or re-fueling in orbit.
- Reusability. The spacecraft should be capable of flying a configuration which permits return to Earth for reuse, utilizing the Martian atmosphere to synthesize fuel for the return flight.
- A monolithic heat shield (no hatches, windows, doors, etc) that is not ejected, so it can be reused on return to Earth.
- Adequate fuel capacity for single stage return to Earth, requiring approximately 7.8km/s of delta-V.
- Significant cargo down mass capability, ideally measured in 10s of tonnes.

How is it done today - what are limits of current practice?

Currently, spacecraft are landed on Mars using Apollo-derived conical capsules, parachutes, rockets, and airbags or skycranes. Current limitations include:

- Mass - Mars Science Laboratory (Curiosity) represents the largest payload to date, of approximately 900kg, and represents an upper limit on the capabilities of aeroshell, parachute, and rocket landing system. Specifically, 900kg is not nearly enough to land humans or a return vehicle.
- Locations - Mars' thin atmosphere greatly restricts the sites where it is possible to land, effectively eliminating the ⅔ of the surface that is above datum.
- Return capability - no existing or proposed Mars spacecraft can leave the surface. Even proposed sample return missions use bespoke staged systems with minuscule upmass capability (<10kg) and no possibility of reuse.

What's new in this approach - why will it succeed?

Specific innovations include:

- Form factor - we exploit the differing requirements of various stages of the mission to provide a long, wide, and flat form factor that acts as a lifting body during entry.
- Descent and landing profile - by orienting the spacecraft to enter the atmosphere on its back, then roll 180 degrees before a rocket powered landing, the spacecraft is always in a stable configuration and ideally positioned on the surface to protect the heat shield while enabling loading and unloading.
- No parachutes or inflatables - hypersonic parachutes for large payloads are difficult to test, heavy, too unreliable for human cargo, and unnecessary.
- Very large included delta-V - with 7.8km/s of delta-V in launch configuration, the spacecraft is capable of returning to Earth from the surface of Mars with up to 25% of dry mass as cargo. Detailed mass tabulation is included below.
- Reusable, multipurpose airframe saves development costs for different missions while also being scalable.
- Unparalleled cargo capacity given rocket launch mass - 20% of low earth orbit capability vs 5% for MSL.

Who cares - what difference will it make?

Current and planned missions to Mars both robotic and crewed are fundamentally limited by the requirement of multiple unique specialized spacecraft, each of which requires separate design, testing, and all of which form single points of failure. None of these spacecraft are particularly versatile, few form a fundamental design which can be updated or improved without substantial redesign and development costs.

The proposed design will form a basic chassis with raw capabilities that can be customized in many directions without requiring redesign of the mission-critical components: entry, descent and landing, propulsion, guidance, navigation and control, and so on. Mass analysis below indicates that as a one-way lander with 50T gross mass, it can deliver ~25T to the surface. With in-situ resource utilization for return fuel manufacture, it can deliver ~15T and return ~5T to Earth, as well as the reusable spacecraft. It can also readily perform missions in the Earth-moon system.

What are risks and payoffs?

We seek to complete a basic design and feasibility analysis. Key uncertainties to be addressed include:

- Minimum viable structural mass. While using a pressurized methane/oxygen tank as a structural backbone, is it possible to complete the rest of the structure with enough margin for landing and launch? Preliminary mass analysis included below suggests it is possible.
- The design requires the development or adaptation of high Isp (380s) methane-oxygen engines each delivering a relatively small ~130kN of thrust.
- Returning the spacecraft to Earth requires the synthesis of fuel and oxidiser on the surface of Mars, which in turn requires a substantial quantity of electrical power, totalling approximately 150kWyears. Realistically, this can only be provided by a space reactor such as the SAFE-400. Such reactors have been developed but never flown.

How much time and money is required?

The spacecraft is estimated to be similar in weight and materials to a mid-size jet aircraft such as the 737, with commensurate development and construction costs. This represents a substantial (order of magnitude) improvement in cost over other proposed Mars mission architectures, such as SEI or Constellation.

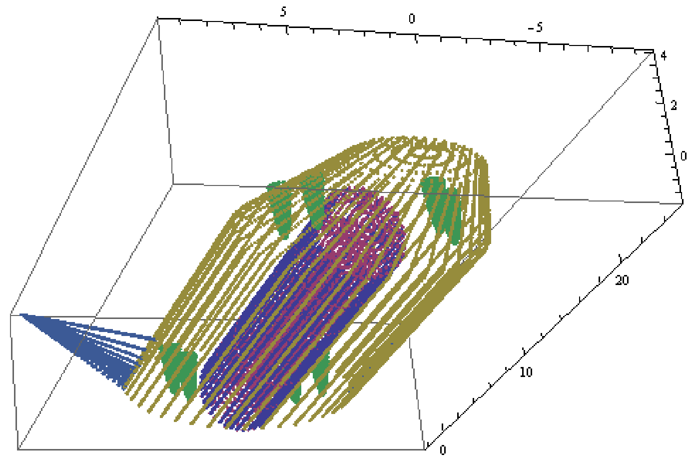
What are stepping stones to success?

Further work in design, manufacturing, and testing must be done. Key stages of the program include:

- Detailed structural analysis.
- Mass cost determination and distribution.
- Propulsion analysis in order to accurately set requirements.
- Mission planning, including EDL.

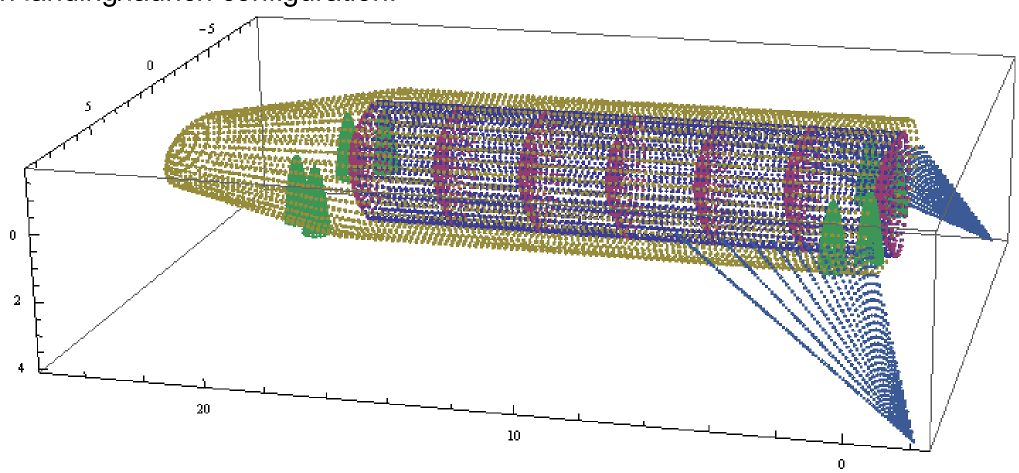
Preliminary analysis

Highly approximate sketch of Wyvern in entry configuration:

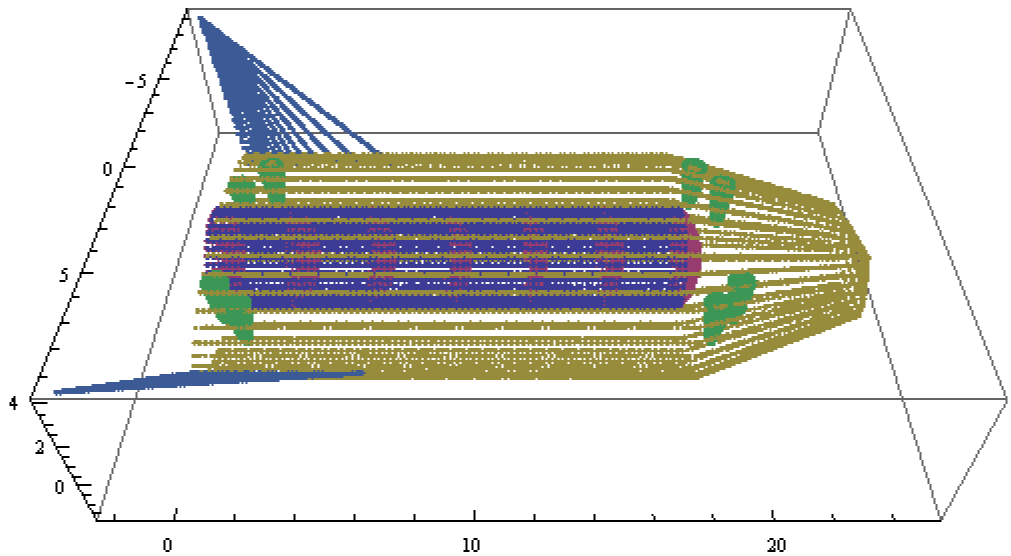


Central blue cylinder is fuel tank, mostly empty, with several magenta domes partitioning it into different sections. Green cones are rocket engines. Blue triangles are tails to shift center of drag behind center of mass. Brown marks the edge of the vehicle envelope, with a basic flattened triconic profile.

Wyvern in landing/launch configuration:



Here, Wyvern has inverted to land with engines facing down, heat shield facing up. With clearance beneath and a spread, stable posture, Wyvern is ideally suited for the loading and unloading of cargo.



delta-V summary

Earth surface - LEO: 9.3-10km/s. 9.3 for KSC to non polar orbit.
LEO-Earth C3: 3.3km/s. (Optional electric propulsion)
Earth C3-TMI: 1km/s (180 day trajectory, for 2 year free-return).
<u>Total from booster(s): 13.6km/s</u>

TMI-Mars surface: aero direct entry + mid course corrections + terminal velocity to landing ~0.83km/s.
<u>Total from Wyvern outbound: 0.83km/s.</u>

Mars surface-LMO: 4.1km/s.
Flat ascent penalty: 0.03km/s (for having rockets fire perpendicular to axis).
LMO-Mars C3: 1.4km/s
Mars C3-TEI: 1.5km/s (190 day trajectory, 0.9km/s minimum)
TEI-Earth surface: aerobraking + mid course corrections + TV to landing ~0.8km/s.

Total from Wyvern+ISRU: 7.83km/s.

A single stage flight from Mars' surface to Earth's surface requires approximately 7.8km/s of delta-V, at best. Given eight advanced methane-oxygen thrusters with an Isp of 380s, the requisite mass ratio is 8:1. That is, a mass of x landing on Earth requires a launch mass of 8x, or 7x in fuel and oxygen. An initial:final mass ratio of 8:1 is small by comparison with the 23:1 ratio achieved by modern booster rockets, such as the Falcon 9 first stage.

Mass allocation

By combining the structural elements of fuel tanks and airframe, the Wyvern achieves a much lower dry mass than more conventional designs.

Component	Mass (kg)	Analogous existing hardware and mass
Fuel/ox tank	5600	Falcon 9 second stage dry mass 4900kg
Non tank structure	5000	40' shipping container 3800kg steel
Main rockets	8x125	RL-10 has similar thrust and use parameters
RCS	500	Dragon Draco RCS system
Solar array	1000	50kW at Mars orbit with 100W/kg at LEO
Heat shield	2400	300m^2 of PICA-X
Avionics/GNC	200	
ISRU - Reactor (nuc)	500	SAFE-400 120kW reactor
ISRU - Feedstock	8500	7500 H2 for 150000 CH4/O2 + margin
ISRU - Reactor (chem)	500	
Fuel/Ox mass	150000	21400kg gross mass to Earth. 180m^3 storage
Spare/cargo upmass	5700	15700 dry mass
Spare/cargo downmass	15800	50000kg entry mass includes 10000kg EDL fuel and 9500 kg ISRU components

Mass summaries throughout duration of full mission

Note that these figures are for the Mars lander only. They do not include the mass of the LEO-TMI booster(s), outlined in the configuration section.

Mission stage	Mass (kg)	Explanation

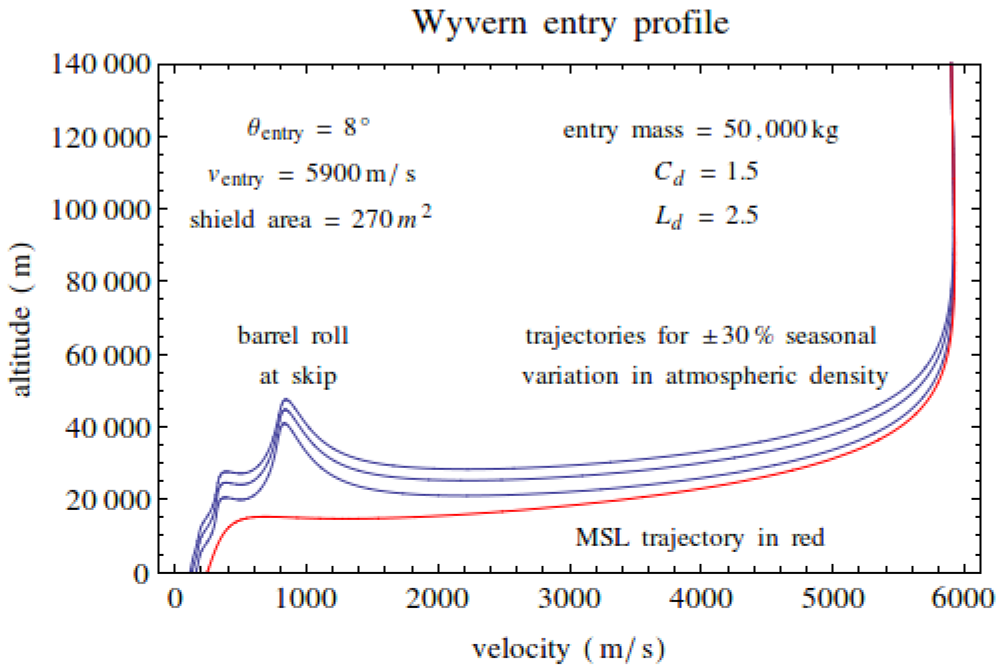
Low Earth orbit	50000	Falcon heavy launch
Trans-Mars Injection	50000	TMI with separately launched booster
Mars Atmospheric Entry	50000	
Mars surface after landing	40000	10000kg for 830m/s delta-V during landing
ISRU fuel	30000	Methane 71m^3
ISRU oxygen	120000	Basic stoichiometric ratio 105m^3
Pre Mars launch dry mass	21400	Structure and return cargo
Pre Mars launch gross mass	171400	Requires 6x110kN thrust minimum to lift off
Trans Earth Injection	26200	4800kg of props remain for Earth EDL
Earth atmospheric entry	26200	
Earth surface after landing	21400	800m/s of delta-V remain for landing

ISRU components

The ISRU unit consists of a chemical reactor, a nuclear reactor, associated plumbing, and hydrogen feedstock. It generates methane and oxygen via the Sabatier reaction and Reverse Water Gas Shift reaction according to well understood principles. In the context of a manned mission, the reactor would be deployed by remote control on the surface prior to fueling and activation. A solar array can provide auxiliary power during cruise or on the surface, though does not produce nearly enough power to complete ISRU within the ~500 day window between landing and return to Earth. If the mission profile calls for two Wyverns; one Earth return vehicle to land two years earlier and produce fuel before the crew transport Wyvern arrives, then the reactor only needs to go with the first vehicle, and can stay on the surface, fueling the crew transport vehicle after the mission has concluded. Later, the crew transport vehicle could fly additional samples back or function as a backup.

Entry, descent and landing profile

Wyvern employs an innovative, back first entry profile. Wyvern's heat shield forms the roof of the spacecraft in standard landing configuration. With a hypersonic L/D ratio of ~1, Wyvern is capable of skip entry and substantial cross-range performance. During supersonic cruise at terminal velocity (~500m/s), Wyvern completes a 180 degree roll, pitch up manouver, and retropropulsive descent and landing using four clusters of 2 130kN redundant high Isp methane oxygen motors analogous to Dragon V2. Powered flight continues for around a minute, first decelerating at full power, then descending under controlled flight to a soft landing. In more detail, with a peak thrust of 8x130kN and an initial mass of 50T, Wyvern can decelerate at $21ms^{-2}$(much greater than Mars' surface gravity of $3.8ms^{-2}$), taking roughly 30 seconds to slow down from terminal velocity to begin a powered descent at reduced thrust.



I performed a basic simulation of Wyvern entry using banking to suppress hypersonic skipping until around 1000m/s, where the barrel roll may be performed during a natural peak in the trajectory. MSL's entry profile, computed using the same simulation and publicly available data, is included in red for comparison.

Launch profile

Wyvern launches from Mars in its horizontal configuration. Mars' atmosphere is thin enough that there is no substantial performance impedance from climbing to orbital speed with the flat side up. Total delta-V loss is less than 30m/s compared to vertical orientation, or -6m/s for no atmosphere.

Internal configuration

Different internal configurations can be built within the framework formed by the aeroshell, central fuel tank, and propulsion units.

Possible configurations include

- Self contained sample return mission with ISRU. Capable of delivering 15T to the surface, returning 5T of samples and/or mission hardware. 15T could include several rovers with specialized instruments, a substantial drill rig, even a small synchrotron.
- Self contained crewed mission with ISRU. With 15T down mass and 5T return mass, a single Wyvern is capable of supporting a crew of 4 or 5 for a complete 2.5 year mission.
- One way crewed mission. Remove the ISRU mass penalty and receive 10 additional tons of down mass, to possibly include more crew, more supplies, or more Mars cars.
- Earth-return vehicle crewed mission. Launched autonomously to Mars, the ERV Wyvern produces fuel on the surface before the crewed Wyvern departs from Earth. With 15T of

spare down-mass, the ERV can also deliver substantial cargo in support of a surface mission.

- One way cargo. Without ERV hardware, Wyvern is capable of delivering 25T to the surface of Mars, and also contains roughly 350m^3 of pressurizable volume.
- Self contained crewed mission without ISRU. If return fuel is present on Mars' surface, either prelaunched or premade, Wyvern can complete a mission without bringing ISRU hardware, with 25T of down mass and 5T of upmass.
- Orbital shuttle. Wyvern could readily function as a shuttle to deliver payloads to or from Mars orbit from the surface. Downmass remains at 25T, upmass increases due to the decreased delta-V required. Surface to Low Mars Orbit is 4.1km/s, allowing a cargo upmass of 58T, given an incremental engine upgrade. Surface to Mars C3 and back to surface, such as required to dock with a large interplanetary spacecraft in a highly eccentric orbit, is 6.3km/s, allowing an upmass of 20T. Intermediate missions fall between these two extremes.
- Trans Mars Injection booster. If Wyvern was launched to LEO from Earth by Falcon Heavy, it would require a booster stage to get to Mars. Three Wyvern-based booster stages, each launched with 125T of fuel by (possibly boosted) Falcon Heavy (preserving 55T after self-boosting to orbit), could dock with the crewed Wyvern in LEO and boost it to Mars. Two booster Wyverns would fall back to Earth and land immediately, while the last booster Wyvern and the crewed Wyvern would then fly to Mars, where the booster stage would aerobrake or use a fly by (or both) to return to Earth via a Venus conjunction class orbit, in time for re-use in the next launch window. Alternatively, a single booster with electric propulsion could gradually lift Wyvern into cis-Lunar space, before adding crew and burning to TMI.
- Lunar lander. With 150T fuel capacity, Wyvern could also land on the Earth's moon and return in a single stage. If fueled on the moon, Wyvern could transport 120T of cargo from the moon to Earth, though could propulsively land with only 90T without engine modifications. If flying from trans-Lunar Injection to the moon's surface and back to Earth's surface, a fully fueled Wyvern could transport 35T of cargo. This cargo could be increased for non-time sensitive payloads by using 3-body interactions in the Earth-moon system.

Scaling

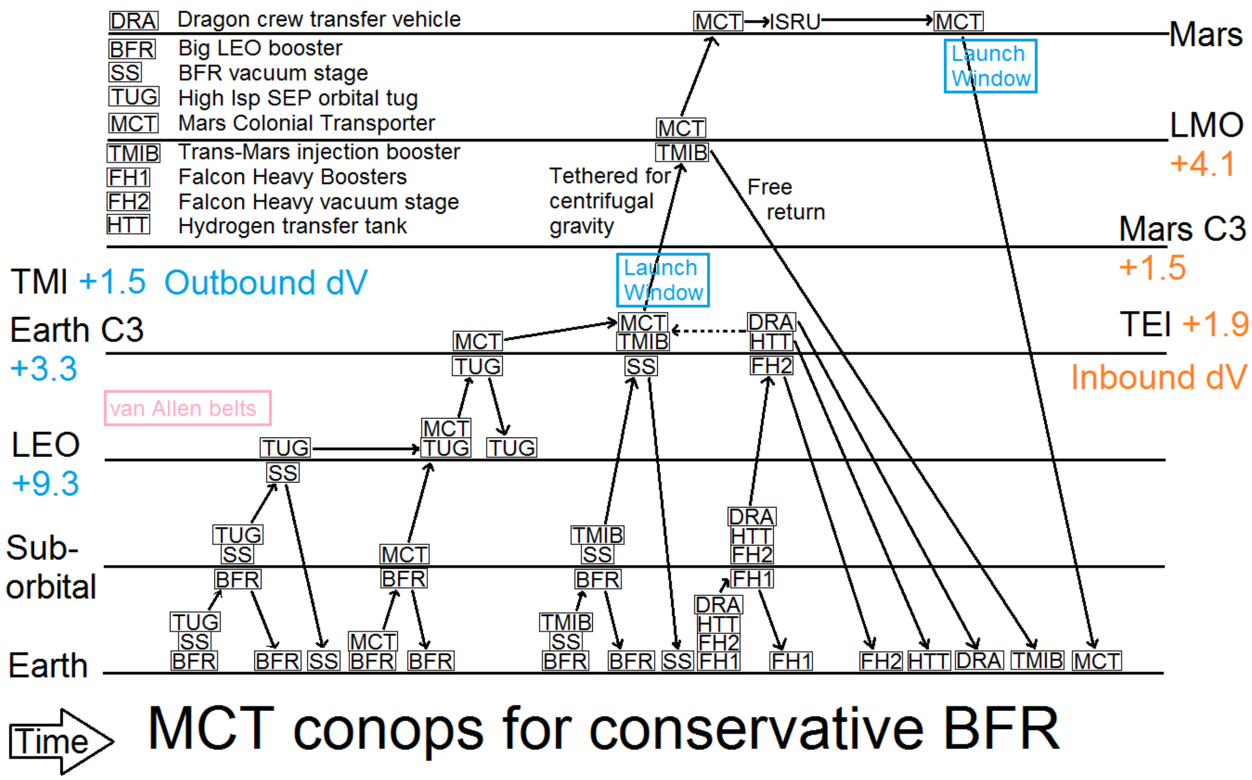
Given a more capable Earth-LEO booster, the Wyvern design can be readily scaled up. Released information suggests a SpaceX BFR LEO capability of 200T. This would enable direct launch of one Wyvern to TMI, or a similar profile to that outlined above with a single Wyvern scaled up by a factor of 4, which would transport 100T cargo to the surface. The only relevant design constraint in scaling is ballistic coefficient, which dictates that a high capacity Mars lander must be, on average, no thicker than a few meters in the transverse direction.

Radiation

With 8.5T of H_2, 8T of O_2, and 2T of CH_4, as well as stores of water or food, there are ample quantities of low atomic mass nuclei to form a radiation shield for coronal mass ejection-type

radiation during the outbound voyage. On the return voyage, reduced quantities of fuel and oxidiser (1T CH_4, 4T O_2 plus consumables) still allow for adequate radiation shielding of roughly 25g/cm^2 of shield wall.
Solar radiation fills the half-space in the direction of the solar magnetic field, where a gyroradius of about 1000km prevents a strictly 'line of sight' shielding methodology.

Conops for maximum up-mass configuration



Substantial simplifications are possible at the cost of payload - for instance direct launch.

Sources

http://www.spaceflight101.com/falcon-9-v11.html
http://www.spaceflight101.com/dragon-spacecraft-information.html