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GOING TO MARS (or anywhere else nearby)

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ABSTRACT

A simple pencil-and-paper bounding study says this is possible: one 9-month round trip, 6 men, 16 one-week landings, nothing thrown away, minimal technology developments (but fairly certain of success), no new launch rockets, under $8 billion in direct launch costs, possibly as soon as 5 years.

This mission study is a clean-sheet design. The differences with other studies are: (1) legacy hardware and contractors are ignored, (2) new developments are minimal, and (3) maximum self-rescue is designed into every phase.

Only direct launch costs were computed: under $8 billion. A guess for the overall program might be 3-4 times that amount, if done by a lean, efficient contractor. All mission assets are reusable, and left in place around Earth and Mars for the next mission to refuel and reuse.

KEYWORDS

Bounding analysis, feasibility analysis, configuration, clean-sheet design, Mars mission, assumptions, fast trip, life support, safety, self rescue, exploration (definition).

EFFECTS OF ASSUMPTIONS

In engineering, it is well-known that the assumptions made about a project completely drive the results achieved. Change the assumptions, those results are completely different. Making the right assumptions is critical to success.

The assumptions made for this study are quite different from those of any other Mars mission study this author has seen, or heard about. It should therefore be no surprise that the results obtained here are at considerable variance with the expectations of most folks knowledgeable of this field of endeavor. ***That difference does not invalidate these results!***

BOUNDING ANALYSIS

This study was a hand calculation assisted by a spreadsheet. It is a bounding or feasibility analysis only. That means the results are "ballpark" correct (for the assumptions made), while the details may not be quite so accurate.

The final modular vehicle designs and mission plan presented here actually reduce the impact of the details turning out a little different from the original calculations. One simply adjusts the stack of modules to cope with the changes.

The following four assumptions are completely at variance with those of most other studies. The last two really say "what would a clean-sheet design look like, given all the technology, expertise, hardware, and lessons-learned accumulated over the last 50 or 60 years?"

> ***What is an appropriate mission objective for effective exploration of another world?***
>
> ***Crew safety and self-rescue capability must be paramount in the design.***
>
> ***Use of legacy hardware is NOT required at all (could be used if appropriate).***
>
> ***Use of legacy infrastructure (mainly contractors) is NOT required (but allowable if appropriate).***

SUMMARY OF RESULTS

From one mission sent to Mars using only four vehicles (one of them manned), we could achieve a serious science return with 16 separate landings widely spaced around the planet.

The possibly of self-rescue or escape is designed into every mission phase to the very maximum extent possible. Only lander descent / ascent lacks an engine-out contingency.

No launcher larger or more expensive than a SpaceX Falcon-9-heavy is required to launch the components of this mission into low Earth orbit (LEO). It should start flying in 2012.

All mission assets (including empty propellant tanks) are left in either low Mars orbit (LMO) or LEO for future missions or projects to utilize.

The count of module launches to LEO for assembly is such that direct launch costs do not exceed $8 billion (in 2010 dollars), based on data published on the SpaceX website in 2010 when these calculations were made. (It should be noted that SpaceX has updated both payload and cost estimates for 2011; Falcon-9-heavy costs are about the same, but payload to LEO is now larger than this study assumed.)

There is only one technology development needed to make this mission happen as planned: a "hot rod engine" capable of a very fast one-way trip time for the manned vehicle. However, neither the prime candidate nor the alternate is a "from-scratch" development.

The modular vehicle designs and components for the Mars mission are also usable (in one combination or another) for missions to Venus, Mercury, or the near Earth objects (NEO's) inside the orbit of Mars, so that manned round trip times are under one year.

Given the right players, this mission could be flown in as little as 5 years from now.

The following sections describe how these results were achieved.

WHAT ACTUALLY IS THE OBJECTIVE?

This is no "flag-and-footprints plus a tow sack of surface rocks" mission. The Apollo moon landings were. This design provides more sites with longer stays, with real on-site science, and deep sampling with a real drill rig.

The imperative to do it this way comes from an analysis of what "real exploration" actually demands. That analysis is based on the most successful of the models used, starting about 500 years ago, to explore and colonize the New World from Europe. See Figure 1 (all figures are located at the end of this paper) for the entire process from exploration to colonization. That figure lists purposes, characteristics, and the mix of players, which are different in every phase.

Exploration's purpose demands the determination of answers to two crucial questions, required before any rational decision can be made concerning subsequent activities. Deceptively simple, those two crucial questions (taken from Figure 1) are:

> ***"What all is there?"***
>
> ***"Where exactly is it?"***

Consider that no two locations on Mars to which we have sent probes have ever produced the same result for a "typical" picture of the planet. The same would be true if we sent probes like that to various locations on the Earth. No two locations are alike here, or there, or anywhere else, for that matter.

That, and the huge expense of spaceflight as we know it, leads immediately to this study's most important mission design concept of a large number of landings, at widely separated sites, all from a single mission. This is also indicated in Figure 1.

That requirement for multiple landings from a single voyage is unlike any Mars mission concept this author has seen, since the 1956 Disney movie about going to Mars.

OPTIONS AVAILABLE

These are location-of-activity options. The same choices were available to the designers of Apollo. See Figure 2.

The historical idea was direct surface-to-surface flight of a single vehicle to the moon. This was also the original design concept for Apollo. The entire Apollo vehicle was its own lander, and the required launch rocket was an enormous concept called "Nova" that was never built.

By adopting "Earth orbit rendezvous", and planning to refuel one vehicle in LEO from a second, the size of the required launch rocket reduced dramatically, and matched up with the Saturn-5 then in development. Under this plan, it took two Saturn 5's to send three men to the surface of the moon. This was the leading Apollo design concept up to the mid-1960's.

The breakthrough came with the notion of "lunar orbit rendezvous", coming from outside NASA. In this version, they would leave most of the Apollo vehicle in lunar orbit, and just send down a lander. Only one Saturn-5 was required to send a mission to the moon in this version. This became the final design for Apollo that we remember so fondly.

The effect of lunar orbit rendezvous was to drastically reduce the weight thrown to the moon, and thus also reduce the size of the launcher. The effect of Earth orbit rendezvous was to reduce the size of the launcher, for whatever weight was thrown. This would be true for refueling, or assembly, in LEO. Apollo did one of these, not both.

A one-way trip to Mars is not so very demanding, especially for an unmanned probe. That we have seen for some decades. A two-way trip is a lot more demanding: note that none has yet been accomplished, even with unmanned probes. Flying with men and their required life support is substantially more demanding than a two-way probe: tough problem.

So, why not combine both techniques into a single mission, so that a big manned mission can be sent two-way, and still require acceptably-small available launchers? See Figure 3.

That is the approach this study takes: assembly of vehicles in LEO, and use of landers staged from low Mars orbit (LMO). No Saturn-5 or Nova class vehicle is needed. Everything can be launched with a Falcon-9-heavy (more or less comparable to the old Saturn-1B, and should be flying by 2012) or a Falcon-9 (already flying). Some small items could even be launched with a Falcon-1 (also already flying).

CONSTRAINTS ON DESIGNS

These include life support issues, crew safety and self rescue issues, the available selection of launch vehicles, and the need to minimize lander weights while still maximizing the number of landing sites.

Life Support Issues

Life support issues are diagrammed in Figure 4. They include adequate space (volume) for privacy and comfort, how to deal with consumables such as oxygen, water, food, and the wastes men produce with them, artificial gravity, radiation protection, and meteoroid protection. These are all time-dependent in some fashion.

Living Space

Adequate living space is often ignored in advanced space mission studies. An example would be a two-year mission to an NEO for four men in two docked-together Orion capsules. The space available per man would be only a little larger than that in the Apollo capsule going to the moon, which was adequate for a two-week voyage, but not much longer. Ask any prisoner who ever served time in solitary confinement, and he will tell you how important this issue is. The standard assumed in this study was to achieve roughly half the volume per person available in the old Skylab space station, which was "super-roomy" for 3 men up to 180 days in space.

Consumables

Regarding consumables, we do not understand how to construct a closed ecology, but we do have a limited understanding of the recycling of air and water. As flight times lengthen, there is an ill-defined tradeoff point beyond which the closed ecology leads to a lower thrown weight. Below that duration, packed supplies are lighter. There is also the fact that we do not yet know how to store food acceptably, beyond about a year and a half. Plus, there is a collision hazard from dumping waste: this should be done only when velocity changes are made, so that the dumped waste track diverges from the spacecraft track.

Artificial Gravity

Our criteria for artificial gravity are woefully incomplete. (After 40 years flying men into LEO, you'd think we would have run the experiments to determine these by now, but we have not.) There is still no direct, trustworthy answer to the question of "how much gee is enough?" We do understand that spin rates in the neighborhood of 4 rpm are about the maximum that humans can tolerate long term.

In the complete absence of better data, we must use 1 full gee at 4 rpm, which leads to a radius of about 56 meters. It does not matter whether we consider cable-connected modules, or truss-connected modules, or just a huge diameter ship, anything we do at a 56 m radius is going to be big, heavy, cumbersome, restrictive of flight maneuvers, and difficult to build in LEO.

Ethics require that we use a 1 gee criterion, because we simply do not know what level of gee is therapeutic. ***We do not know that Mars's 0.38 gee is therapeutic***.

But, we do have data from the various LEO space stations that zero-gee exposure up to about a year is tolerable, given adequate exercise. This alone suggests designing to short mission times in order to avoid the need for artificial gravity.

Radiation

Radiation comes in two forms, a dilute drizzle of extremely-energetic cosmic ray particles almost impossible to shield under any circumstances that we understand, and massive brief outbursts of solar flare radiation, which is far less energetic, and thus easier to shield. Both are lethal dangers beyond the Van Allen Belts.

Short mission durations limit cosmic ray dosage. Appropriate thicknesses of various materials can provide shielding against solar flare radiation. In Apollo, the cosmic ray threat was averted by very short flight times. The solar flare threat was ignored; had there been a flare during an Apollo mission, the crew would have died an ugly death within hours.

For the much longer voyage to Mars, the message is very clear: ***shorten mission times as much as possible*** for cosmic ray exposures, and provide effective solar flare shielding.

Meteroid Protection

Meteoroid protection is needed for a threat that grows more certain with the passage of time. Recent experiments indicate that alternating layers of metal foil and low density foam would actually stop small objects, as seen in a recent Nova Science Now broadcast from PBS.

The Life Support Message

Every one of these issues, plus what things we currently know how to do, point toward ***shortening total mission flight times to under one year***, for manned vehicles. Those times are incompatible with the minimum-energy orbit transfer times that conventional chemical propulsion can effectively provide. Thus, ***some sort of "hot rod propulsion" is actually a hard life support requirement*** for all manned vehicles flying to Mars at this time.

Crew Safety and Self-Rescue Capabilities

Crew safety and self-rescue capability is something many other studies have ignored, but not this one. Given choices otherwise equivalent, safety makes the decision every time in this study. It is the prime design requirement. We are ethically bound to address as best we can every risk we can identify. That means designing-in a self-rescue capability or a way out, at every mission phase. Remember, once this crew leaves LEO, there is no practical possibility of rescue from home, at our current state of the art.

The following list of safety criteria is also pretty much a list of the mission flight rules for this study.

> ***3 men in LMO monitor 3 men on the surface (while doing science from orbit).***
>
> ***There must be at least one lander in reserve for rescue (sending 3 keeps the loss of 1 from terminating the entire mission).***
>
> ***Use multi-engine designs wherever possible to handle engine-out contingencies.***

Manned vehicle flight deck is also the solar flare radiation shelter (enables executing critical flight maneuvers no matter what the solar "weather" is like).

Use redundant crew return vehicles (in case one fails), that are also capable of a max velocity free "bailout" return, in case the final engine burn into LEO fails.

The manned vehicle must have enough propellant to fly fast both ways, just in case LMO rendezvous fails.

We can send unmanned assets ahead "slowboat" and rendezvous with them there.

Available Launch Vehicle Sizes and Costs

Another constraint on the mission design is available launcher sizes and costs. This is restricted to vehicles currently flying, or flying within the next two or three years. The list in Figure 5 is pretty representative and current. For this mission design, the module size for docking and assembly (and thus the number of launchers) is set by launcher payload capacity. The largest (and least expensive) in the list is the SpaceX Falcon-9-heavy. The 2010 data from SpaceX's website used in this study indicated that Falcon-9-heavy could send 32 metric tons of payload to LEO from Cape Canaveral. (For 2011, SpaceX has upped this to 53 metric tons, at about the same cost as 2010.)

Costs per kilogram of payload were far lower with the SpaceX family of launchers than any others flying currently or soon. Accordingly, Falcon-9-heavy (2010 data) set this study's 32 ton module size. The modified Dragon crew return capsules and other 10-ton-class items launch on Falcon-9, and any 1-ton items fly on Falcon-1. Things could be a bit cheaper if this design were revisited with a 53 ton module size, in accordance with SpaceX's 2011 data, but this author did not do that redesign. Therefore, this study is more conservative than it really needs to be.

Just for comparison, the data for the old Saturn family (not shown in the figure, as these vehicles no longer exist) show 119 metric tons deliverable to LEO for the Saturn-5, and 20.8 metric tons for the Saturn-1B (roughly intermediate between the Falcon-9 and Falcon-9-heavy).

Minimizing Lander Weights

This plays a very large role in minimizing thrown weights to Mars. The dual requirements to maximize landings while minimizing lander weights seems contradictory, unless one thinks "outside the box": requiring reusable landers, so that a few landers can visit many sites. These machines need to be of rugged construction, and will have equipment not normally associated with flight vehicles, such as tough landing legs, a refueling probe of some kind, and a big loading crane.

Mars's atmosphere is too thin to provide much aerobraking for a large object, yet too thick to ignore. This study assumes rocket braking descent and rocket ascent, as if it were an airless planet. Yet the vehicles will require some heat protection during descent. That is another reason why a 20% structural inert fraction was assumed.

The two-way velocity requirement is about 8 km/s with no plane change, nearly 12 km/s with a 30-degree plane change. With rugged inert fractions and chemical propulsion, single stage is infeasible. With chemical, a reusable second stage is feasible if multiple single-use first stages are sent. As the number of landings required increases, this gets heavy quickly.

The other option is higher specific impulse but "thrusty" propulsion, such as the nuclear thermal rocket (NTR). The old NERVA solid core NTR was extensively ground-tested in one form or another from 1959 through 1973, and came within about a year or two of flying as a substitute for the Saturn S-IVB stage. Its final demonstrated performance and thrust make a single stage reusable lander practical in this application, which is the lightest option for a large number of landings. See Figure 6.

Once that lander propulsion decision is made, one can address exactly how best to use the lander vehicle to accomplish the mission objective outlined earlier. This study assumes that a crew of three, a week's consumables, a rover car and a few small robot rovers, an inflatable Quonset hut, and some science lab equipment will weigh in the neighborhood of 6 metric tons. With a payload fraction of 10%, this roughs-out as a 60 ton lander vehicle, fully loaded and fueled, capable of the maximum plane-change scenario. The hut is an "armored inflatable", similar to the inflatable modules already flown by Bigelow Aerospace.

The reason for the inflatable Quonset hut is the radiation inherent with a solid core NTR. While low enough to be tolerated for the flights, this is exposure that should be avoided during the weeklong stay on the surface. So, in this study, the concept is to pack all the gear in the rover car, and set up camp a safe distance away from the lander, say a kilometer or two. This Quonset hut would be considerably lighter than the descent stage of a chemical lander. Using the lab equipment inside the hut, field science can be done on-site in a shirtsleeve environment.

This study presumes each crew of three is composed of a pilot/engineer, a geologist/geochemist, and a biologist/biochemist. These individuals would be cross trained to assist, or fill-in for, each other at need. The rover car and robot rovers gather samples and data remote from camp, to be analyzed in the hut afterwards. There is a drill rig on the rover car such that deep samples may be obtained, from perhaps as much as a kilometer down, if necessary. The idea, as stated earlier, is to determine ***what all is there***, and ***where exactly it is***, at that landing site. Each landing has one nominal week's effort. The only things left behind are wastes and a transponder that future missions might use to revisit the site.

This lander and camp exploration scenario is depicted in Figure 7. This is the best way to answer those two fundamental exploration questions, with the least weight thrown to Mars.

SIZED-OUT COMPONENTS

Lander

The roughed-out lander design is "cartooned" in Figure 8. That figure gives weights and weight fractions, an indication of where some of those guessed figures came from, and the estimated performance of the NTR engine. The acceleration capability of the fully-loaded vehicle will exceed Mars surface gravity shortly after ignition for descent. The final burnout acceleration of the vehicle is still quite tolerable for humans, even those exposed to microgravity.

This vehicle's form factor needs to be rather squat and fat, to maximize mechanical stability on the landing legs. There is a cargo space below the actual crew cabin in which the equipment is stored. These items plus the propellant load should make an adequate radiation shield for the short exposures of descent and ascent.

The propellant load is adequate for up-to-30-degree plane change maneuvers off the parking orbit. Depending upon that parking orbit inclination, the majority of Mars's surface is within reach, even the poles. Calculated performance and requirements are shown in Figure 9.

Manned Vehicle

The manned vehicle comprises a habitat, crew return vehicles, propellant modules, and "hot rod propulsion". All the modules in this study were designed at 32 metric tons, and are to be assembled by docking in LEO, similar to the International Space Station (ISS).

Habitat

The habitat is three such modules, as shown in Figure 10. One is the command deck, surrounded by water and wastewater tanks plus a little steel plate, as the radiation shelter for solar flare events. There is room in here for all 6 crew, plus a day or two's emergency food. This allows executing critical flight maneuvers, no matter what the solar "weather" is.

Another module is the basic living area, which is largely wide open, to give the necessary space per person. The galley, some supplies, and the exercise area are all within this module. The "wide open" feature covers the "distance apart" aspect of living space, something missed by simple volume ratio criteria.

The third module is a sleeping dorm and packed-supplies storage module. This one carries a little over a year's packed supplies. No wide-open spaces here.

There are no artificial gravity provisions, as this design is restricted to total mission times of 1 year or less. The nominal Mars mission planned here is 9 months.

The combined habitat has a mass of 96 metric tons, quite comparable to the old Skylab space station, although its form factor is skinnier than Skylab's.

Crew Return Vehicles

To one end of this habitat are docked two somewhat-modified SpaceX Dragon capsules as crew return vehicles. The nominal role is simple reentry from LEO after the manned vehicle has returned to Earth. However, in the event the final "burn" into LEO fails, these capsules must also serve as emergency "bailout" high-velocity free return vehicles. This may require a bit thicker heat shield, since the free return velocity from a 75 day trip is ***at least*** 16 km/s. One capsule can carry all six crew; two are included for the safety of redundancy.

This emergency role also requires considerable velocity change capability from the capsule's Draco thruster system, in order to hit the atmosphere correctly from an adverse trajectory. To that end, using data on the Dragon from SpaceX's website, this author "reverse-engineered" a pretty close approximation to the pressurized and unpressurized spaces available. For this application, the unpressurized space is filled with additional thruster fuel tanks, plumbed into the thruster system. The result gives a velocity-change capability (with 6 persons aboard) closer to 2 km/s than the "stock" just-under-1-km/s. See Figure 11.

Common Propellant Tank Module

There is a common propellant module for both the manned and unmanned vehicles. As shown in Figure 12, these are 32 metric ton dockable modules, loaded. Each module is a double-wall cryogenic Dewar, with foam and foil meteor armor doubling as insulation on the outside. Each module has its own solar-powered cryocooler to keep the liquid hydrogen propellant cold over long periods of time. Each module also is equipped with a "plumbing hook-up kit" of pipe and fittings, so that connections and cross-connections may be arranged as needed during LEO assembly, or anywhere else. Structural loads for the acceleration of a cluster of 20 to 25 of these modules must be considered. The 10% inert weight fraction reflects all of these added items.

"Hot Rod Propulsion"

The baseline "hot rod propulsion" scheme is an open-cycle gas core NTR concept worked 4 decades ago under Project Rover along with the NERVA solid core NTR. See Figure 13 for a "cartoon" of this device. At reactor power levels exceeding those for about 2000 s specific impulse, regenerative cooling was thought insufficient, so a waste heat radiator had to be included, which reduced engine system thrust-to-weight ratios below one.

This is not a "from-scratch" development, since controllability of gas-phase fission, and the flow scheme to provide confinement of the uranium fireball within the chamber, were both demonstrated decades ago. But, it's not a "sure thing" either, since these were never combined and tested as a single propulsive device. That was still about two years away when the 1972 order to shut the project down came.

Back then, this device was considered "likely enough" to be a serious candidate for the Mars mission that had been planned for the 1980's. The data projected for that Mars engine (as best this author can remember them) are those given in Figure 13.

Gas core NTR not being a “sure thing” demands that an alternate be worked in parallel. The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) electric rocket device has been ground tested by ex-astronaut Franklin Chang-Diaz, and may soon be tested on the ISS at the 200 KW power level. This device has higher specific impulse capability, at less thrust for the machinery weight, compared to values expected for gas core NTR.

The risk here is not the VASIMR device, it is the source of the electricity required to run it. Scaled up and used in multiple-engine form (for sufficient thrust) as the “hot rod propulsion” for this mission, it is probable that multiple MW of electricity will be required. You just don’t get that from solar panels or radioisotope generators; a real nuclear-electric power plant is necessary. We already build those, just not in a flight-weight, spaceworthy form. That flyable power plant is the real development item if VASIMR is used.

Hydrogen is the propellant for the prime gas core NTR “hot rod propulsion”. For the alternative VASIMR, the propellant is argon. The same common propellant module could be used with either cryogenic liquefied gas, an important propulsion selection consideration.

Other Considerations Impacting Design

This mission is planned and calculated such that nothing is jettisoned, not even the emptied propellant modules. These tanks are pressure vessels, and can be vented to space to clean them out. Empty tanks are left in LMO from the lander-powered unmanned vehicles, and in LEO as part of the manned vehicle. These assets can be refueled and reused, or they can be converted to pressurized habitable volume.

Potential pressurized volume will be at a premium in space or on other worlds, as the years go by. Pressured propellant tank assets should never, ever, ***ever*** be wasted! They can, at the very least, be reclaimed as construction or structural material that need not be launched.

MISSION PLAN

Figure 14 illustrates the basic Mars mission plan worked out in this study. Four vehicles are assembled in LEO from the modules and components just described, three unmanned, one manned. The three unmanned vehicles are “slowboat” minimum-energy one-way Hohmann transfers of landers and landing propellant supplies to LMO. This positions those supplies at Mars by the most efficient means, ***and without introducing a third type of propulsion***, also a very important design consideration.

The manned vehicle makes a very fast transit to Mars using “hot rod propulsion” that does not yet exist, but very soon could, as already explained. The nominal one-way manned transit time is 75 days. There are 16 week-long landings conducted sequentially at Mars, followed by a 75-day fast return to Earth with the manned vehicle. The manned vehicle must carry all the propellant for a two-way trip, just in case rendezvous in LMO should fail.

The landers and their tank assets are left in LMO for future missions to refuel and reuse, or otherwise utilize. The manned vehicle is left in LEO for refuel and reuse in future missions.

Thrust levels on all vehicles should be high enough so that the velocity changes are effectively impulsive. A rule of thumb says vehicle accelerations should be at least around 0.05 gee.

VEHICLES

Unmanned Vehicles

The unmanned vehicles comprise a lander and a stack of propellant modules as illustrated in Figure 15. There are three such vehicles in this study. The propellant for one third of the landings, plus that required for the lander to push this stack to Mars, determines the number of propellant modules in each stack. Minimum-energy single-stage Hohmann transfer one-way is well within the reach of the lander's solid core NTR propulsion. Nominally, that is a 259 day trip. The performance estimates and design requirements are given in Figure 16.

This modular approach to design has great benefits for the assembly process in LEO. It also leads to flying with extra propellant, since each module is launched fully loaded, even if only a fraction is ever used. In this way, it is very likely that after 16 landings, there will still be enough propellant left to take a lander and visit Phobos briefly, before the departure for Earth!

The same unmanned vehicles would serve for a mission to Mercury, but are not needed for missions to Venus or the near Earth objects, since landers are unnecessary for those destinations.

Manned Vehicle

Similarly, the modular manned vehicle (illustrated with the gas core NTR "hot rod propulsion") is shown in Figure 17, with performance estimates and requirements given in Figure 18. This entire vehicle is recovered in LEO at mission's end, for refuel and reuse by future missions.

This manned vehicle must fly very fast in order to hold the mission time under a year. With 16 sequential week-long landings at Mars, the nominal 75-day one-way travel times to and from Mars then add up to a nominal 9 month mission in this study. Such flight requirements can be crudely but accurately estimated from a simple square-wave velocity trace approach, since the trajectory is nearly a straight-line "shot" at high speeds. A nominal 100 million km path length, divided by about 75 days, is almost 16 km/s constant coasting speed between burns. Because each leg is 2 such velocity changes, and the manned vehicle must carry propellant for emergency return without rendezvous, the total velocity-change requirement is nearly 62 km/s! ***That is what drives the need for "hot rod propulsion".***

The same basic manned vehicle works for missions to Venus, Mercury, and the NEO's inside the orbit of Mars. Once built, this hardware makes those other missions far less expensive, a very important benefit simply not seen in studies that do not require reusable hardware.

To go outside the orbit of Mars (such as to the main belt asteroids) incurs mission times beyond the one year limit for this manned vehicle, thus requiring the addition of some kind of artificial gravity, and also some much better, longer-term food storage techniques. We don't yet know how to do those things effectively! When we do, we can add them to this same basic vehicle.

OTHER PROGRAMMATIC ITEMS TO WORRY ABOUT

As already described, the solid core NTR engine for the lander is not really a technology development. Yet, some effort is required to recreate the old hardware and update it slightly. Significantly more effort is required to recreate the expertise (engineering art) that underlaid it, an item often forgotten. However, these are not likely to be the pacing items in this mission.

Another item not previously mentioned is the need for a dexterous, rugged, simple, and lightweight space suit. This will be necessary during assembly operations in LEO, during refueling operations in LMO, and in exploration on the surface of Mars. This study presumes its existence, when in fact such a thing does not yet exist. It does not have to be a pacing item, but we will have to think "outside the box" to get this done in a timely fashion. This author would suggest the mechanical counterpressure approach, with a serious look at what the true design compression level requirements might be, not just what has been traditional so far.

The "hot rod propulsion" is actually two items worked in parallel, so that one will be ready in time. Those are the gas core NTR, and the nuclear-electric power plant for a scaled-up VASIMR. These are most likely the true pacing items in any program that flies this mission.

The other components are "routine engineering" in the sense of design/construction/checkout. While those efforts are significant, they are unlikely to be pacing items.

FINAL COMMENTS

This is not an optimized design, it is just a ballpark exploration of what is feasible under these very realistic assumptions and constraints. The crew size, number of landings made at once, details of rendezvous in LMO, and a host of other details, all need exploration and optimization with far more rigorous calculations than this. ***However, all of these other possibilities will be found to operate within the same basic ballpark that this study identified.*** That is: multiple vehicles to Mars, manned items flying very fast, combined use of LEO and LMO rendezvous to reduce launcher size to something reasonable, and multiple landings from a single mission.

The real critical factor for success is not any of the technical things, but in having lean, efficient private and public entities to do this work.

The Good News

This particular study design adds up to a direct launch cost of about $8 billion (2010 dollars), based on cost figures right off the SpaceX website, and a total number of launches to orbit all of the required modules. A set of "lean" contractors led by a "lean" government agency (per Figure 1) could actually get this done rather quickly, in perhaps as little as 5 years. In this context, "lean" means dedicated, focused, efficient organizations, unhampered by outside bureaucratic or political interference. Done by "the usual crowd", the cost would be many times higher, and the timeline at least 15-20 years, if at all.

The Bad News

The NASA that could lead and manage this project as presented herein, is very most definitely ***not*** the NASA that we have. We have an enormous government space agency trying to do an entire plethora of things, in which every little project is a budgetary line item and "political football" in Congress. This is a Congress that now arrogantly "designs" heavy lift rockets (that we may or may not even need) by pork barrel politics instead of engineering realities!

It is this author's opinion that we have not done the government space agency function correctly for some 40 years now, which in large part explains why men have not flown anywhere new in all that time.

But, that's another topic.

REFERENCES

This being a paper-and-pencil "what-if" study, there are no formal citations, really. A lot of this was just evaluating the rocket equation. However, the author did use two references to help with the orbital mechanics and velocity-change requirements:

Fundamentals of Celestial Mechanics, J.M.A. Danby, MacMillan, New York, 3rd printing, 1970 (an old textbook, this had data for celestial bodies and orbital mechanics equations).

AIAA Aerospace Design Engineers Guide, 3rd Edition, American Institute of Aeronautics and Astronautics, Washington, DC, 1993 (section 10-18, elliptical orbit parameters)

For the solid core NTR (NERVA) characteristics, the author used his memories from old Project Rover reports seen in the 1970's, confirmed by what the Atomic Rocket website has listed.

For the open-cycle gas core NTR characteristics, the author used his memories of old Project Rover reports seen in the 1970's. There is little agreement among current web sites about this engine. There is more about the gas core nuclear lightbulb concept. Even so, much of this information is vague or contradictory. The remembered data are better.

For characteristics of the VASIMR device, the author simply consulted the Wikipedia article and the company website.

For characteristics of the Falcon family of rockets and the Dragon capsule, the author obtained data directly from the SpaceX website. His study data were from fall/winter 2010. About

February 2011, Spacex revised these data, increasing the Falcon-9-heavy payload, at about the same cost as prior.

The characteristics of the other launch vehicles were obtained by several web searches.

FIGURES

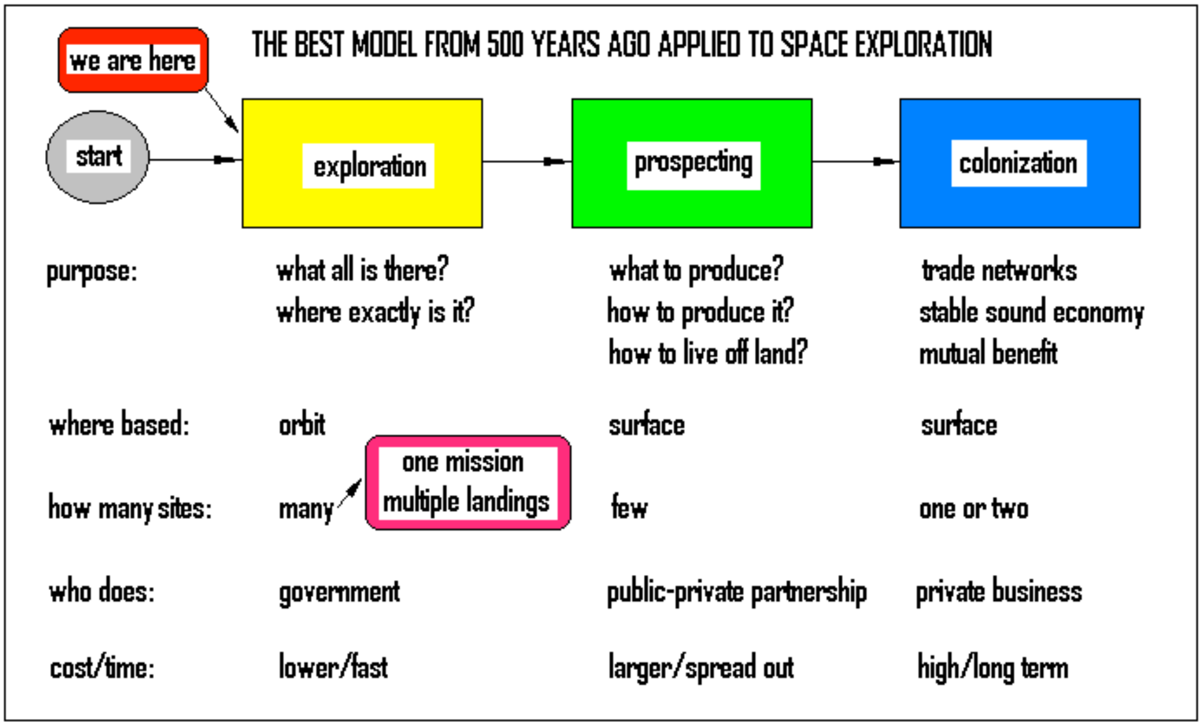


Figure 1 – The Most Successful Model in History for Exploration and Colonization

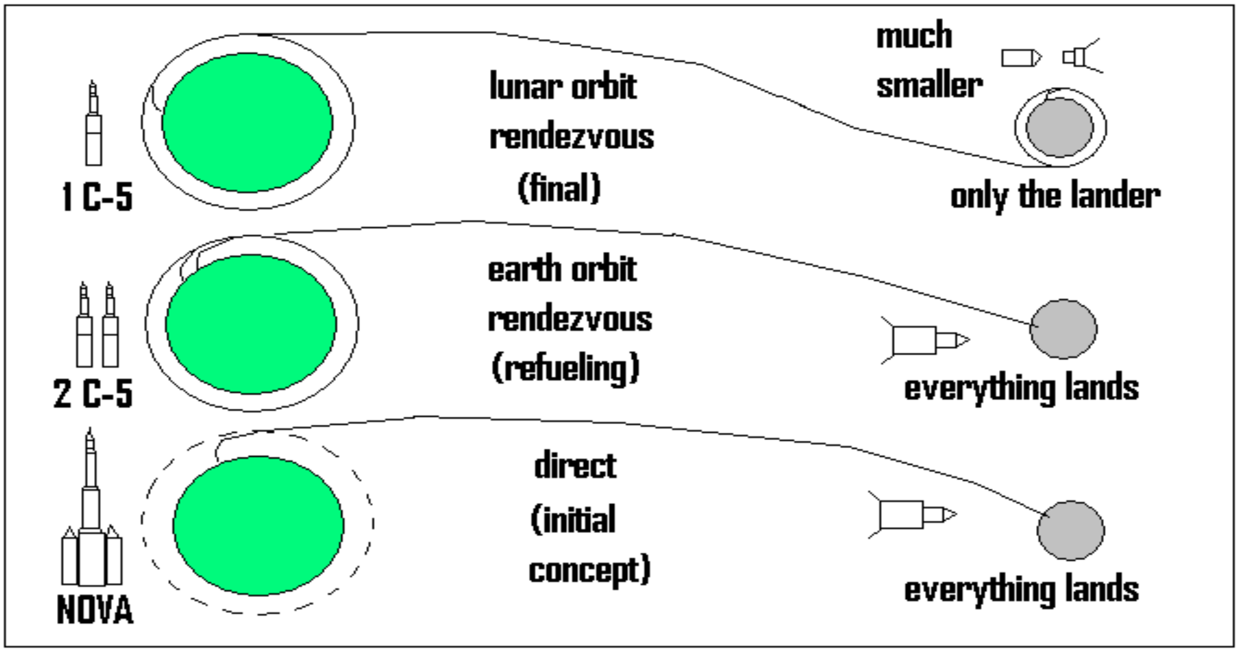


Figure 2 – Choices of Mission Architecture for Apollo to the Moon

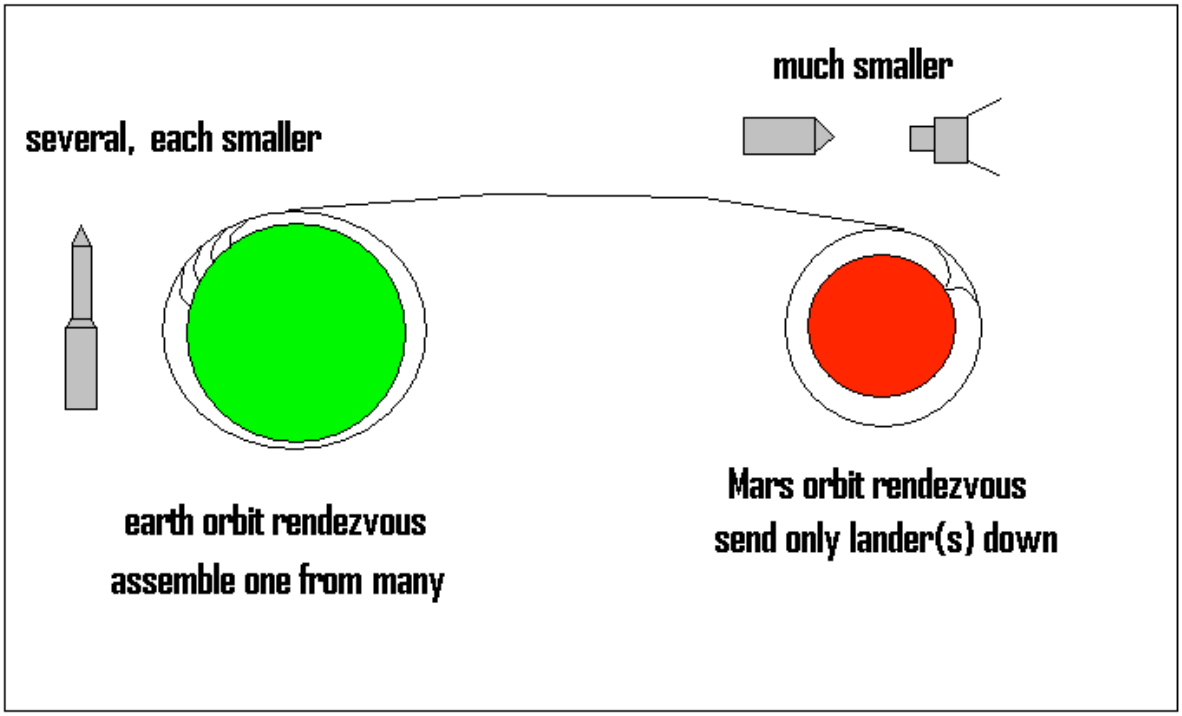
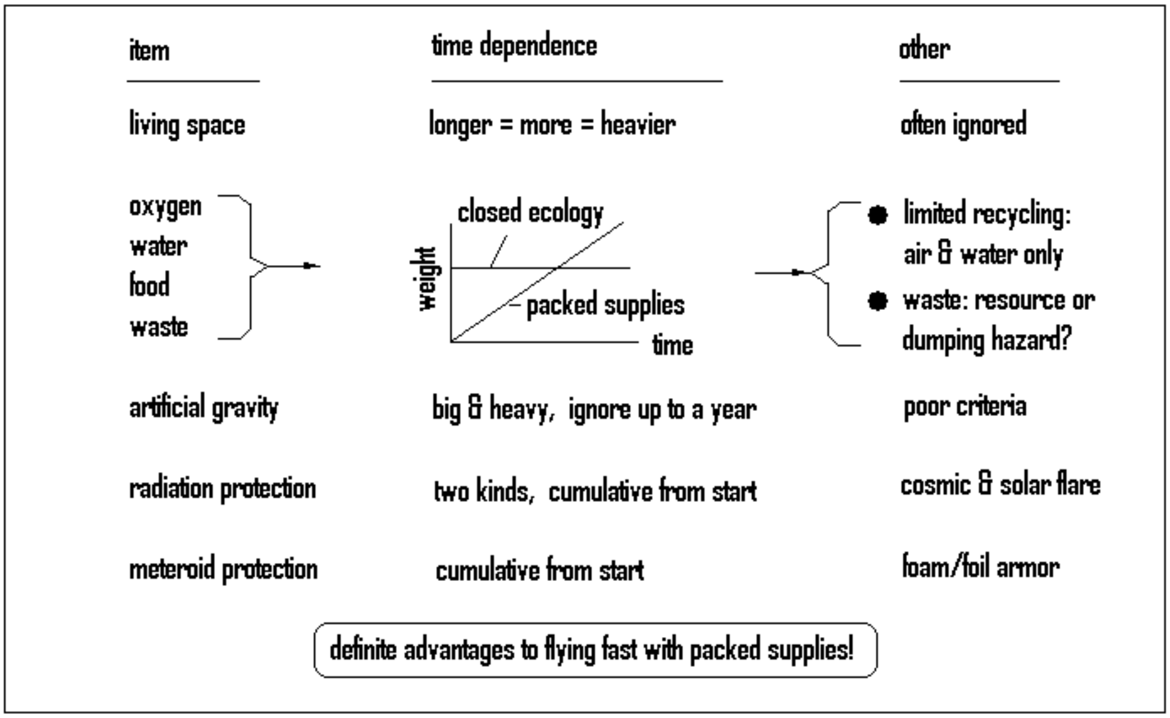


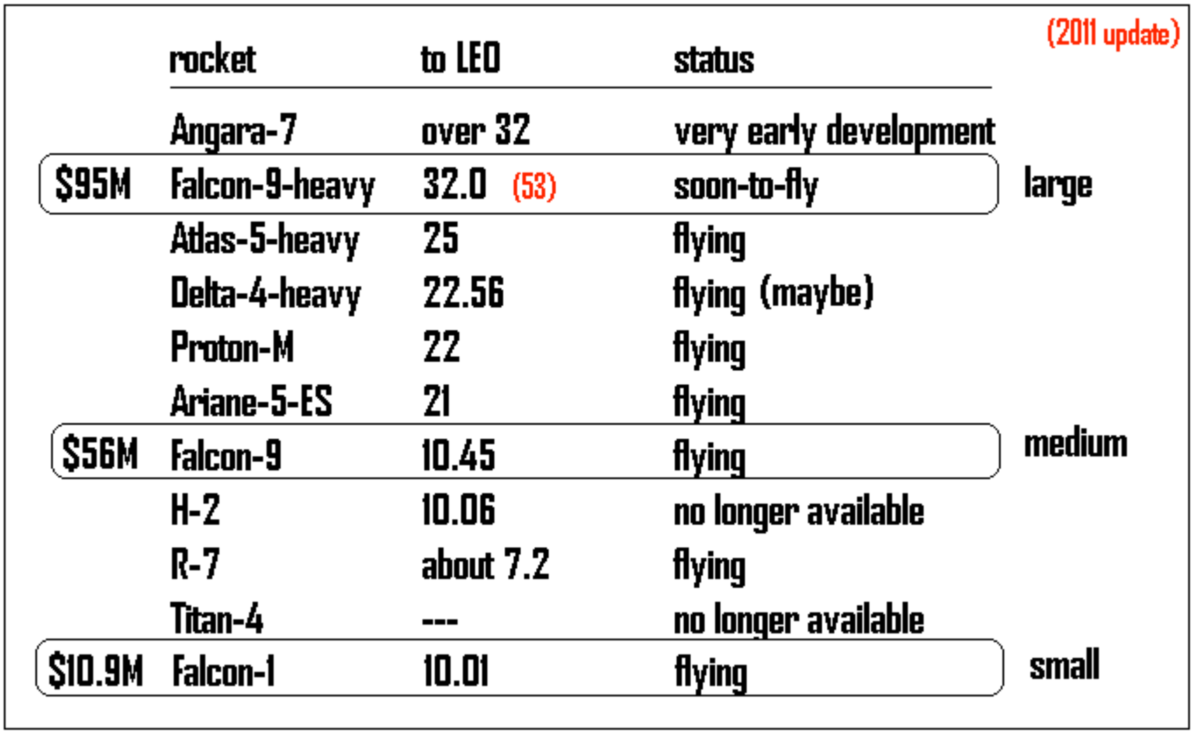
Figure 3 – Use Both LEO Assembly and LMO Landers to Reduce Launcher Size



item	time dependence	other
living space	longer = more = heavier	often ignored
oxygen water food waste		limited recycling: air & water only waste: resource or dumping hazard?
artificial gravity	big & heavy, ignore up to a year	poor criteria
radiation protection	two kinds, cumulative from start	cosmic & solar flare
meteroid protection	cumulative from start	foam/foil armor

definite advantages to flying fast with packed supplies!

Figure 4 – Life Support Issues Are Time-Dependent



(2011 update)

	rocket	to LEO	status	
	Angara-7	over 32	very early development	
$95M	Falcon-9-heavy	32.0 (53)	soon-to-fly	large
	Atlas-5-heavy	25	flying	
	Delta-4-heavy	22.56	flying (maybe)	
	Proton-M	22	flying	
	Ariane-5-ES	21	flying	
$56M	Falcon-9	10.45	flying	medium
	H-2	10.06	no longer available	
	R-7	about 7.2	flying	
	Titan-4	---	no longer available	
$10.9M	Falcon-1	10.01	flying	small

Figure 5 – Selected Launcher Data

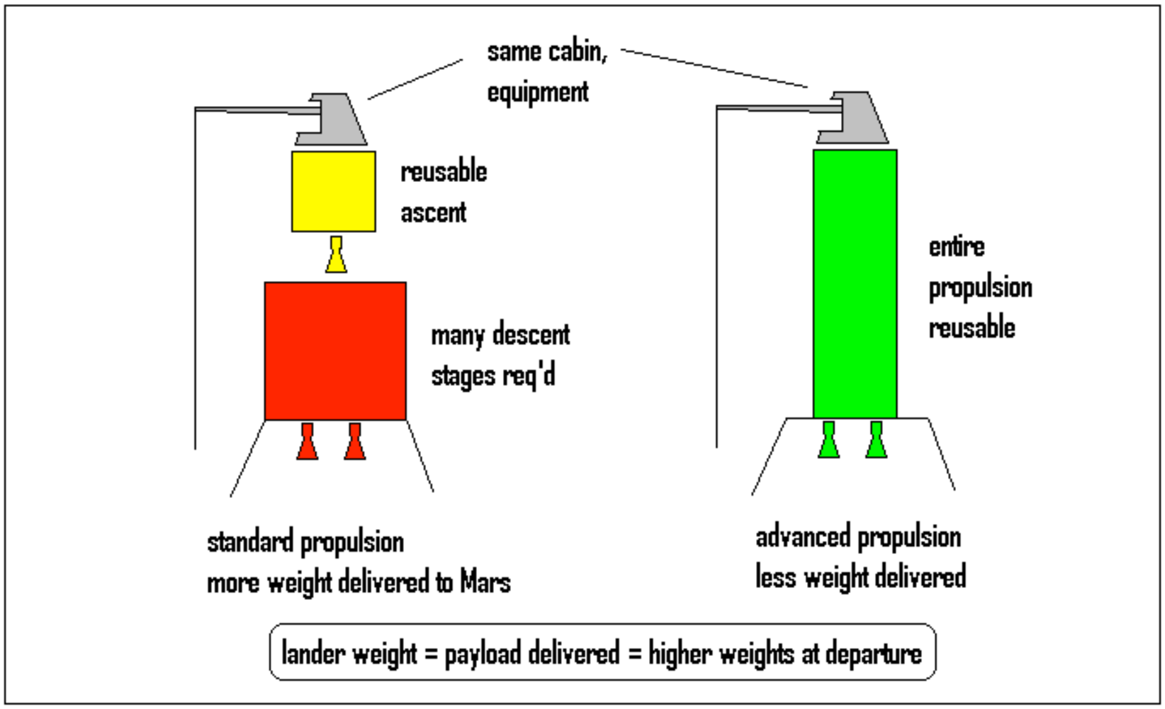


Figure 6 – Why a Nuclear Rocket Single Stage Reusable Lander Makes Good Sense

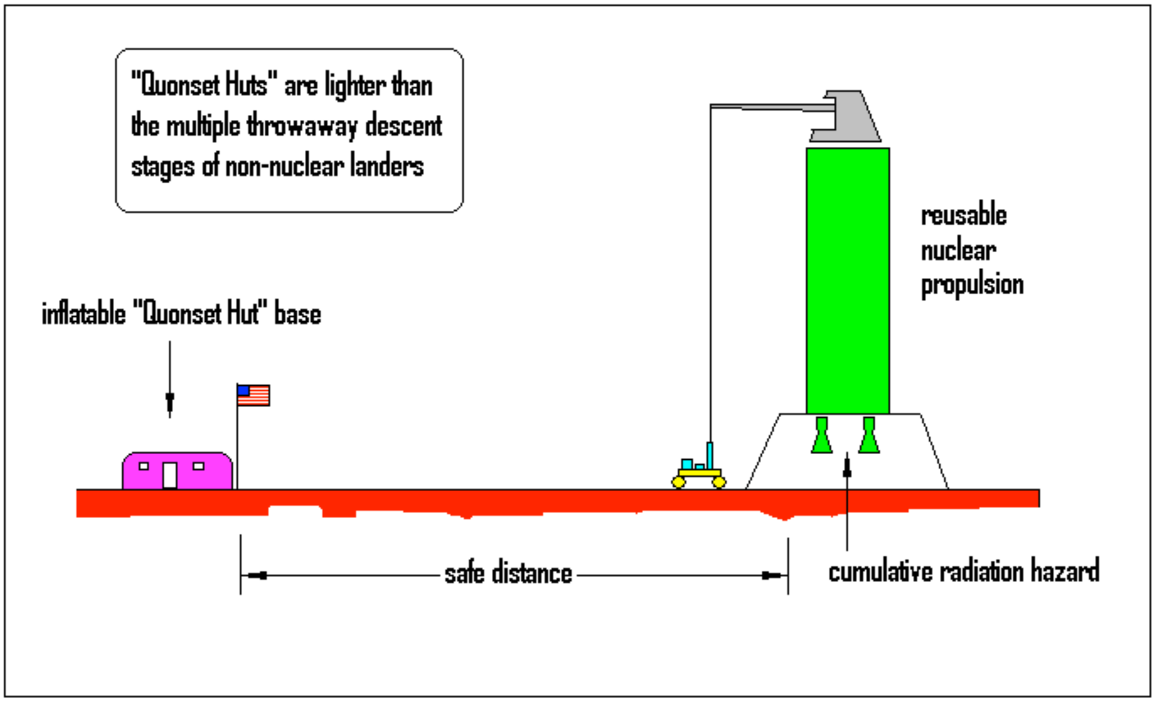


Figure 7 – Baseline Site Camp Scenario with the Single Stage Nuclear Lander

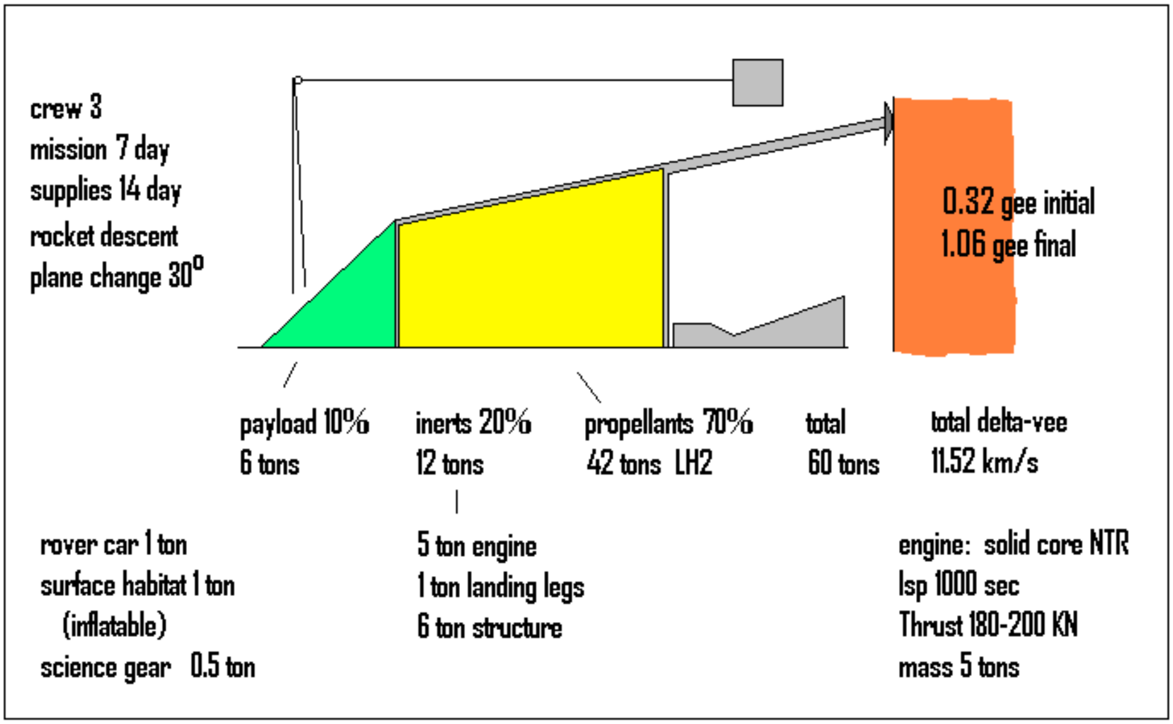


Figure 8 – Configuration Layout and Data for the Reusable Single-Stage Lander

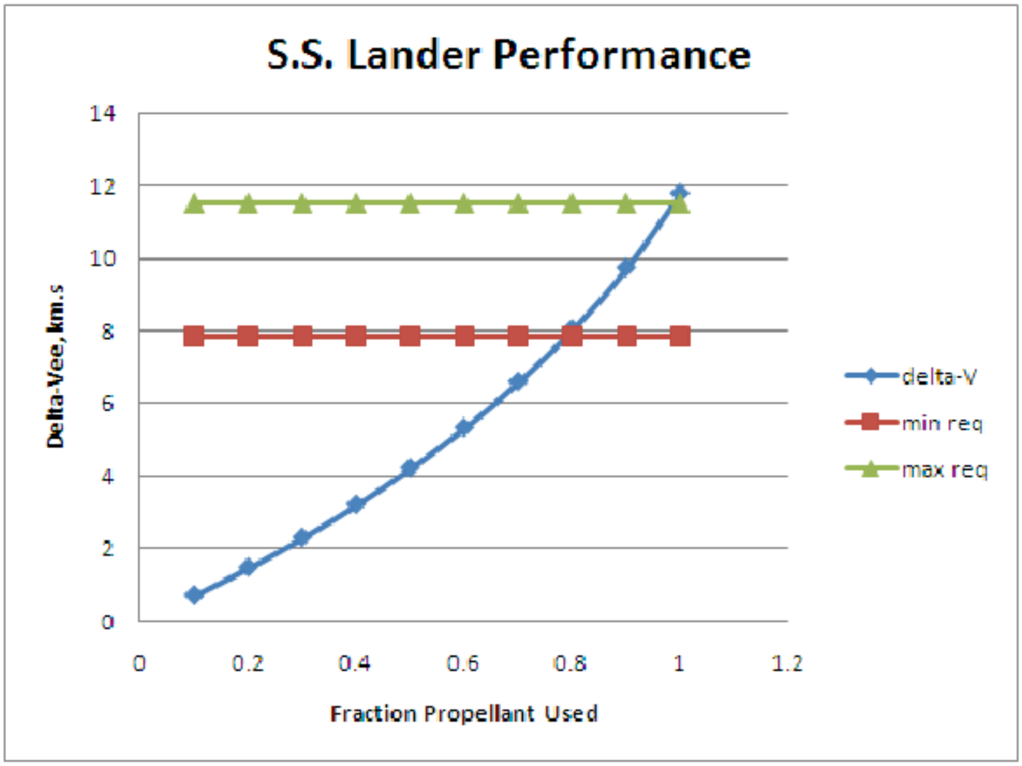


Figure 9 – Estimated Performance and Requirements for Lander

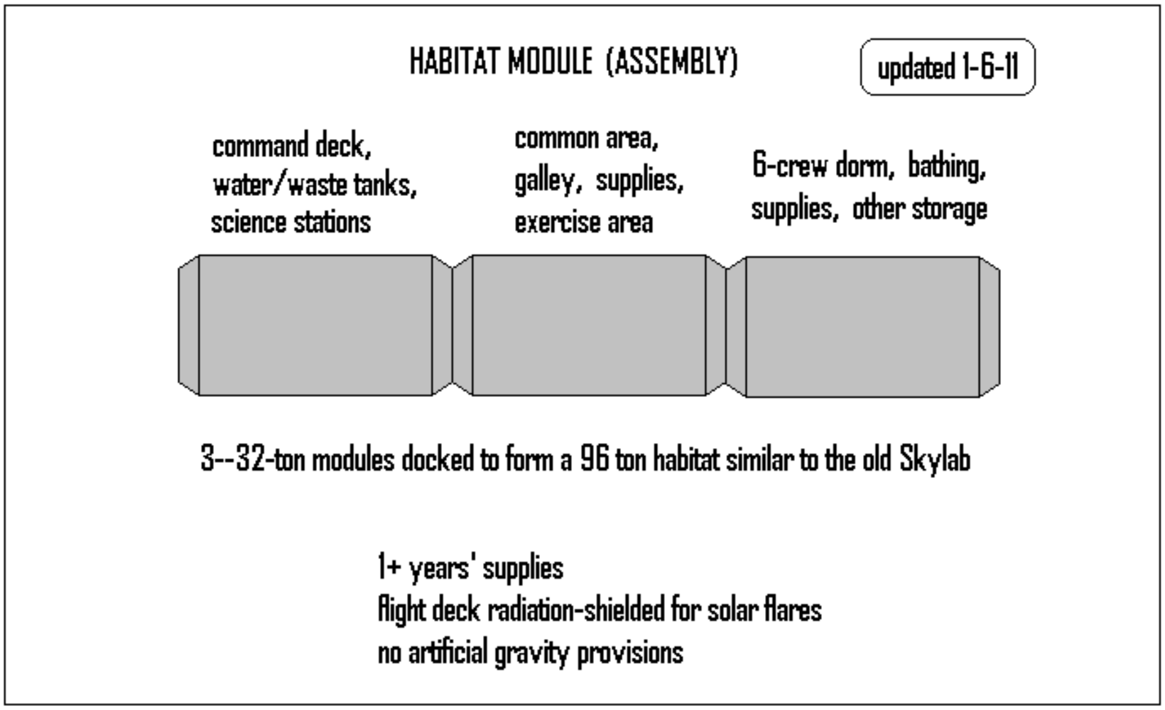


Figure 10 – Three-Module Crew Habitat Section Layout

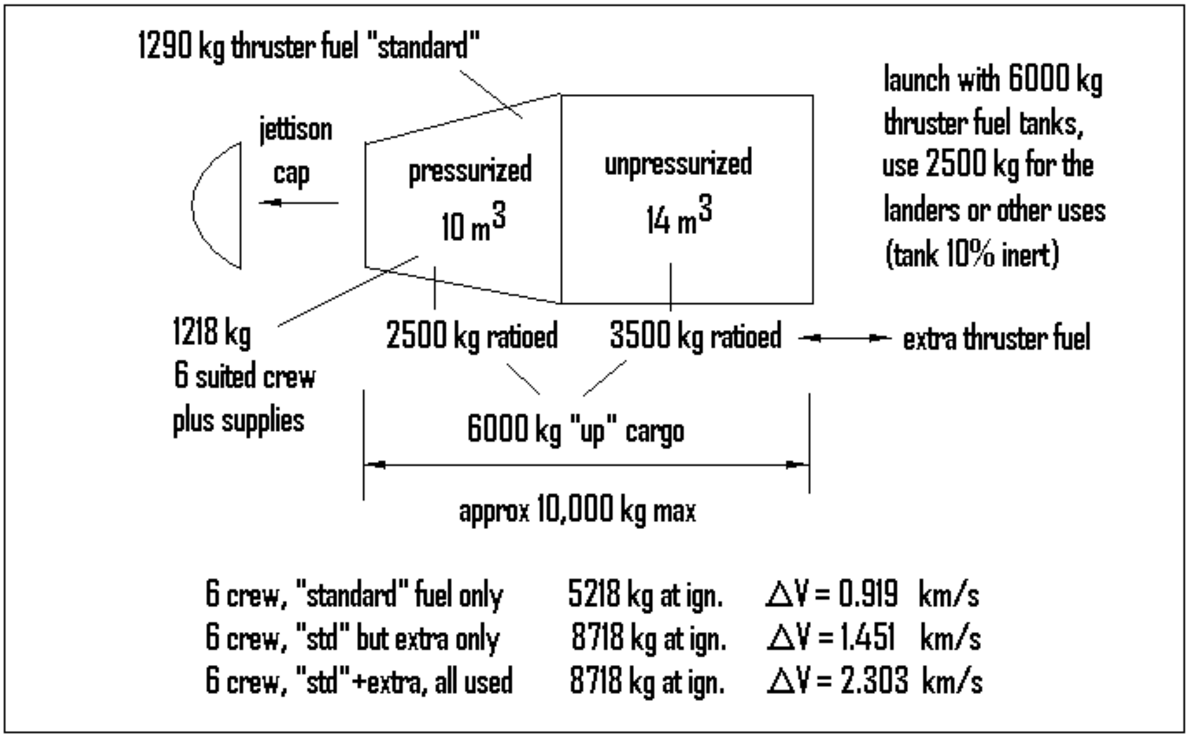


Figure 11 – Modified Spacex Dragon Capsules as Crew / Emergency Return Vehicles

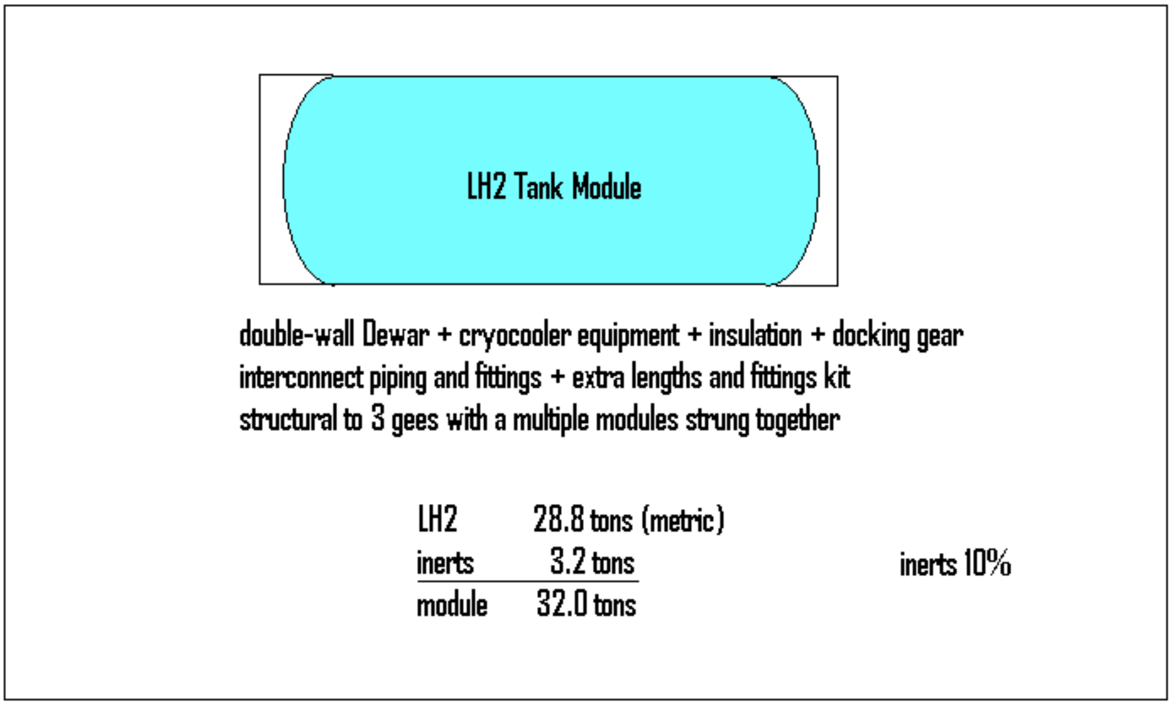


Figure 12 – Rough-Out Layout of the Common Propellant Module

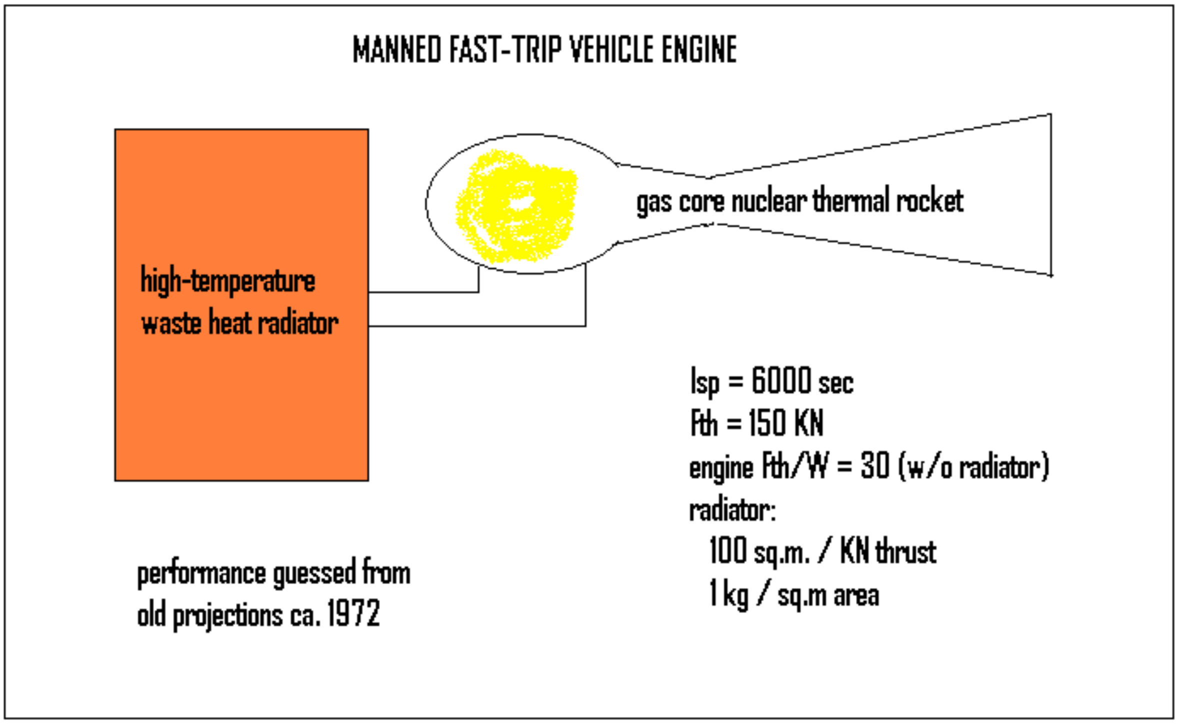


Figure 13 – The Open-Cycle Gas Core Nuclear Thermal Rocket

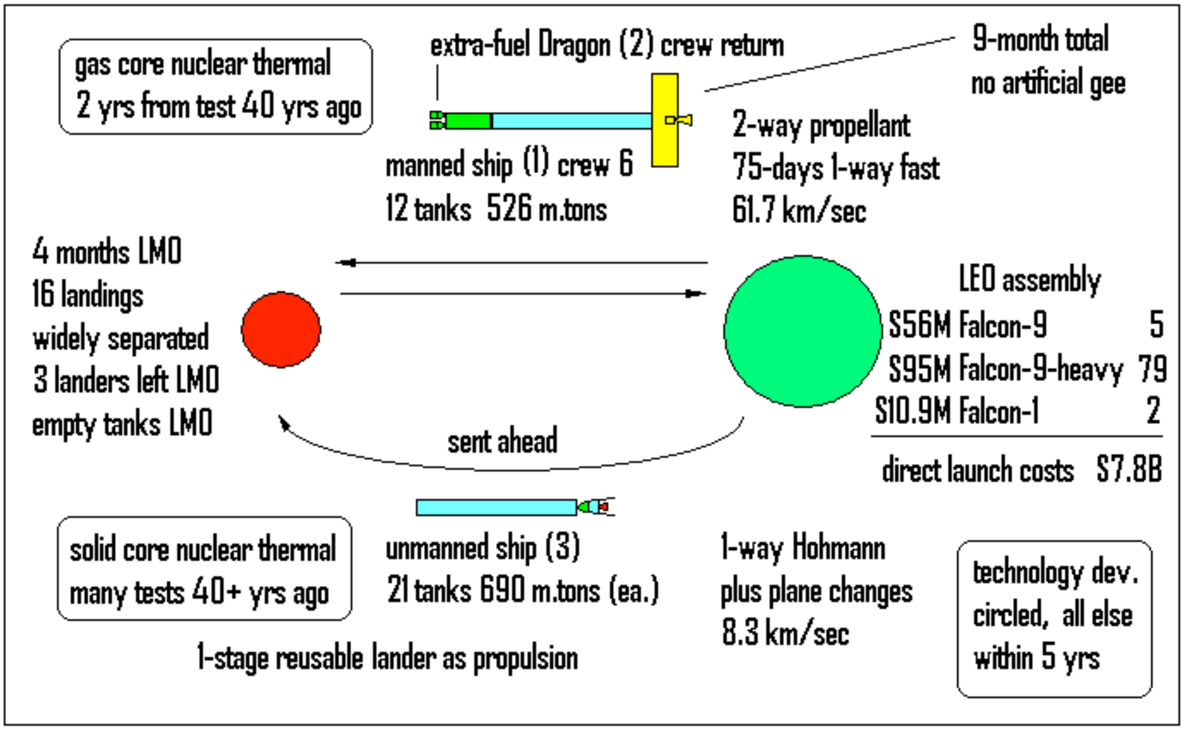


Figure 14 – The Basic Mission Plan

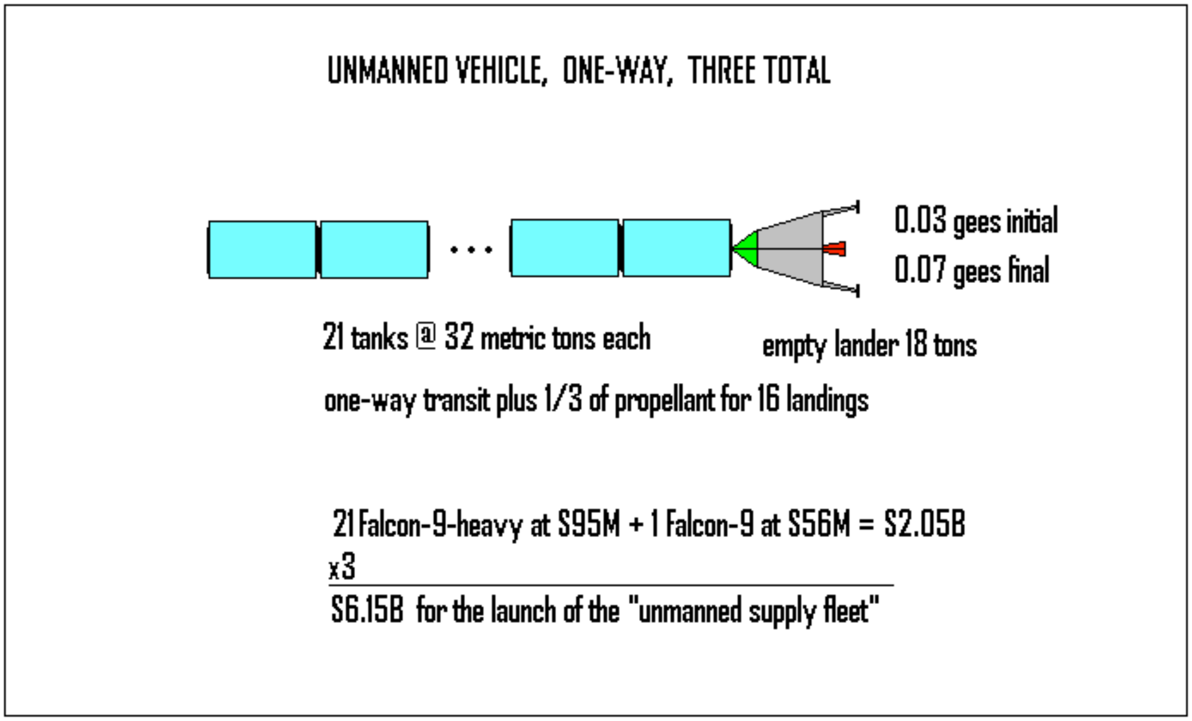


Figure 15 – Unmanned Vehicle Configuration for the Mars Mission

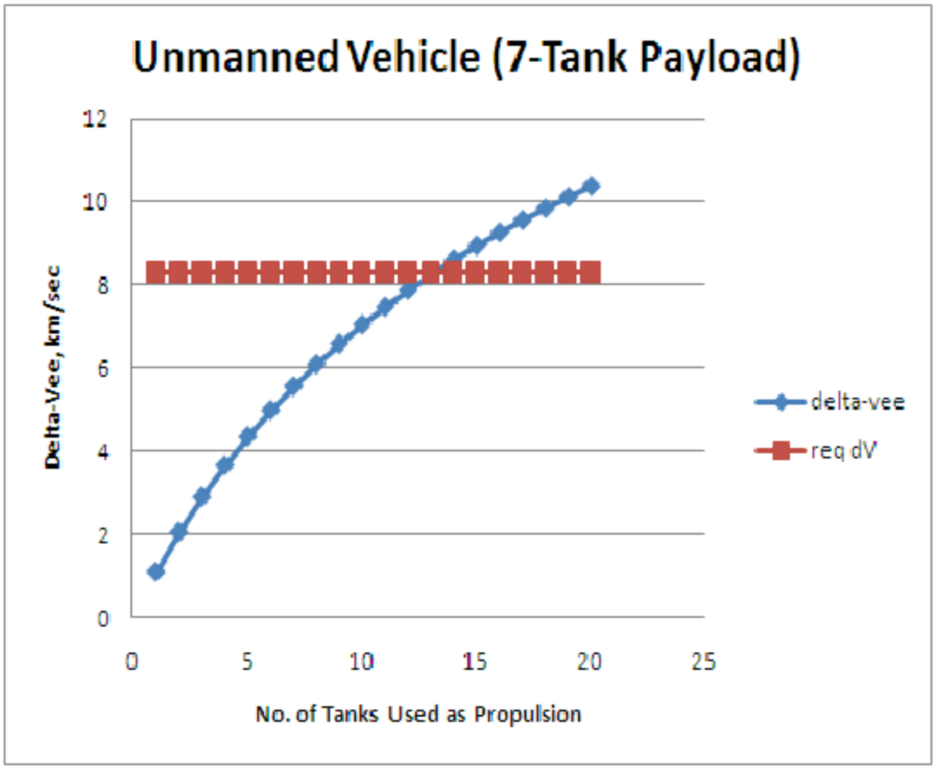


Figure 16 – Estimated Performance and Requirements, Unmanned Vehicle

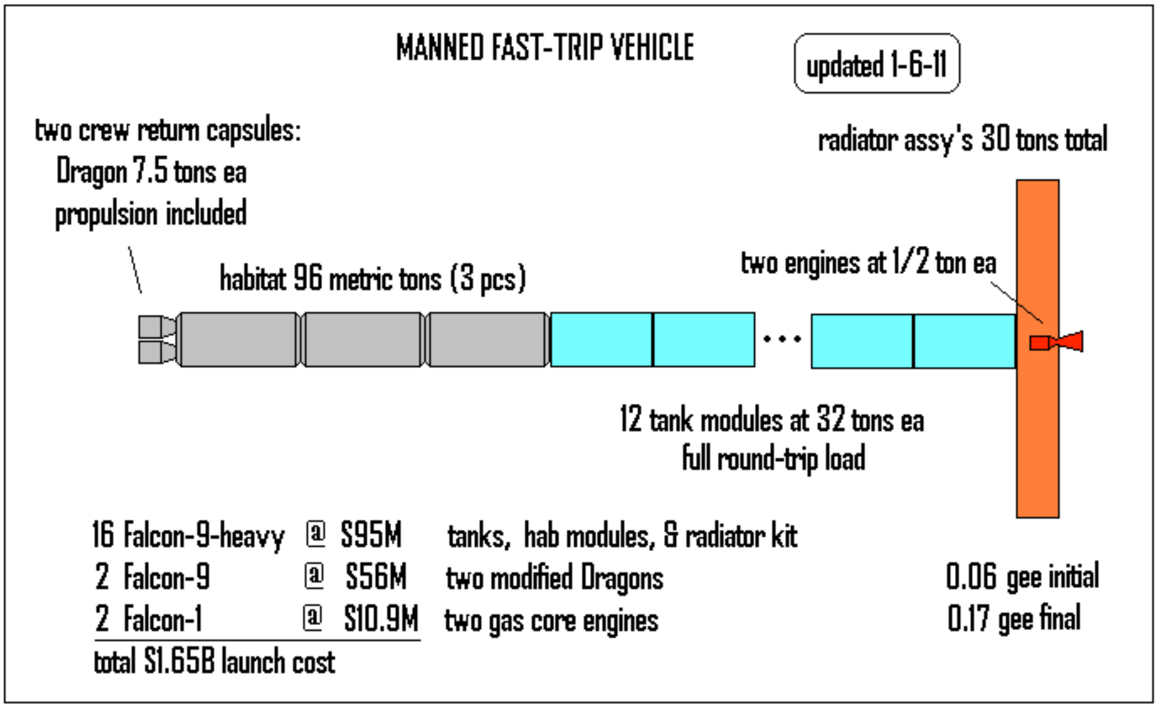


Figure 17 – Manned Vehicle Configuration for the Mars Mission

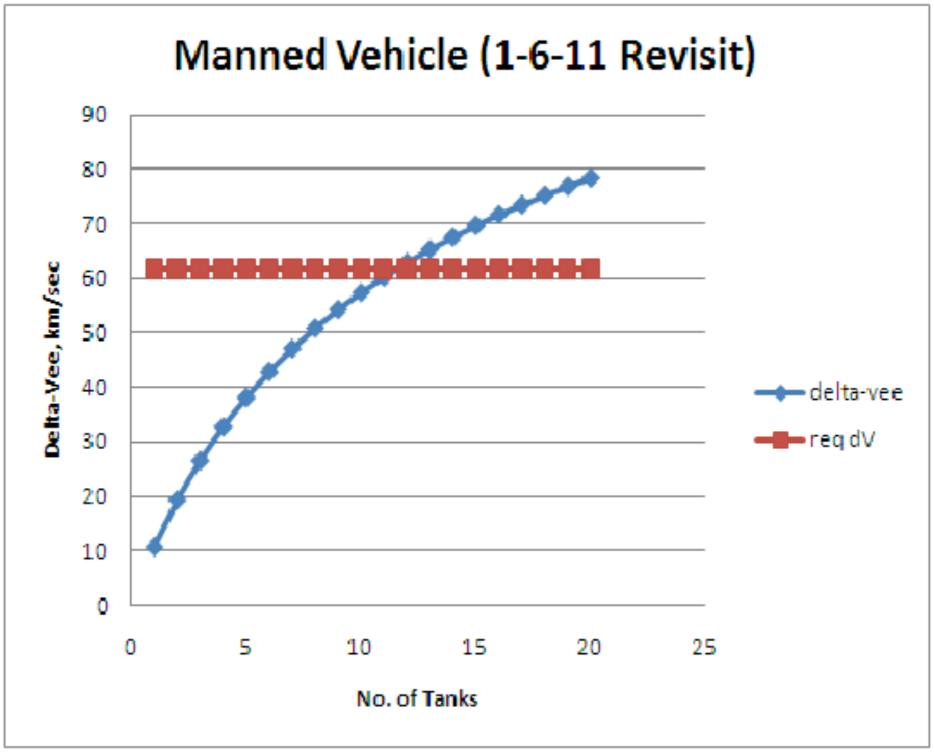


Figure 18 – Estimated Performance and Requirements, Manned Vehicle