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Human Exploration of Mars: Cost Realities of a First Mission

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Abstract

There is a growing discussion of sending humans to Mars. NASA discussions, as detailed in the Mars Design Reference Architecture (DRA) 5.0 and its more recent derivatives, envision multiple launches in support of ground activities in the Mars system, as well as providing for propellant for the return home. Even for minimum energy transfers, the total velocity change is ~10 km/s. This physical reality, along with requirements of mass for food, breathable air, potable water, and living space for a minimum crew drive the scope of the effort. Even with the use of in situ resource utilization (ISRU) to provide propellant for a return to Earth with maximum recycling of expendables, the mission scope will still be large. For the sake of "bounding the box," the simplest mission is to send a few people to the surface of Mars, place a footprint, and return to Earth safely. Cost is ultimately driven by the initial mass in low Earth orbit (IMLEO). For the lowest energy conjunction-class missions, trip times are ~900 days with stays of up to ~500 days at Mars. Opposition-class missions can cut the total time to ~500 days, at the expense of larger energy requirements, a shorter stay of ~1 month at Mars, and the use of a gravity assist at Venus. Such numbers are not new; they have been well known since the time of the Early Manned Planetary-Interplanetary Roundtrip Expeditions (EMPIRE) studies of the 1960s. Two things are new: (1) we have lost the capability to build nuclear thermal rocket (NTR) engines, developed under the Nuclear Engine for Rocket Vehicle Application (NERVA) program of the 1960's and 1970's and (2) we have learned what is required to design, assemble, and maintain a six-person permanent outpost in space, the 420-mt International Space Station (ISS). At a zeroth level of analysis, a 400-mt interplanetary transfer vehicle taken through a delta-V of 10 km/s at an NTR specific impulse of 850 would require a total IMLEO of ~1300 mt. Scaled to the $150 B cost for the ISS, the IMLEO would imply ~$500 B for a Mars mission, which does not include the cost of the nuclear items and contingencies. These simple scalings suggest that up to ~$1T for a "foot-print" mission to Mars is not an unreasonable cost estimate.

Keywords: Mars, Human exploration, Interplanetary transfer vehicle

Nomenclature

I_{sp}	specific impulse
mt	metric ton (1,000 kg)
$B	billions (10^9) of U.S. dollars
$T	trillions (10^{12}) of U.S. dollars

Acronyms/Abbreviations

Committee on Space Research (COSPAR), cost and technical evaluation (CATE), Design Reference Architecture (DRA), Early Manned Planetary-Interplanetary Roundtrip Expeditions (EMPIRE), fiscal year (FY), galactic cosmic rays (GCRs), initial mass in low Earth orbit (IMLEO), in situ resource utilization (ISRU), International Geophysical Year (IGY), International Space Station (ISS), liquid hydrogen (LH2), liquid oxygen (LOX), low-Earth orbit (LEO), Mars Transit Vehicle (MTV), metric ton (mt), National Academy of Sciences (NAS), National Aeronautics and Space Administration (NASA), Nuclear Engine for Rocket Vehicle Application (NERVA), nuclear thermal rocket (NTR), orbiting sample (OS), solar energetic particles (SEPs), Space Science Board (SSB).

1. Introduction

Scientific interest in the planet Mars as a place to visit, and perhaps find life, has a modern history of 140 years. Schiaparelli's observation of liner features on the planet during the "Great Opposition" of 1877, his *canali*, upon mistranslation into English as "canals," [1] began the sequence of events that remains with us to this day. Backed with family money, the American Percival Lowell established an observatory in Flagstaff, Arizona Territory in 1894 [2] and proceeded to observe and popularize the planet Mars [3].

Meanwhile a salesman turned writer named Edgar Rice Burroughs brought out a first novel *Under the Moons of Mars* and serialized in a pulp magazine in 1912 [4]. Its publication as the novel *A Princess of Mars* [5] began a series of books (Fig. 1) that made both Burroughs and his fantasy Mars, which he called "Barsoom," both famous and popular while also inspiring numerous science fiction writers, who, in their turn, further popularized Mars.

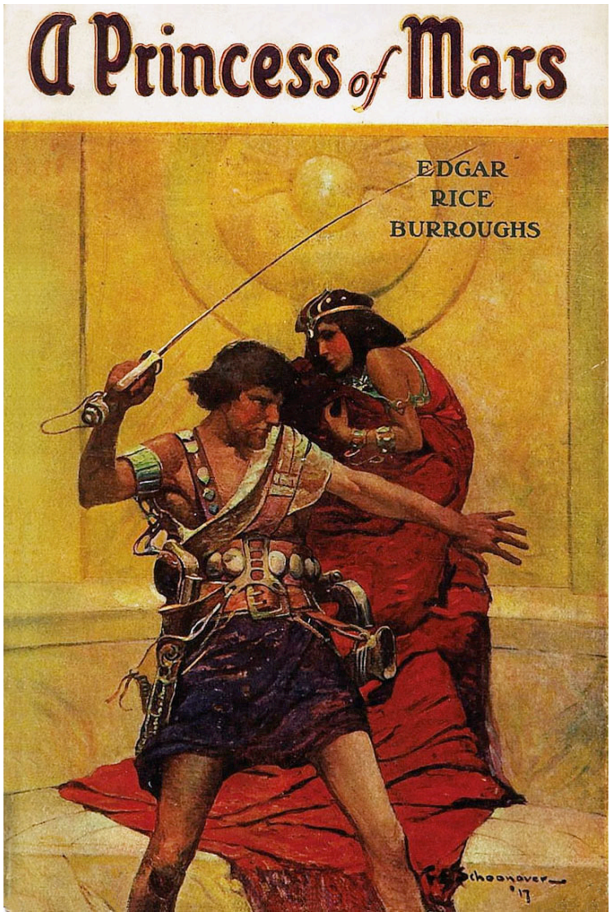

Fig. 1. Dust jack of Burroughs' first Mars book *A Princess of Mars*. (Illustration from Wikimedia Commons is in the public domain).

At the end of World War II, von Braun produced the first quantitative study of what might be required to send men to Mars (in 1948, the question of women to Mars was not posed). *The Mars Project* [6] drew upon technologies of the time, e.g., hydrazine fuel (N_2H_4) and nitric acid oxidizer (HNO_3) and logistical analogies with the U.S. Antarctic "Operation Highjump" and Berlin airlift. Von Braun himself drew analogies with Magellan's expedition to circumnavigate the world and noted that his expedition to Mars would cost as much as a "small war" (without actually suggesting a price tag) [7].

In his preface to the 1962 issue of *The Mars Project*, Von Braun noted that his original estimate of scope was too pessimistic and that "on the basis of technological advancements available or in sight in the year 1962, a large expedition to Mars will be possible in fifteen or twenty years at a cost which will be only a minute fraction of our yearly national defence budget." Of course, both 1977 and 1982 came and went with no human expedition to Mars, and, indeed a cessation of human expeditions to the Moon.

Referring to these advancements, he noted: "The greatest single advance is probably the availability of reliable rocket engines burning liquid hydrogen and liquid oxygen." He further noted that additional advances using nuclear power were on the horizon with nuclear thermal rocket (NTR) engines heating liquid hydrogen and the "nuclear-powered ion engine." Each development would increase the available specific impulse I_{sp}, and, hence, lower the propellant and total initial mass in low-Earth orbit (IMLEO) from which an expedition would depart. Perhaps the most significant driver for the cost is this mass, and this is no different from the primary issue facing human space missions up through today.

Perhaps what was not so obvious at the time is the huge increase in electronics capabilities which have driven reliability, computational power, and autonomy. However, even with these advances, there remain many robotic space missions just out of reach due to cost issues, e.g., a robotic sample return from Mars.

Cost issues have also thwarted the nuclear options noted. In 1962 great progress was being made with the Nuclear Engine for Rocket Vehicle Application (NERVA) program. The Phoebus 2A test runs in 1968 demonstrated operation at 80% of design power for 12 ½ minutes with an I_{sp} of ~820s and a thrust of 250,000 lbf (1,112 kN). The engine had the overall power output equivalent to that of a single F-1 engine on the S-IC stage of the Saturn V, but at over twice the vacuum I_{sp} [8]. The NTR and space power reactor programs, after an expenditure of billions of dollars in inflation adjusted dollars was cancelled in 1973 because "…their termination now is related to the emphasis on near-term objectives and the fact that NASA mission activity is such that they will not be used in the foreseeable future" [9]. More recently, the Prometheus Project to develop nuclear electric propulsion (NEP) for robotic missions was terminated following an expenditure of $464 million (then-year) due large to projected costs of implementing missions baselining the system (over $20B including launch costs) and identified issues with autonomous reactor operation for over a decade [10].

Hence both of these options beyond that of liquid oxygen (LOX) / liquid hydrogen (LH2) engines remain to this day developmental items.

The issues of cost and development of flight systems for such a deep space mission with a human crew have been the problems, which like the unhinged relative at a formal dinner party, are ever-present yet are ignored as they present significant difficulties that have no obvious solution.

The enormity of some of the issues had already emerged in the early 1960s with the Early Manned Planetary-Interplanetary Roundtrip Expeditions (EMPIRE) studies [11, 12]. The studies had extremely cramped quarters but also relied upon NTR and the

Saturn V, as these were viewed as being "available." Perhaps one of the most important outcomes was the study of transfer orbit possibilities, with the somewhat faster, but higher energy, roundtrips making use of a Venus gravity assist either en route to, or returning to Earth from, Mars. A significant number of studies have followed up to, and including the current U.S. National Aeronautics and Space Administration (NASA) Design Reference Architectures (DRA). Many of these from Von Braun through the beginning of this century have been documented in some detail [13]. Much detailed technical information exists on these studies and ones done since then [14].

The orbit of Earth and Mars are close to coplanar but not in any simple resonance. Couple with the orbital eccentricity of Mars, while there are favourable launch windows about every 26 months, "favourable" opportunities (lower energy) occur every ~15 to 17 years [15]. Given the modulation of solar energetic particles (SEPs) and galactic cosmic rays (GCRs) by the ~11-year solar cycle, and the need to take the ensuing radiation effects on the crew into consideration, e.g. [16], some have advocated looking at only the optimal radiation times for a mission, as extra shielding requires extra mass. Yet the less favourable transfer opportunities require more mass in the form of propellant and trying to optimize mission opportunities over combined 11 and 15 to 17-year cycles rapidly deplete the number of opportunities over a century.

Additional constraints are driven by (i) the desire to enter Mars orbit and actually land on the surface, and (ii) the desire to reuse as much of the vehicle as possible on multiple voyages. The latter implies that one must brake into low-Earth orbit (LEO) following the return from Mars, rather than just land a minimal "capsule" upon return, letting the larger interplanetary transfer vehicle burn up on return in Earth's atmosphere (as with the Apollo Service and Lunar Modules).

As with Apollo, landing the entire transfer vehicle on the planet is wasteful of propellant, and some type of surface excursion vehicle will be required for the same reasons as applied with the Apollo lunar landings [17]. Just the transfer from LEO to an equivalent orbit at Mars requires a ΔV ~ 5 km/s. Escape velocity from Mars orbit is also ~5 km/s [6]. Hence, for the transfer vehicle one must plan on a total ΔV ~ 10 km/s or at least ~7 km/s if one "throws away" the entire ship on return, plus a significant amount of propulsion (~ 8 km/s) for at most one excursion to the surface.

Combining these numbers with the rocket equation and a vacuum I_{sp} ~460s, at most, for a LOX/LH2 propulsion system, along with trip time, radiation, living space, and expendables, not to mention the issue of prolonged crew weightlessness, is why "Mars is hard" [18]. What should be more sobering is that none of these issues are going to go away with a human crew; it is not going to get easier.

It is important to note that in the grand scheme of scientific exploration of the solar system, missions to Mars are of significant scientific import, and have been so since before the beginnings of NASA. The scientific exploration of Mars was a central goal in the first global assessment of space research carried out by the Space Science Board (SSB) of the National Academy of Sciences in 1962 [19] (the name was changed to the "Space Studies Board" in 1989; the SSB is also the U.S. National Committee for the Committee on Space Research (COSPAR)). In summarizing the findings of the various Working Groups, the SSB noted that with respect to NASA's Planetary Program: "In particular, manned exploration of Mars represents an extraordinary scientific opportunity; preliminary planning, especially of long lead-time items, should begin at an early date (11-5) [referring to sections of the report" and, further

> The acquisition of chemical information about the atmosphere and surface composition of Mars should receive high priority (9-8). Of special biological interest are: O_2, CO_2, CO, CH_4, H_2S, NH_3, H_2O (including water of hydration), and organic compounds in general. Physical parameters such as temperature, pressure, and the flux of ultraviolet and ionizing radiation are of great interest, not only intrinsically, but also biologically. The collection (and enrichment) of samples of the Martian surface for microscopic examination and the transmission of vidicon images (with or without data reduction) are areas that warrant accelerated effort (9-8). As a relatively simple device for the detection of macroscopic life forms, a microphone should be included on vehicles designed to land on Mars (9-10).

Targeted exploration of the atmosphere and the use of radars and magnetometers are also especially called out. Especially with respect to Mars and its recognized potential for life, concerns about spacecraft sterilization were paramount

> The problem of keeping extraterrestrial bodies from, being contaminated by terrestrial organisms is obviously international in scope (10-7). International cooperation in the field of space probe sterilization is highly desirable (9-13, 10-7, and 15-14). We must make arrangements for the exchange of information about sterilization technologies if possible. If the exchange of information is not completely possible, even the unilateral transmission of information would be helpful (9-13). In particular, the planet Mars is at present our most important biological objective. We urge that it be a matter of national policy that Mars becomes a "biological preserve" (10-9), and that steps be taken to obtain international agreements to this end (15 - 13).

Regarding Mars in particular, the SSB provided:

> FINDING: The needs of future manned flights must be anticipated by obtaining practical information about the surfaces and environs of the planets well in advance of scheduled manned landings or visits. Specifically, the

> Mariner program should be emphasized and extended to provide a continuing flow of scientific information about the planets - especially about Mars, since that is probably the next manned landing site [after the Moon].

The current efforts were placed in the context of the robotic space exploration program, for which travel to Mars at the time was already pushing the edge of technological boundaries and possibilities*.

By the time of the next study of Space Research by the SSB (carried out at Woods Hole in June and July 1965), Mars – again largely because of the biological potential – was ranked first in priority for planetary and lunar exploration [23]. With respect to robotic exploration the accomplishments at Mars continue to grow [24, 25]. The primary mission of returning a sample of Mars to Earth lies within technical means, but has remained elusive due to projected costs. Nonetheless, the upcoming Mars 2020 lander will take the first technical step in such a return [25].

NASA has been riding high on the excitement of the scientific missions across the Science Mission Directorate: Not just Mars missions but also other mission and programs including, e.g., the Hubble Space Telescope, Discovery, New Frontiers, Living With a Star, Solar Terrestrial Probes, Explorers, Terra, Aqua, Aura, and the list goes on. Robotic missions have been "the jewels in the crown" of space exploration and discovery. It has not been "cheap." From 1969 through projected program runouts in 2026, the 31 "large strategic missions" incurred an expenditure of just over $70B in inflation-adjusted Fiscal Year (FY) 2015 dollars [26] (one can compare this number with NASA's total expenditures (operating plan in FY 2015: $18.010B total, of which $5.243B went to science).

So, what happened to a human mission to Mars?

NASA continues to be actively selling to the public the notion that Mars human exploration is in the near future [27-29]. Extremely optimistic cost numbers have been used to justify human mission, if there are even any numbers given. The actual cost of a "footprint" mission is likely to be about $1T in real year dollars. If 50% of the current NASA budget were to be spent on it, it will take 100 years to implement. Such a program is totally unrealistic. A realistic fiscal plan is needed to carry humans to Mars.

*This study was carried out at the State University of Iowa, Iowa City, Iowa, June 17-August 10, 1962. The previous year on May 5, 1961, Alan Shepherd became the first U.S. astronaut to space on a suborbital flight and following the Soviet orbital flight of Yuri Gagarin on April 12. The day after Shepherd's flight on May 6 during a meeting on advising President Kennedy on what goal should be announced for the American space program, Robert McNamara, the Secretary of Defence, pushed for a manned landing on Mars. Robert Seamans, NASA Associate Administrator at the time talked the assembled group out of that as being a goal for which the technical means did not and would not exist in the near future [20-22].

2. Is $1T the right number?

In the 80's, the number was $400B [30], and then in ~1990 Mars Direct came forward at $50B [31]. In the recent Planetary Decadal Survey For a footprint mission, a simple extrapolation from the current Mars Sample Return mission scenario gives about this amount†. With conservatism on mission safety and all of the required developmental items, this number could well increase.

We would all like to see a much lower number but the true costs will not be known until detailed designs are initiated. Mars human exploration has been extensively studied over the years [13], but only when a comprehensive Phase A design has been completed will we know the initial estimate and the serious technology issues. At present the strategic knowledge gap list is large and the true cost of closing the gaps remains unknown [35].

3. NASA history

We were able to go to the Moon, so why does it cost so much more today? In the post-war/Cold-War years test pilots had a low life expectancy, and pilots/astronauts were willing to take significant risks in flying developmental craft. The winding down of Cold-

† In the most recent planetary decadal survey [25], a cost and technical evaluation (CATE) process was used to provide some measure of a cost estimate for a variety of missions considered. A Mars sample return campaign required three missions: (1) a Mars Astrobiology Explorer-Cacher ($3.5B) or its descope alternative ($2.4B), (2) a Mars Sample Return Lander and Mars Ascent Vehicle ($4.0B), and (3) a Mars Sample Return Orbiter and Earth Entry Vehicle ($2.1B). This provides a range of $ $8.5B to $9.6B (all in FY 2015 dollars. Thirty-five samples of ~10 g each may be returned [25], a total of 0.35 kg of sample, but the actual mass ascribable to the samples assembly, the Orbiting Sample (OS) container, less its aeroshell is currently estimated as ~6.3 kg [32] in an Earth Entry Vehicle of ~33 kg that would be a hard lander. The Apollo missions brought back 381 kg of rock samples from six missions to the Moon, a factor of 1,000 more than the anticipated mass return from Mars. The Apollo Command Module Block II had a mass of 5,560 kg [33] and the Orion Multi-Purpose Crew Vehicle capsule has a mass of 10,387 kg at launch [34]. Completion of the Orion program by 2023 is currently estimated as ~$20.4B; costs through the present in inflation adjusted dollars of ~$12B [34] are equivalent to expenditures to date on the Hubble Space Telescope, NASA's most expensive (to date) robotic science mission [26]. Scaling costs is always a subject of controversy; however, it is clear that a linear scaling of cost with mass provides a good zeroth-order cut. Apollo cost ~$25B in 1970 dollars. NASA's new start inflation index tables for 2016 give a multiplier of 7.693 to FY2015 dollars, so one could ascribe to lunar samples a cost of 25 x 7.693 / 318 = 0.505 $B/kg for lunar returned samples. For Mars sample return we would have ~8.5/0.35 = $24 B/kg, a factor of about 50 larger. Scaling up Apollo by this factor would yield 25 x 7.693 x 22.5/0.505 = $8.5T, but amortizing over the six Apollo mission brings the first mission to Mars back down to $1T. Another approach is to scale the "return canisters" – call it 33 kg for Mars sample return and 5,560 kg for humans (the Apollo Command Module with a three-man crew. Then we would get 5,560 / 33 x $8.5B = $1.4T. Using the OS container mass (less aeroshell) would yield ~ $8.5B/6.3 = $1.3 B/kg for a returned sample plus carrier; for just the sample tubes plus samples, the number would be $8.5B/2.9 kg = $2.9B/kg.

War rivalries between the U.S. and former Soviet Union, combined with the losses of the Challenger and Columbia space shuttles have made NASA even more sensitive to the loss of life. In addition, other technical failures have increased the oversight costs. While future astronauts may say they would be happy with even a one-way trip to Mars, NASA, and the U.S. government, would never condone such risk.

4. Footprint Mission

For the sake of "bounding the box", the simplest mission is to send one or two people to the surface of Mars, place a footprint, and return to Earth safely. Orbital mechanics make even this "simple" proposition challenging from a reliability and expendables (air, food, and water) standpoint.

Radiation shielding requires both some mitigation of long-term galactic cosmic ray exposure as well as an astronaut protection vault with sufficient particle absorption to protect against worse case solar energetic particles (SEPs) [16, 36]. The size and mass of such a vault and the mean time duration significant event need to be traded against implications for system mass and loss-of-mission risk. This item alone is a significant mission-design driver, as it dictates how much infrastructure mass must be carried in transit as well as emplaced on the surface for such an eventuality [37]. Of equal importance is protecting the electronics against unrecoverable radiation damage to ensure safe return.

Ultimately the coupled issues of mission design, propulsion implementation, and radiation protection drive the initial mass in low-Earth orbit (IMLEO) and, thus, launcher requirements and mission cost.

At the same time, one must evaluate whether Would such a footprint mission meet the public, i.e., political, expectations?

5. Putting a Real Mission Together

No technical endeavour, and especially expensive ones, are ever "made from scratch." Developmental issues that really are required and not just "nice to have" are developed, but maximizing use of existing technology and infrastructure as always there‡. At the same time, mass is everything and the use of new approaches and technologies to minimize mass tend to "win." This outcome led to the lunar-orbit rendezvous approach for Apollo, even though at the time, the idea of trying to rendezvous two spacecraft in lunar orbit, with failure leading to a catastrophic loss of mission, was viewed as a significant risk. But there were also risks with the Earth-orbit-rendezvous approach and the development of the far larger Nova vehicles ("a million pounds to orbit") [38-40]. The take home message is that the lowest mass approach won because it was seen as ultimately also costing the least amount.

6. Propulsion and Duration

None of the constraints identified in the EMPIRE studies have changed. What has changed is that with our experiences with the International Space Station (ISS), we know what it takes to assemble large structures in space, what type of supplies we need (how easy is it really to recycle air, food, and water), better insights into the deleterious effects of weightlessness, and dome more insight into the issues of long-term radiation exposure. On this latter subject, the cautionary note is that the Earth's magnetosphere provides additional protection to crew on the ISS that those on deep space voyages (Moon, L1L2, Mars, and beyond) do not have [16, 37, 41].

The lowest mass human mission to Mars is a conjunction-class mission that will take ~3 years; opposition-class missions take less time, with significantly less time on Mars, but require more propulsive energy and typically a Venus flyby. There are other variations making use of staging supplies, solar and/or nuclear electric propulsion, manufacture of propellant on Mars with ISRU, etc. But even if the first crew to Mars does not land on the planet, but remains in orbit, they still have to get there and back again.

A prudent solution might be to have a six-person, rather than truly minimal two-person crew. We have experience in space with a crew of six working together on the ISS. We can also calculate the need for expendables with the same level of relied-on recycling that we have developed – and used – to date on the ISS. An equally prudent solution might be to assume an interplanetary transfer vehicle of about the same mass as the ISS. This will of course drive propulsion, IMLEO, in-orbit construction, etc. But it is also likely a good first cut on living and working space, supplies, and availability of backup systems for a three-year voyage to Mars and back.

The real question is whether one could actually have a six-person crew survive weightlessness, radiation, and Isola-ion for this long a period. Also, how well would the real expendables hold out? The good news is that all of these questions could be answered by a crew of six people on the ISS for the entire duration of a conjunction-class mission to Mars. Unlike, a real mission, the exercise could be discontinued if it were about to fail. If a crew could not survive, the one could consider an opposition-class mission, but the propulsion needs will go up, and one will likely be driven to NTR.

The hard part of this is due to physics, not lack of technology. That is not going to change.

‡ The maximum diameter of the Saturn V was fixed by the existing building at the Michoud facility because "raising the roof" would have incurred significant, and not necessary costs, to the Apollo program [17].

7. Mars Transit Vehicle (MTV) Costs

The ISS is our solid reference for a human habitat. So, the questions are wat sort of "delta's" are required to come up with a Mars Transit Vehicle (MTV) to keep six people alive in deep space for three years in a self-contained habitat? Questions to be answered include:

– What parts of the ISS do not have to be included in the MTV?
– What has to be added to the MTV to place it in Mars Orbit?
– What can be left in Mars Orbit?
– What has to be added to return to Earth orbit?
– How do we "qualify" it for a three-year mission?

The MTV costs will be >>$100B (ISS cost) because

– Its components must be lighter than for the ISS
– Exist without re-supply
– Include a radiation vault
– Support the lander
– Include a repair workshop for unknown problems
– Be non-claustrophobic (ISS had at least the Earth to look at)

8. Mars Cost Reality in Light of the ISS

The ISS with a crew of six, a mass of 420 mt, including 388 m^3 of habitable volume, and providing 84 kWe [42] for a cost of ~$150B [43] was not easy, but it was straightforward (~$360,000/kg). Using these numbers, a ~2.9 kg sample robotic return of ~$8.5B (the descoped robotic sample return number referred to above) scales to ~$1.2T [§] for a 400-kg return mass. Humans are "softer" than electronics (to radiation), less acceleration tolerant, and require more expendables (air, food, and water) and living space – so this cost is, again, likely a lower limit, but also consistent with our other, previous estimates of ~$1T above (see also the estimates and estimate history given in [30]).

One can then ask if "Mars Direct" [31] really is feasible at even $100B considering all the technical challenges? Our answer is "No," if development and all infrastructure costs are included (cf. [44] but also note that autonomously running nuclear power reactors and commercial scale ISRU units are key).

As we noted, the Mars Transit Vehicle(s) will require ~5 km/s of propulsion each way from Low-Earth Orbit (a number that varies with the mission approach and over the 15-17 year "cycle). To change the speed of 400 mt of an MTV by 7 km/s (assume it is "thrown away" at return requires ~480 mt of LH2 for a nuclear thermal propulsion (NTP) system (900s I_{sp}) or ~1480 mt of LH2 + LOX; at $50k/kg the cost differential alone for launch from Earth is ~10^6 kg x $50k/kg = $50B, but with larger tanks and structure the vehicle mass would go up significantly as well.

Development and forward pre-positioning of ISRU production of propellant would mitigate the cost associated with any crewed excursion back from the surface of Mars, similar to "Mars Direct." But the problem is the upfront establishment of such a capability, and the cost for that is unknown.

9. Real Human Mars Exploration

At some point science fiction and science fact must interact. This dynamic comes about due to the multiple – and diverse – stakeholders in such an activity. Potential "action" activities for Humans on Mars, easily derivable from "fiction," but with a nod to "fact" include:

View Valles Marineris from the rim,
Travel down the bottom of Valles Marineris,
Climb Olympus Mons,
Watch polar avalanches,
Experience springtime at the poles,
Go caving,
Mine for water,
Look for fossils,
Build a radiation-protected habitat, and
Conduct (other) scientific research

Many studies have shown ways to accomplish Mars exploration: Things like the Mars up/down escalators are essential for rapid transit times [45], yet consideration of the required propulsion requirements tend to rule such possibilities out. Indeed, closing an engineering solution with conjunction-class missions, requiring ~3 years for the round-trip and over an Earth year in the Mars system, already strains the foreseeable state-of-the art for the next several decades. Yet these are the "easiest" approach.

10. Technology Issues Are Major

Sufficient radiation shielding is required for transit, Mars orbit, and operations on Mars surface. Minimum trip times are possible using the up/down escalator orbits, but these, as well as opposition-class missions are not credible [46] without at least nuclear thermal propulsion (NTP) – abandoned by the U.S. in 1972 [47, 48].

Significant other technological challenges remain. These likely can be addressed and developed to flight readiness, but the type of focused, well-funded efforts required do not currently exist. Pinpoint landings of large masses remains to be developed. Fuel production at Mars from the CO_2 atmosphere and water sources (in situ resource utilization (ISRU)) may enable simpler surface transport systems and return liftoff, but

[§] The Orion Multi-Purpose Vehicle crew module has a landing mass of 8.8 mt for crew of 4 and a return payload of 100 kg; hence, we can estimate a 400-kg return mass industrial production levels – hundreds of kg to metric tons of materials must be producible reliably and autonomously. These require power levels best met by the use of fission reactors. While some promising ideas exist [49], they are far from flight ready, and that itself has been a recurring problem in developing space nuclear reactors [50] (the same hard lessons were dealt with in the course of building terrestrial reactors [51]). Failsafe, maximal food, water, and air recycling are required to minimize IMLEO and mission complexity. For a first mission, on-board storage of required expendables at launch will increase launch mass but may be required in the absence of significant forward basing of supplies.

Long-term, i.e., mufti-year storage of cryogens, notably LH2, is required for credible chemical or nuclear propulsion. This far outstrips current in-space storage requirements of tens of hours at most, e.g. for Centaur upper stages. While some concepts have been discussed [52], no such capabilities currently exist. Trades of mass versus technology are required (insulation and passive storage versus powered active storage). The issue is not unlike that faced by liquefied natural gas transports, which adopted passive storage and use of the thermal boil-off gas for powering the ship engines. Reliability is mission critical; LH2 is required for practical nuclear of chemical systems. Too much loss of propellant at any needed point would results in a catastrophic wend of mission.

11. A Mission timeline

A “Real Mars Human Exploration” program must ultimately consist of some variation on at least three phases.

Phase1: There are two distinct activities –

(1) Understand Mars scientifically, which includes the actual implementation of a Mars Sample Return and the determination of optimum human landing sites
(2) Develop technologies for expanded robotic exploration. The latter includes initial investigation of ISRU and cryogen-storage.

Phase 2: Develop and demonstrate the technologies for human activities. These require a serious engineering based analysis of alternatives and could include (i) NTR development and reliability demonstration, e.g. on the Moon, (ii) aerobraking of large payloads, (iii) radiation protection, (iv) strategy evaluation, (v) pin-point landing, and (vi) large-scale propellant production and storage.

Phase 3: The first human expedition.

12. Summary

12.1 Budget Requirements

The current NASA budget is in need of an estimated 5X increase to meet the “footprint” mission needs and 20X to explore Mars fully. One can make the point that on a per-mass basis, to say nothing of selectivity flexibility, the return of Mars samples selected by humans is far more economical than with automated robotic probes; however, the “buy-in” cost will be higher by orders of magnitude [53]. It is a truism that money spent on space exploration is spent on the Earth and not in space. Such an endeavour is not going to contribute on a profit basis to the U.S. on a quarterly basis, vis-a-vis trading partners. It would be, however, an investment in capital, including our most valuable resource, our people and the coming generations, in technological and scientific training that both inspires and enables problem solving of the type that has served both the U.S. – and the world – well in the post-World-War II years. Civilizations face the reality of either moving forward and stagnating and going by the wayside. Observers of global real politick will not miss the point.

12.2 The Stakes Are High

Von Braun once noted that the real costs of sending humans to Mars would likely equal those of “a small war” [6]. And there is no real reason to think that has changed [7]. The Planetary Society and the Mars Society have been active in pushing for human Mars exploration for the past 20 years. Astronauts and Cosmonauts have been ready to go since the 1980’s. More than a science mission, such an undertaking is a choice of whether to follow the route of 15th century China (the fate of the treasure ships and the Nanjing shipyards [54] has an almost eerie connection with the fate of the Apollo 18 and 19 flight hardware), or boldly, but realistically, step forward to this challenge. Our economy could use a real stimulus package as a new focus to motivate technical knowledge and education in an increasingly technological society. Humans-to-Mars remains the right answer for everyone.

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