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A comparison of approaches for the Mars Sample Return Mission

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A Comparison of Approaches for the Mars Sample Return Mission

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Abstract

This paper analyzes the three major approaches to the Mars Sample Return mission; direct return using propellants transported from Earth, Mars orbit or interplanetary rendezvous with all propellants transported from Earth, and direct return from the Martian surface using in-situ propellants. It is found that the direct return with terrestrial propellant fails on the basis of cost, while the orbital rendezvous approaches fail on the basis of risk. In contrast, the approach employing direct return utilizing indigenous propellants appears to be attractive on both a cost and risk basis. In addition, the in-situ propellant technology is found to offer maximum benefits for follow-on missions, including robotic Mars hopper science missions and human exploration missions.

Introduction: Three Approaches to the Mars Sample Return Mission

The Holy Grail of the robotic Mars exploration program is the Mars Sample Return (MSR) mission. In contrast to the limited capability offered by investigations performed on Mars, a sample returned to Earth could be subjected to thousands of different types of tests an investigations. Thus for example, while the results of the Viking life detection experiments are still regarded by some as contradictory and ambiguous, the return of such samples to terrestrial labs would have enabled a battery of tests and examinations that would have left no doubt in interpretation of results. For these reasons, among others, NASA's solar system exploration branch has penciled in a Mars Sample Return Mission (MSR) mission for 2005. There are fundamentally three ways this might be done: The Brute Force (BF) method, the Orbital Rendezvous (OR) method, and the In-Situ Propellant Production (ISPP) method. All three of these approaches have been the subject of considerable study for some time.

The Brute Force Approach

The first, and conceptually the simplest of the MSR mission strategies, is the "brute force" method. In this case, a launch vehicle in the class of a Titan IV is used to deliver to the surface of Mars a very large payload consisting of a Mars Ascent Vehicle (MAV), massing perhaps 500 kg, completely fueled for an ascent from Mars and flight back to Earth. The lander also has on board a robotic rover which is dispatched to wander about under human operator control and collect samples of geologic interest. The samples are then loaded aboard a capsule on the rocket vehicle. When the launch window from Mars back to Earth opens up, about 1.5 years after arrival, the MAV ascends and flies back to Earth. Upon approach to Earth, the capsule separates from the rest of the vehicle and performs a high-speed re-entry, much in the manner of an Apollo manned capsule. Depending upon design, the capsule may be decelerated by a parachute or simply use a crushable material like balsa wood or styrofoam to cushion the landing shock, when it hits the targeted desert landing area.

This Brute Force mission is pretty simple conceptually, but the problem with it is that is likely to be very expensive, as robotic explorations missions go. The Titan IV needed costs NASA $400 million, and the large lander needed to carry to fully fueled ascent vehicle is also likely to be very costly. Thus, while studied numerous times in the past as the baseline for the MSR mission, the brute force approach has always led to cost estimates that have made the mission a non-starter. A possible method to reduce the cost of the Brute Force approach is to use a Russian Proton as the launch vehicle. There is a technical problem with this, as the large payload required by the BF mission requires a large aeroshield, that may not be able to fit within the 3. 6 meter diameter Proton fairing. (the Titan IV fairing has a inner diameter of 4.6 meters). Moreover, recent history has demonstrated a willingness of Russian

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authorities offering transportation for interplanetary missions to engage in bait and switch tactics that may make the prospective savings resulting from Proton use quite illusory. Therefore, in an effort to reduce costs, several other methods have also been studied.

The Orbital Rendezvous Approach

One of the most popular alternatives to the brute force plan is the Mars Orbital Rendezvous, or OR plan. In this scheme, two spacecraft are sent to Mars, each launched by a comparatively low cost ($55 million each) Delta 2 booster. One of the launches delivers to Mars orbit and Earth Return Vehicle (ERV) and entry capsule, and the other delivers to the Martian surface a Mars Ascent vehicle (MAV) equipped with a rover and sample can and fully fueled for an ascent to Mars orbit. The rover is deployed to collect samples which are placed in the sample can. When this is completed, the MAV takes off and flies to Mars orbit where it performs an autonomous rendezvous and dock with the ERV. The sample can is then transferred from the MAV to the re-entry capsule on board the ERV. The two craft then separate, the MAV to be expended and the ERV to wait in Mars orbit until the launch window back to Earth opens up, and which point it fires its engine to send it on a trans-Earth trajectory. The rest of the mission is then performed in the same manner as the Brute-Force mission.

The main talking point of the OR plan is that it brings launch costs down considerably relative to the Brute Force scheme. Since the MAV only has to fly to Mars orbit, and not all the way back to Earth, and moreover only has to lift the sample can and not the complete re-entry system, it can be made much smaller than the ascent vehicle used in the Brute Force scheme. Thus the lander required to deliver it can be made smaller, lighter, and cheaper, and a much less muscular launch vehicle used to send it to Mars. However, there are major problems associated with the OR scheme. In the first place, two launch vehicles are needed, which double the risk of launch failure causing mission failure. Secondly, two complete spacecraft are needed, each of which has to be designed, built, checked out, and subjected to launch environment testing, and each must be integrated into a launch vehicle. Basically, doing all this will double mission costs. Furthermore, the interfaces between the two spacecraft must be perfect, not only in the factory, but after launch and years of space flight and thermal cycling both in space and on the Martian surface. Guaranteeing this is a very tough design problem, and in fact it probably can't be guaranteed since it can't be tested in advance. In addition, the simple fact of the matter is that the mission requires two complete spacecraft, and if *either* fail for any reason at any point in the mission the whole mission is lost. The history of actual Mars robotic missions to date gives a pretty good idea of how risky such a proposition is. Finally, the autonomous rendezvous, dock, and sample transfer in Mars orbit required to do this mission is an undeveloped technology which will be very costly to develop and which *cannot be tested in advance of the mission.* This multiplies the risk associated with this already marginal mission plan still more.

In an effort to make the OR plan look more attractive, some OR advocates have taken to various tricks, such as cooking the books in such a way so as to assign the cost of the two required launches to separate missions. Some more extreme cases have also adopted the plan of flying the rover out on a prior mission, so that its costs and the costs of its mission operations can be charged to someone else[1]. In this case, the lander carrying the MAV now must satisfy the additional requirement of performing a landing with nearly pin-point accuracy next to the rover. Once again, this cannot be tested in advance, and represents a drastic improvement (~5 orders of magnitude) over the current state of the art for targeting unmanned Mars landers, which involve landing errors of up to 100 km. In a recent study, the advocates of this plan suggested that mass could also be saved through the elimination of landing gear, provided that the MAV could be made to fly straight to the rover and hover over it while the samples are quickly transferred. The technological requirements for accomplishing such a maneuver are so far beyond the current state of the art that even one of its authors[2] has conceded that it can only be regarded as flaky in the extreme. Perhaps for the sake of novelty, the same group has also proposed moving the location of rendezvous from Martian orbit to interplanetary space. This saves propellant on the ERV, because now it does not have to capture into or inject out of Mars orbit, but it adds not only a considerable amount of propellant to the MAV, but also an untestable requirement that the MAV be able to blast off at exactly the right moment to catch and perform a *hyperbolic rendezvous in deep space* with an ERV which is moving past Mars at a relative velocity of 5 km/s. This could be very tough to guarantee, from the point of view of MAV engineering systems alone, putting aside the possibility of bad weather on the pre-appointed take-off date.

The In-Situ Propellant Option

This third plan is known as the In-Situ Propellant Production[3], or ISPP option. In the ISPP plan a single Delta 2 is used to send a single *unfueled* MAV to the Martian surface together with a rover. While the rover is out collecting samples, the MAV employs a small on-board chemical plant to turn gas pumped in from the Martian atmosphere into rocket propellant, filling the tanks of the MAV. Both methane/oxygen[4,5], and carbon monoxide/oxygen[6] production systems for this have been proposed application have been proposed and demonstrated. By the time the launch window back to Earth opens, all the propellant needed for the return flight has been made, and with the samples all collected, the MAV takes off and flies directly back to Earth, just as in the case of the Brute Force mission. The direct return to Earth is possible with a Delta-launched spacecraft because the Delta and its lander only had to deliver the MAV's dry mass (perhaps 70 kg) to the Martian surface, instead of the much larger wet mass needed to perform the Brute Force mission.

It can be seen that the ISPP mission is likely to be by far the cheapest of the mission plans discussed, because instead of employing a Titan IV with one large spacecraft, or two Delta's with two small spacecraft, it can be flown with a single Delta with one small spacecraft. It is also much lower in risk than the OR plan, because the "advanced technology" required, the in-situ propellant production (ISPP) plant, can be *fully tested* to any degree of satisfaction in advance in Mars simulation chambers on Earth. In addition, the ISPP unit represents a system of a much lower order of complexity (essentially 19th Century chemical engineering) than the avionics required for autonomous Mars orbit (let alone deep space) rendezvous. As discussed in references 4 and 5, a full-scale ISPP unit making both methane and oxygen was built and demonstrated successful operation at Martin Marietta, for an amount of money ($47,000 Phase I, $110,000 Phase II) that would literally be "in the noise" in an MSR mission budget.

Mission Risk:
Technical Maturity vs. Testability

The ISPP approach has frequently been attacked as a risky method of attempting the sample return mission. This argument is in error. Now, it is true that both the Martin and Univ. of Arizona ISPP machines are working brassboards, not mature flight hardware, and no one can rationally argue that in-situ propellant production today represents a mature flight ready technology. However what needs to be understood is that *the issue of mission risk associated with a new technology is not one of maturity, it is one of testability*. Because it is testable, ISPP technology is much lower risk than the in-space rendezvous technologies required for the OR mission. Furthermore consider this; If it is decided to use two spacecraft on the ISPP mission, they will be *identical* spacecraft (i.e. still cheaper than two *different* spacecraft needed for the OR mission), and if either one makes it back the mission is a success. In contrast, in the OR mission, if either spacecraft fails the mission is lost. So even putting aside the risk associated with untestable autonomous Mars orbital rendezvous, the risk of the OR mission is much greater. For example, let's assign a success probability of 0.7 to each of the two spacecraft used in the ISPP and OR missions (NASA program managers will sometimes claim that the success probability of their interplanetary spacecraft have been calculated by various sophisticated techniques to be 0.99 or better, but if we look at the track record it is evident that 0.7 is a much more realistic number.) Then the failure probability of the ISPP mission is $(0.3)(0.3) = 0.09$, while the failure probability of the OR mission is $1-(0.7)(0.7) = 0.51$. In other words, even ignoring the risk associated with the untestable rendezvous maneuver itself, the probability of failure of the OR mission is almost *six times* greater. If you want to minimize MSR mission risk, a direct return from the Martian surface is the only way to fly. Furthermore, if both vehicles on both the OR and ISPP mission work successfully, the OR mission will have only returned one sample from one location, while the ISPP mission will have returned two samples from two widely separated locations. Thus the ISPP mission also offers higher potential science return than the OR approach.

Because the ISPP mission can be done much more cheaply than the Brute Force approach, it offers much better potential for the launching of multiple sample return vehicles. Thus the ISPP plan offers both lower risk and higher potential science return than the Brute Force approach as well.

Cost and Mass Estimates for MSR Missions

The ISPP mission described in reference 3 had a trans-Mars injection mass of 540 kg, giving it 85% launch margin if launched by a Delta 7925. A cost estimate of $302 million was generated for the mission by Lockheed Martin cost analysts. This cost included not only the dual-string spacecraft, but the Delta launch vehicle and all operations, technology development, reserves, profit, and so forth. The Mars surface-hover followed by interplanetary rendezvous OR variant mission described in reference 1 also had cost estimates generated by Lockheed Martin costing analysts, and the results were in the same general range. However, very different assumptions were used in these two studies. In the case of the ISPP mission, no avionics technology advances were assumed beyond those actually planned for the 2001 landers to be built for the Mars Surveyor program. In the case of the OR mission, much lighter avionics were assumed, as was advanced CPF propulsion (storables with 400 s Isp), and the cost of development of these systems (and the Mars surface rendezvous and hover capability) was not included in the OR mission cost. In addition, the OR mission kept mass and costs down by employing a single string spacecraft for Mars descent and ascent to rendezvous, which introduces an intolerable level of risk into the mission. Also, the cost of the rover mission required to gather the sample prior to the arrival of the OR mission's ERV was not included. The inclusion of these costs would have roughly tripled the OR mission's cost estimate.

A comparison of the two Lockheed Martin mission designs is given in Table 1. A crude estimate of mission success probability is also provided, based upon the assumption that a dual string interplanetary spacecraft has a 0.7 success probability, a single string spacecraft has a 0.5 success probability, and each untestable operation by a dual string spacecraft has a 0.9 success probability while each untestable operation by a single string spacecraft has a 0.8 success probability.

It can be seen that the the Lockheed Martin ISPP mission is superior to the Lockheed Martin OR mission by about a factor of 2.7 in cost and a factor of 4 in mission success probability.

Table 1. Comparison of Lockheed Martin Mars Sample Return Mission Designs

	Hyperbolic Orbital Rendezvous	ISPP
Trans-Mars Injection Mass	~500 kg	540 kg
Launch Vehicle	Delta II	Delta II
Nominal Estimated Cost	~$300 million	$302 million
Spacecraft type	Single String	Dual String
Required Avionics	Speculative Microspacecraft	Mars Surveyor 2001 SOA
Required Propulsion	CPF 400 s Isp	CH_4/O_2 380 s Isp
Required Precursor	Rover Mission	None
Unpaid Costs	Rover Mission CPF propulsion Microspacecraft avionics Precision surface rendezvous tech. Auto. Hyperbolic rendezvous & dock tech. Hover & rapid surface sample transfer	None
Untestable Operations	Mars Ascent & Earth Return Precision surface rendezvous Hover and rapid surface sample transfer Autonomous hyperbolic rendezvous, dock & sample transfer All weather descent/ascent capability	Mars Ascent and Earth Return
Estimated True Cost	~$800 million	$302 million
Mission Success Probability	(0.7)(0.5)(0.8)(0.8)(0.8)(0.9)= 0.16	(0.7)(0.9)= 0.63

Table 2 SAIC Study of MSR Mission Options

	OR lander/ERV	Brute Force	ISPP
TMI Mass (kg)	1031/477	1428	587
Proposed Launch Vehicle	Delta II/Med lite	Atlas II	Delta II
Launch Margin	-3.1%/4.8%	-2.8%	70.4%
SAIC Cost Estimate	$565 million	$413 million	$365 million
Required Launch Vehicle	Atlas IIAS	Atlas IIAS	Delta II
Unpaid Developments	None	N_2H_4/Be-H_2O_2 Propulsion	None
Revised Cost	$606 million	$476 million	$365 million

In a recent study[7], Science Applications International compared the three mission options considered in this paper on both a cost and mass basis, using a common technological baseline for all three concepts. A summary of the SAIC results is presented in Table 2.

In Table 2 the mass and cost estimates and proposed launch vehicles above the central line are those presented by SAIC in the cited reference. It can be seen that according to SAIC, the ISPP option is the cheapest of those considered. However, the SAIC report understates the case, since the launch vehicles proposed by SAIC for the OR and BF missions are actually inadequate. (An Atlas II can only deliver 1400 kg from CCAFS to a minimal TMI C3 of 10 km^2/s^2, and Atlas IIA can deliver 1600 kg. For adequate margin, an Atlas IIAS with a throw capability of 2000 kg is needed for both of these missions[8].) Furthermore, the SAIC Brute Force mission required use of very advanced N_2H_4/Be-H_2O_2 propulsion technology (400 s Isp), whose development cost was not included in the SAIC estimate for that mission. A very conservative estimate for this cost is $30 million (Be is highly toxic, which makes testing expensive.) If the costs of this development and the more powerful launch vehicles are taken into account, we see that the OR mission is 66% more expensive than the ISPP mission, while the Brute Force mission is found to be 30% more expensive than the ISPP mission.

Benefits for Future Missions

In evaluating the benefit of various scenarios for the MSR mission, it is also necessary to take into account the benefits that the technology developed for that mission will provide for exploration missions to follow. In this respect the ISPP mission benefits greatly exceed those offered by the alternatives.

For example, currently Mars landing missions can each only visit one site. Mars however, is a vast planet with hundreds of sites of interest. Exploring these on the basis of one dedicated lander per site would be enormously expensive. What really is needed is the ability to deliver to Mars a vehicle which has long range mobility, allowing it to visit a large number of sites. This can be accomplished by the use of a ballistic hopping vehicle utilizing rocket propulsion for vertical take off and landing. However the delta-V's required to visit several sites in succession rapidly add up to the point where, due to the exponential nature of the rocket equation, the mass of a rocket hopping vehicle that starts its mission carrying all of its required propellant goes to infinity. However, if the vehicle is able to make a substantial portion of its propellant after each hop, a very large number of hops can be accomplished. This is shown in Fig. 1, where we see that even if H_2/O_2 propulsion is employed, the mass of a Mars ballistic hopper without ISPP goes to infinity after four 500 km hops, while that of a hopper producing CH_4/O_2 by combining an onboard supply of hydrogen with Martian atmospheric CO_2 feedstock has hardly increased at all even after 6 hops. The reason for this is despite the fact that the H_2/O_2 system has an Isp of 450 s compared to the CH_4/O_2 vehicle's 380, the CH_4/O_2 vehicle produces its propellant with a leverage factor of 18 kg bipropellant produced for every 1 kg of H_2 transported. Thus its effective specific impulse is actually (18)(380) = 6840 seconds, *allowing it to perform 45 hops* before its mass ratio equals that of the H_2/O_2 system after 3 hops. It can thus be seen that the advantages offered by ISPP technology for the Mars hopper mission

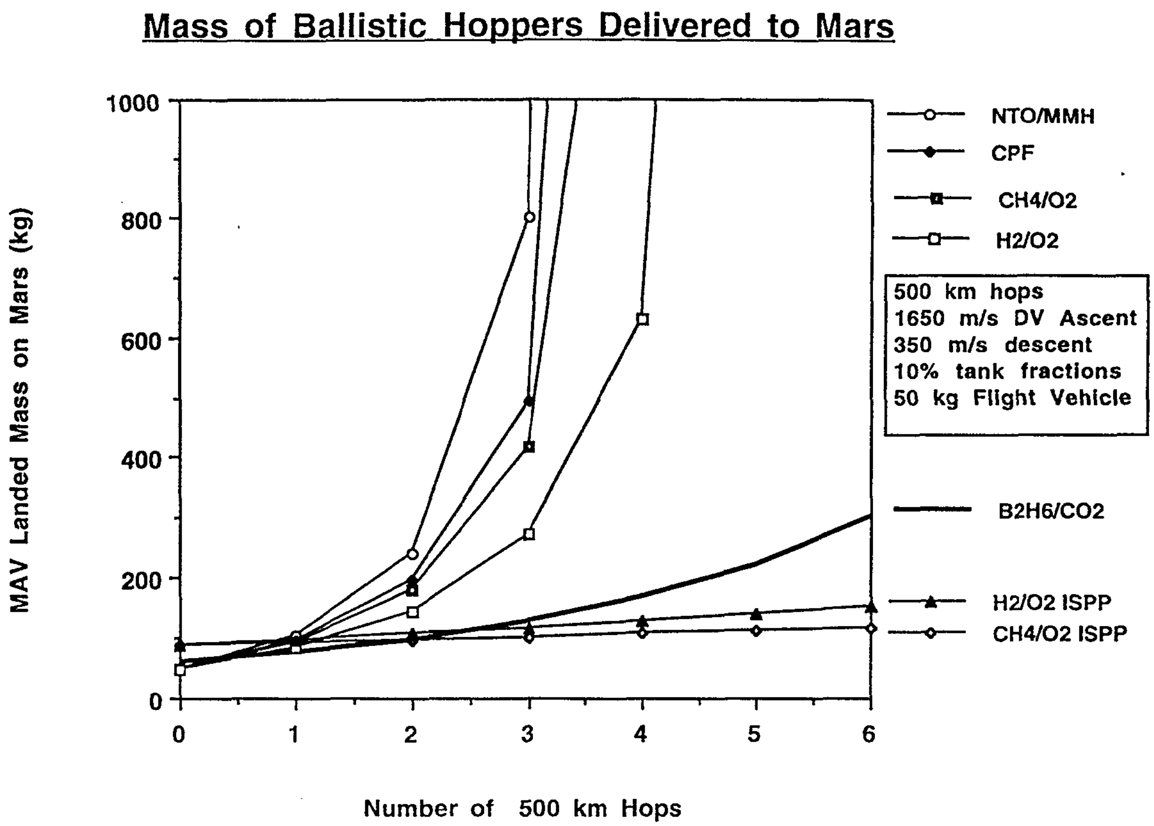

Fig. 1 Mass of Mars Ballistic Hoppers as a function of the number of hops taken.

are overwhelming.

It has been shown[9,10] that using in-situ produced propellant is the most promising way to make human exploration of Mars affordable. As far as MSR mission planing is concerned, that should be decisive. The MSR mission's value will be greatly increased if it can be used to demonstrate the key technology needed to save *billions of dollars* that would otherwise be needed to support human flights to Mars. Consider this: the MSR mission will only be able to return a kilogram or so of samples gathered from the surface of Mars within at best a few kilometers of the landing site. Since it is unlikely that there is life today on the Martian surface, the search for Martian biology will largely be a search for fossils. Small robotic rovers with their limited range and long time delay (up to 40 minutes due to speed of limitations of radio signals) in Earth-Mars command sequence data transmission are a very poor tool for conducting such a search. For example, consider parachuting rovers such as Sojourner or Marsokhod into the Rockies. It is likely that the next ice age would arrive before one of them found a dinosaur fossil. Fossil searches require mobility, agility, and the ability to use intuition to immediately follow up very subtle clues. Human investigators, rockhounds, are required.

It is sometimes argued that the ISPP technologies used by human explorers will be different from those used on an MSR mission. In particular some have said that human explorers will use H_2/O_2 derived from permafrost. This argument is incorrect. First of all, mining permafrost is difficult, as is long term storage of hydrogen on Mars, and human explorers will desire to shun such operations. More importantly, however, is this fact: In order to obtain significant savings from the incorporation of ISPP technologies into a human Mars transportation architecture, *it is necessary to be able to produce propellant prior to the arrival of humans on the planet.* Only in this way can the need to develop "Battlestar Gallactica" megaspacecraft for Earth-Mars transportation be avoided. Adding ISPP technology to a mature Mars base provides some benefits but completely misses the point. The essential requirement to get humans to Mars is to drop the development costs for the first mission - it does little good to use ISPP to enhance downstream missions if the threshold cost for the first mission prevents the program from ever happening. Thus the only relevant ISPP technologies for use on Mars are those that rely upon the Martian atmosphere for raw material, because only these can be conducted autonomously in advance of human arrival. Thus, in fact, the ISPP technologies proposed for the MSR mission are *precisely* those that will be needed to support human explorers.

If Mars is to be made to give up its secrets, people, "who do not shrink from the dreary vastness of space"[11] will have to go there. The demonstration of the technology for in-situ production of propellant on the MSR mission will make that possible.

Conclusions

We have examined the three primary options for Mars Sample Return, and have found that of them, the direct return mission employing in-situ propellant offers the lowest cost, the lowest risk, and the highest science return. In addition, the ISPP mission offers the greatest potential in proving enabling technology for follow-on Mars exploration missions, including robotic Mars ballistic hopper missions and piloted human exploration missions as well. We therefore recommend that the ISPP mission plan be made the baseline for future MSR mission studies, and that funds be provided to accelerate the development of ISPP propellant production and storage technology and the associated rocket engines.

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