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Summary

Advanced chemical propulsion using metallized propellants can lead to significant reductions in launch mass for piloted Mars missions. Metallized propellants allow the propellant density or the specific impulse I_{sp} of the propulsion system, or both, to increase. Increasing propellant density and I_{sp} can reduce the propellant mass and the propulsion system dry mass. These effects are discussed and analyzed in this report. Detailed mass-scaling equations and estimates of the I_{sp} for several metallized propellant combinations are presented.

The most significant savings with metallized propellants are derived from increasing the payload delivered to Mars. For the same mass in low Earth orbit (LEO)[1] a metallized Mars transfer vehicle can deliver 20 to 22 percent additional payload to the surface of Mars. Using metallized propulsion can accelerate the delivery and construction of a Mars base or outpost. This 20-percent payload increase reduces the total number of Mars flights and therefore significantly reduces the number of Space Transportation System–Cargo (STS–C) launches for the entire Mars architecture.

Using metallized propellants to reduce the mass in LEO per flight is not as effective as increasing the payload delivery capacity. Although over 20 percent more payload can be delivered to Mars per mission, the mass saving per flight (while delivering the same payload with a higher-I_{sp} system) is much smaller. Using metallized propellants in all of the Mars propulsion systems would produce a modest 3.3-percent LEO mass saving. This translates into a saving of 38 000 kg over the mass required with oxygen/hydrogen (O_2/H_2) propulsion.

A Mars excursion vehicle using Earth- or space-storable propellants for the ascent can be an alternative to storing cryogenic H_2 on Mars. There will be a mass penalty for using these alternatives because of the lower I_{sp} of their propulsion systems. A space-storable system using oxygen/monomethyl hydrazine/aluminum (O_2/MMH/Al) would deliver the lowest mass penalty over O_2/H_2. For "expedition" missions the LEO mass penalty for using metallized O_2/MMH/Al would be only 3 to 5 percent.

Introduction

Over the past several years NASA has conducted many new studies of the missions that would send humans to the first landing on another planet (refs. 1 to 7).[2] Human exploration of the solar system will require that large masses be transported to Earth orbit. The high-energy missions planned for Mars expeditions (using O_2/H_2 chemical propulsion on a sprint mission) require up to 1 760 000 kg in low Earth orbit (LEO) per flight.

In the Office of Exploration studies $0_2/H_2$ propulsion has been considered as the state-of-the-art system for all Mars missions (ref. 1). These studies, however, have shown that the mass in LEO is primarily the propulsion system. Figure 1 compares the masses of two fast "sprint" missions (with a 400-day round-trip) with those of lower-energy "evolution" and "expedition" Mars missions (with a 700- to 800-day round-trip). The propellant makes up 75 percent of the mass in LEO for the piloted sprint mission and 67 percent for the evolution mission. Even the low-energy vehicle for the cargo sprint mission has 55 percent of its mass invested in propellant (oxidizer and fuel).

These large propulsion systems are a major influence on the entire mission infrastructure: design, fabrication, launch, orbital assembly, flight, and recovery. In order to reduce this strong influence, advanced propulsion systems have been considered for these ambitious Mars missions. Advanced propulsion can either reduce the mass in LEO or allow a greater payload to be delivered to the final destination. This performance increase results from the higher specific impulse I_{sp} of the propulsion system. Other benefits that can be derived from advanced propulsion are a reduction in the system's dry mass, a reduction in Mars outpost delivery and assembly time, or a reduction in mission complexity.

Why Metallized Propellants?

One advanced propulsion system that can provide benefits for Mars missions uses metallized propellants. These propellants offer increases in the overall propellant density or the I_{sp} of a propulsion system, or both, significantly reducing the launch mass relative to conventional chemical propellants. Metallized propellants have metal added to the fuel or the oxidizer. Typically, the metal is in the form of micrometer-sized particles gelled with the H_2 or other fuel to increase its

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[1]Acronyms are defined in the appendix.

[2]And personal communications and analysis notes from A. Friedlander of Science Applications International Corp., Schaumberg, Illinois, and B. Donahue, Boeing Aerospace, Huntsville, Alabama.

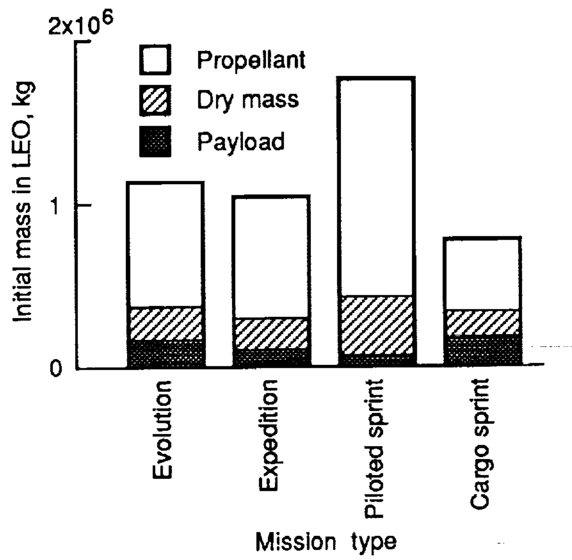


Figure 1.—Initial mass in low Earth orbit for various Mars missions.

density. Combusting metal in the exhaust increases the combustion temperature and hence the I_{sp} of the propulsion system.

Table I contrasts the performance of several propulsion systems with and without metallized fuel. Using metallized propellant ($O_2/H_2/Al$) increases I_{sp} by 5.9 lb_f-s/lb_m over O_2/H_2 systems. The expansion ratio for the O_2/H_2 engines was 500:1. Also listed are the engine efficiencies η, the ratio of the actual delivered performance to the theoretical maximum performance.

The mixture ratios and metal loadings for these designs are provided in table II. The metal loading represents the fraction (by weight) of aluminum in the fuel. The mixture ratio is defined as it is for traditional chemical propulsion: the ratio of the total oxidizer mass to the total fuel mass.

The increases in propellant density lead to reductions in the tankage mass as well as in the overall propulsion system dry mass. Because many of the propulsion system elements are dependent on the propellant mass, the propellant density can have a large effect on the overall dry mass.

TABLE I.—ENGINE PERFORMANCE FOR INTERPLANETARY TRANSFER PROPULSION
[Expansion ratio, 500:1.]

Propellant	Specific impulse, I_{sp}, lb_f-s/lb_m		I_{sp} efficiency, η
	No metal	Metallized, aluminum	
NTO/MMH	341.2	366.4	0.938
O_2/MMH	381.9	386.2	.940
O_2/CH_4	382.1	384.3	.940
O_2/H_2	479.5	485.4	.984

TABLE II.—ENGINE DESIGN PARAMETERS

Propellant	Mixture ratio	
	No metal	Metallized (aluminum loading)
NTO/MMH	2.0	0.9 (50)
O_2/MMH	1.7	.9 (35)
O_2/CH_4	3.7	1.8 (45)
O_2/H_2	6.0	1.6 (60)

In order to determine the benefits of using metallized propellants for Mars missions, the mission and propulsion system designs must be considered together and analyzed. The succeeding sections discuss these designs and the results of the overall systems analysis.

Human Missions to Mars

Several types of Mars missions have been considered in the current NASA studies—most recently, the evolution and expedition missions (ref. 1). In the evolution mission the crew and the cargo are both sent to Mars on the same vehicle. The round-trip flight times (not including the time on the surface) for these missions are 700 to 800 days. The departure from Earth to Mars requires a lower energy than the sprint missions (a 400-day trip).

The expedition mission is similar to the evolution mission. The primary difference is the orbit of the orbiting vehicle. The expedition Mars excursion vehicle (MEV) descends from and returns to a vehicle orbiting at 500- by 582-km altitude and 50° inclination. The evolution mission orbits are either around Phobos (6030-km altitude, 2° inclination) or highly elliptical and highly inclined (250- by 18 000-km altitude, 28° inclination; or 250- by 33 120-km altitude, 0° inclination). These orbits require a larger MEV than does the expedition mission.

Earlier studies had proposed the sprint mission (refs. 3 and 4 and personal communication from A. Friedlander). This mission scenario separates the piloted crew elements from the unmanned cargo elements that are not required until the crew arrives at Mars (the excursion vehicle, science instruments, and the propellant and tankage to return the crew to Earth). The heavy cargo elements are delivered to Mars on a low-energy trajectory. The sprint missions have been given less emphasis because of the large LEO masses required. Also, the separation of the crew from its ability to return to Earth (its return propellant) is currently considered a great mission risk.

Mission Analysis

In estimating the vehicle masses the maneuvers are described by a series of velocity changes ΔV's. The ΔV is computed as follows:

TABLE III.—MISSION VELOCITY CHANGES
[From reference 1.]

(a) Evolution and expedition missions

Maneuver	Evolution mission	Expedition mission
	Velocity change, ΔV, km/s	
Preinjection preparation	100	10
Trans-Mars injection	4300	4400
Trans-Mars coast	50	50
Mars orbit insertion	20	100
Mars orbit operations	50	20
Trans-Earth injection	2650	3900
Trans-Earth coast	50	50
Earth orbit insertion	40	(a)
Earth orbit operations	200	(a)
Excursion:		
Pre-deorbit preparation	10	10
Deorbit to landing	1400	600
Ascent	5800	4200

(b) High-energy split sprint mission (personal communication with A. Friedlander)

Maneuver	Velocity change, ΔV, km/s
Piloted mission:	
Preinjection preparation	0
Trans-Mars injection	[b]7780
Trans-Mars coast	50
Mars orbit insertion	0
Mars orbit operations	207
Trans-Earth injection	3148
Trans-Earth coast	50
Earth orbit insertion	0
Earth orbit operations	121
Cargo mission:	
Preinjection preparation	0
Trans-Mars injection	[c]3556
Trans-Mars coast	50
Mars orbit insertion	0
Mars orbit operations	207
Excursion:	
Pre-deorbit preparation	0
Deorbit to landing	1100
Ascent to orbit	4500

[a]Not applicable.
[b]Three stages are used for departure and the first and second stages are reused. The return ΔV is 0.032 + 0.121 = 0.153 km/s for the first stage and 2.59 + 0.032 + 0.121 = 2.745 km/s for the second stage.
[c]One stage is used for departure and is reused. The return ΔV is 0.964 + 0.032 + 0.121 = 1.117 km/s.

$$\Delta V = I_{sp} g \ln\left(\frac{m_0}{m_f}\right)$$

where

ΔV velocity change, m/s

I_{sp} specific impulse, lb_f-s/lb_m

g gravitational acceleration, 9.81 m/s

m_0 initial mass, kg

m_f final mass, kg

The ΔV's for the Mars missions were taken from reference 1 and a personal communication with A. Friedlander. Table III lists the ΔV's for the different types of missions analyzed. In table III(b) the ΔV's for similar-energy maneuvers (Earth and Mars orbit insertions) do not correspond exactly to those shown in table III(a). They were produced before the Office of Exploration had developed their current standard set of Mars mission assumptions. The differences between the cases, however, are small. Table IV provides the payload masses for the three types of Mars missions. Note that a large propellant load for the Earth return is the major payload on the sprint cargo vehicle.

Evolution and Expedition Missions

In the evolution and expedition missions, all of the mission elements are on one vehicle: crew, excursion vehicle, Earth return propellant, and crew modules. Aerobraking is used for the Mars orbit insertion and the Earth orbit insertion maneuvers. The trans-Mars injection is performed with a single stage. This stage is expended and not returned to Earth. Before Mars orbit insertion the excursion vehicle is separated from the main crew module. Because each vehicle enters Mars orbit separately, the aerobrake on each is smaller than one designed to protect the entire payload. Also, the excursion vehicle's aerobrake is used twice: once for aerocapture at Mars and once for the descent to the surface. In the evolution mission

TABLE IV.—MISSION PAYLOAD MASSES
[From references 1 and 4 and personal communicaton with B. Donahue.]

	Types of mission		
	Evolution	Expedition	Split sprint
	Mass, kg		
Crew modules and consumables	46 192	46 192	[b]80 717
Mars excursion (O_2/H_2)	124 058	69 448	[a]60 000
Return propellant and tankage	-------	-------	[a]120 167
Science payload, etc.	-------	-------	[a]20 000
Mass returned to LEO	46 192	7 000	[b]5 000

[a]Cargo.
[b]Piloted.

both the crew and its module return to LEO. In the expedition mission the crew module is expended prior to Earth orbit insertion and the crew proceeds to LEO in a small capsule.

Sprint Missions

In the split sprint mission the crew and their return propellant are on separate vehicles: a piloted vehicle and a cargo vehicle. The piloted vehicle uses three stages for the trans-Mars injection. Aerobraking is used to return the first two stages to LEO for reuse. The third stage remains with the piloted vehicle and is later used for the trans-Earth injection.

The cargo vehicle's trans-Mars injection is performed with one stage. Again aerobraking is used to return the stage to LEO. The cargo vehicle carries the excursion vehicle, the mission science payload, and the propellant to return the astronauts to Earth. After performing their mission the astronauts return to either the space station or Earth's surface in a small capsule, the module that sustained them during the Mars-Earth transfer having been expended prior to Earth orbit insertion.

The reusability of the sprint mission stages requires several maneuvers to return them to LEO. The piloted vehicle has its trans-Mars injection ΔV broken into three parts: 2.59 km/s delivered by the first stage, the same ΔV by the second stage, and 2.60 km/s by the third stage. The total ΔV is 7.78 km/s. The first stage performs two small maneuvers to return to LEO with a total ΔV of 0.153 km/s. Because the second stage is on an Earth-escape trajectory when it separates from the piloted vehicle, it must return to the Earth's gravitational influence before it can aerobrake into LEO. Therefore, it delivers an additional 2.59-km/s ΔV as well as the 0.153-km/s ΔV for aerobraking. Once it has burned out, the cargo mission stage has also exceeded Earth's escape velocity. It must therefore perform an added 0.964-km/s ΔV (as well as the 0.153-km/s ΔV for aerobraking) to return to LEO.

Propulsion System Design

Engine Performance

The engine performance of several metallized propellant combinations was estimated with a computer simulation code (ref. 8). An engine I_{sp} efficiency was used to reduce the code-predicted I_{sp}. The efficiency is the ratio of the actual delivered performance to the theoretical maximum I_{sp}. This reduction reflected the losses incurred from the nozzle boundary layer, engine cycle inefficiencies, and other propulsion system losses. The engine efficiencies were derived by comparing the performance estimates from references 9 to 12 with the vacuum I_{sp} predicted by the engine code.

Tables I and V provide the design I_{sp}'s selected for the various Mars missions. The engine chamber pressure was 1000 psia and the propellants were provided to the combustion chamber in the liquid state. Because packaging constraints may limit the size of the large-expansion-ratio nozzles, an expansion ratio of 500:1 was selected for the transfer vehicle and 200:1 for the excursion vehicle. The I_{sp}'s were 485.4 lb_f-s/lb_m for the trans-Mars injection stage and the Mars transfer vehicle and 475.3 lb_f-s/lb_m for the Mars excursion vehicle.

TABLE V.—ENGINE PERFORMANCE FOR MARS EXCURSION PROPULSION
[Expansion ratio, 200:1.]

Propellant	Specific impulse, I_{sp}, lb_f-s/lb_m		I_{sp} efficiency, η
	No metal	Metallized (aluminum)	
NTO/MMH	334.7	354.4	0.938
O_2/MMH	371.5	374.4	.940
O_2/CH_4	371.4	372.2	.940
O_2/H_2	470.1	475.3	.984

Propellant Density

When the aluminum loadings considered in the engine performance calculations are used, the H_2 propellant density can increase from 70 kg/m^3 (H_2 with no aluminum loading) to 169 kg/m^3 (H_2 with a 60-percent aluminum loading). The density increase is computed by the following equation:

$$\rho_{p,m} = \frac{\dfrac{ML}{1-ML}+1}{\dfrac{ML}{(1-ML)\rho_m}+\dfrac{1}{\rho_p}}$$

where

$\rho_{p,m}$ density of metallized oxidizer or fuel, kg/m^3

ML metal loading (fraction of fuel mass)

ρ_m density of metal in oxidizer or fuel, kg/m^3

ρ_p density of nonmetallized oxidizer or fuel, kg/m^3

Selection of Best Density-I_{sp} Design Points

Tradeoff studies must be conducted to determine the "best" I_{sp} and propellant density for each propulsion system so that the maximal reduction in LEO mass or the maximal payload increase can be achieved. Figure 2 shows the results of one of these tradeoff studies on I_{sp}. The maximal metal loading considered was 60 percent of the fuel mass. A higher I_{sp} is produced at higher metal loadings. The selection of the 60-percent loading performance level was determined by the metal loading experience with solid rocket motors. The total metal loading of all of the propellant (oxidizer and fuel) was 23 percent. This loading is comparable to that of solid propulsion systems. Although a higher I_{sp} is predicted for

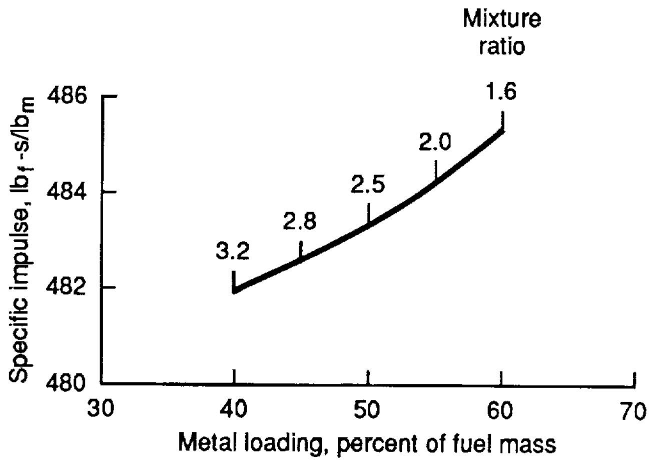


Figure 2.—Specific impulse as a function of metal loading. Expansion ratio, 500:1

higher metal content, the 60-percent loading was chosen to stay within the experience level gained with solid propulsion systems. An I_{sp} of 485.4 lb_f-s/lb_m was delivered at a metal loading of 60 percent of the H_2/Al, an expansion ratio of 500:1, and a mixture ratio of 1.6. The effect of metal loading on the propulsion system dry mass and its influence on the selection of the I_{sp} design point are discussed later in this report.

Mass-Scaling Equations

In determining the dry mass of the Mars vehicles the following general mass-scaling equation was used:

$$m_{dry} = A + Bm_p + Cm_p^{2/3} + Dm_{entry}$$

A,B,C,D mass-scaling parameters (provided in table VI)

m_p propellant mass, kg

m_{entry} total entry mass during aerobraking maneuver, kg

TABLE VI.—PROPULSION SYSTEM MASS-SCALING PARAMETERS FOR VARIOUS PROPELLANTS

Propellants	Scaling parameter			
	A	*B*	*C*	*D*
Trans-Mars injection stage and Mars transfer vehicle				
O_2/H_2	1363.51	0.1668	0.0799	0.15
O_2/H_2/Al	1363.51	.1669	.0786	.15
Mars excursion vehicle				
NTO/MMH/Al	1363.51	0.1484	0.0000	0.15
O_2/MMH/Al	↓	.1504	.0183	↓
O_2/CH_4/Al	↓	.1580	.0439	↓
O_2/H_2	↓	.1811	.0806	↓
O_2/H_2/Al	↓	.1812	.0793	↓

TABLE VII.—PROPULSION SYSTEM MASS-SCALING PARAMETERS FOR THREE METAL LOADINGS

[Propellant, O_2/H_2/Al; trans-Mars injection stage and Mars transfer vehicle propulsion systems.]

Metal loading, percent	Scaling parameter			
	A	*B*	*C*	*D*
40	1363.51	0.1661	0.0785	0.15
50	1363.51	.1656	.0777	.15
60	1363.51	.1669	.0786	.15

Table VII provides the propulsion system mass-scaling parameters for the metallized systems. These parameters model all of the masses required to store and provide propellants to the main engines. They include tankage, engines, feed system, thermal control, structure, residuals, and contingency. The scaling parameter *A* varied from 349 to 1364 for the Mars vehicles. The variation is due to the differing feed system configurations and number of engines for each stage. Only the latter value of *A* is shown in the table. The specific mixture ratios and the metal loadings are listed in table II. All of the propellant combinations other than O_2/H_2 were used only for the Mars excursion vehicle ascent stage.

The propellant tankage for all of the systems has a 50-psia maximal operating pressure. The propellant is stored at 30 psia. All of the tankage for O_2, H_2, and methane (CH_4) is composed of aluminum alloy. The tanks for nitrogen tetroxide (NTO) and monomethyl hydrazine (MMH) are made of titanium. The flange factor and the safety factor for the propellant tanks are 1.4 and 2.0, respectively. The safety factor is based on the tank material's ultimate stress. The propellant residual and holdup factor for the transfer vehicle equation is 1.5 percent of the total propellant mass. This factor is 2.7 percent for the smaller excursion vehicle tankage.

Each space-storable and cryogenic propulsion system uses autogenous pressurization. Only the NTO/MMH system uses regulated pressurization. The pressurant is helium. The maximal operating pressure in the pressurant tank is 3722 psia. The storage pressure is 3444 psia. The flange factor and the safety factor for the pressurant tanks are 1.1 and 2.0, respectively. A small helium pressurization system is provided for the autogenous systems. It can pressurize one-tenth of the total propellant tank volume.

For thermal control the cryogenic propellants (O_2, H_2, and CH_4) have a high-performance multilayer insulation and a thin-wall vacuum jacket. The jacket is sized for a 30-psia maximal operating pressure. After the vehicle reaches space, it is vented and evacuated. The storable propellants only require a lower-performance multilayer insulation.

The aerobrake mass is 15 percent of the vehicle mass entering the atmosphere. This mass includes the payload, the propulsion system dry mass, any needed propellant for the post-entry circularization firing, and the aerobrake.

As discussed previously, the metal loading may have an important effect on the propulsion system dry mass. The maximum-I_{sp} design point, however, may require a heavier propulsion system than the nonmetalized propellant design case. Table VII compares the propulsion system mass-scaling parameters for three metal loadings. There is a small variation in the total mass of the propulsion system with the different metal loadings. On the basis of the tradeoff studies the highest-I_{sp} system (which has a metal loading of 60 percent) was selected.

Design and Sizing of Mars Excursion Vehicle

The excursion vehicle is sized to deliver the ΔV's listed in table III. In the baseline evolution and expedition mission scenarios, the payloads delivered to the Mars surface have a total mass of 25 000 kg per flight. An additional 4000-kg module carries the crew during the landing mission and is returned to Mars orbit. In the sprint mission scenario, only 12 400 kg is delivered to the surface. As in the other missions a 4000-kg module is returned to Mars orbit.

During the descent the same aeroshell is used for the aerocapture maneuver for Mars orbit insertion and the atmospheric entry at Mars. The aeroshell is separated from the excursion vehicle before the final landing, but not until all but 0.3 km/s of the descent ΔV has been delivered. This reduces both the total mass of the excursion vehicle and the total propellant mass required for landing. The aeroshell is 15 percent of the initial excursion vehicle aerocapture mass. For the Mars evolution mission using O_2/H_2 this mass is 18 600 kg. For the ascent stage the parameters in table VI are used but without the aerobrake mass. Another important aspect of the excursion vehicle is its leg structure to support it on Mars. It is part of the descent stage and the leg mass is 2 percent of the total mass landed on the surface.

The mass-scaling equation for the excursion vehicle stages is

$$m_{dry} = A + Bm_p + Cm_p^{2/3} + Dm_{entry} + Em_{landed}$$

where

E mass parameter for leg structure, 0.02

m_{landed} total landed mass on surface, kg

No aerobrake or leg structure is used for the ascent stage.

Results

Several mass sensitivity studies are discussed in this section. They include the added payload that can be delivered to Mars (given a constant initial LEO mass), the LEO mass reductions afforded by cryogenic metallized propellants, and the potential effect of using storable metallized propellants for the Mars ascent.

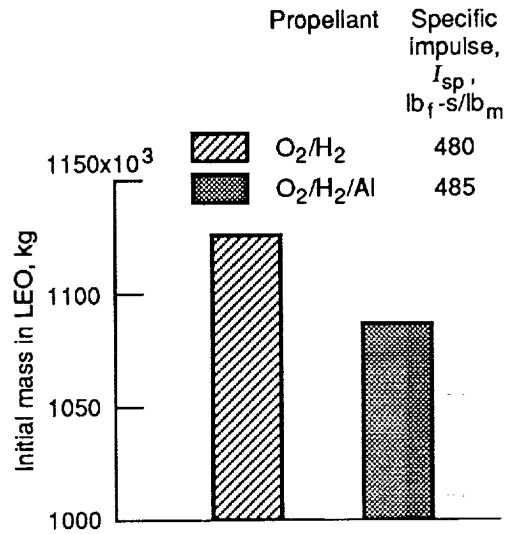


Figure 3. —Initial mass in low Earth orbit saved when metallized propellants are used for all propulsion systems—evolution mission.

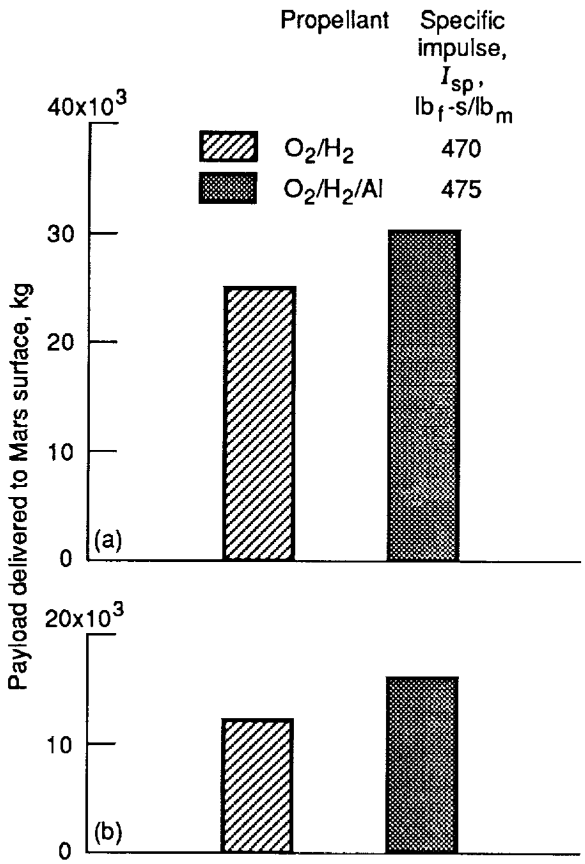
LEO Mass Reduction for Trans-Mars Injection Stage

Figure 3 shows the LEO mass saving for the Mars evolution mission vehicle when metallized propellants are used. If they are used for all of the mission maneuvers, the LEO mass is reduced by 3.3 percent. Using the increased I_{sp} of metallized propulsion to reduce the LEO mass on a per-vehicle basis does not produce a significant saving. As discussed later, the most significant mass advantage is gained by increasing the payload delivered to Mars.

Payload Mass Sensitivity of Mars Excursion Vehicle to Constant LEO Departure Mass

The most significant benefit of metallized propellants is their ability to deliver added payload to Mars. Figure 4(a) contrasts the payload delivery capabilities of O_2/H_2 and metallized propulsion for the Mars expedition mission. Using metallized $O_2/H_2/Al$ increases the payload to the surface of Mars by 22 percent for the expedition mission. The initial masses in LEO for the two types of vehicles (metallized and nonmetallized propellant) are equal. However, the mass saving (in the excursion vehicle ascent stage, the Mars transfer vehicle, and the trans-Mars injection stage) by using the higher-I_{sp} metallized propellants is placed into the excursion vehicle's mass. Hence, the metallized excursion vehicle has a higher initial mass and is able to place 20 to 22 percent more payload on Mars.

A similar benefit is possible with the split sprint mission. The payload increase to the Mars surface (shown in fig. 4(b)) is 33 percent (16 500 kg with metallized propellants versus 12 400 kg). The potential benefits of added payload are longer stay time on the surface, more flexibility to land large, massive payload on the surface, and the ability to land added science payload on the surface.



(a) Expedition mission
(b) Split sprint mission.

Figure 4.—Increase in Mars excursion vehicle payload with metallized propellants—expedition mission.

The evolution and expedition excursion vehicle masses are summarized in table VIII. The descent payload increases from 25 000 to 30 000 kg for the evolution mission and to 30 500 kg for the expedition mission when metallized fuels are used. The descent stage propellant mass to land the added payload increases by 1600 kg for the evolution mission and by 980 kg for the expedition mission.

Reduced Launch Requirements

Figure 5 compares the total mass delivered to Mars using O_2/H_2 and $O_2/H_2/Al$. With the increases in delivered payload the total number of launches required is reduced significantly. For a large Mars base construction or extensive exploration program the 20-percent payload increase translates into 16 fewer STS–C launches (80 versus 96) for a total of 150 000 kg of payload delivered to the Mars surface. For the evolution mission, a minimum of 16 STS–C launches (68 000 kg per flight) would be required to deliver the 1 052 000-kg vehicle mass to LEO (table IX). Similarly, 17 STS–C launches would be saved when using expedition vehicles (or a 1 124 000-kg initial LEO mass). With metallized propellants only five Mars

TABLE VIII.—MARS EXCURSION VEHICLE MASSES FOR ASCENT AND DESCENT STAGES WITH O_2/H_2 AND $O_2/H_2/Al$ PROPELLANTS

Element	Evolution mission		Expedition mission	
	O_2/H_2	$O_2/H_2/Al$	O_2/H_2	$O_2/H_2/Al$
	Mass, kg			
Ascent stage				
Ascent payload	4 000	4 000	4 000	4 000
Adapter (second stage and payload)	211	211	211	211
Propellant tankage	514	491	225	218
Pressurization	110	115	48	51
Engines and feed system	1 240	1 240	1 240	1 240
Thermal control	1 187	1 144	527	514
Structure	1 828	1 764	799	781
Residuals and holdup	725	699	317	310
Contingency (10 percent)	560	545	316	311
Usable propellant	26 115	25 207	11 418	11 159
Descent stage				
Descent payload	25 000	30 000	25 000	30 500
Adapter (first and second stages)	3 236	3 443	2 321	2 594
Propellant tankage	647	672	187	205
Pressurization	138	158	40	48
Engines and feed system	317	317	317	317
Thermal control	1 489	1 554	442	484
Structure	2 302	2 412	666	734
Residuals and holdup	913	956	264	291
Contingency (10 percent)	581	607	192	208
Leg structure	1 451	1 542	990	1 106
Aeroshell	18 609	19 683	10 417	11 607
Usable propellant	32 885	34 462	9 511	10 491
Total[a]	124 058	131 222	69 448	77 380

[a]The total masses differ because for a constant mass in LEO the metallized propulsion option will allow a larger mass to be delivered to Mars orbit and the excursion vehicle is able to deliver more payload to the Martian surface.

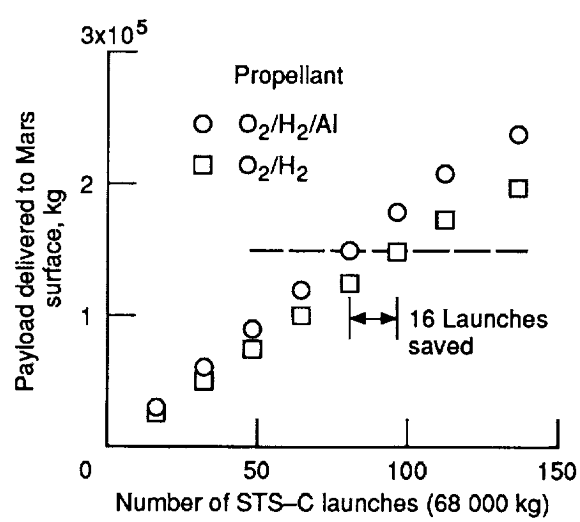


Figure 5.—Mars surface payload as a function of number of STS-C launches—evolution mission.

TABLE IX.—MARS-EXCURSION-VEHICLE AND LOW-EARTH-ORBIT MASSES WITH EARTH- AND SPACE-STORABLE (METALLIZED) PROPELLANTS FOR ASCENT PROPULSION

Propellant	Mars excursion vehicle		Low Earth orbit	
	Evolution mission	Expedition mission	Evolution mission	Expedition mission
	Mass, kg			
Expansion ratio for metallized propellants, 200:1				
O_2/H_2	124 058	69 448	1 124 000	1 052 000
NTO/MMH/Al	214 898	84 333	1 478 800	1 108 400
O_2/MMH/Al	180 321	79 972	1 344 000	1 091 300
O_2/CH_4/Al	194 946	81 952	1 401 000	1 099 000
Expansion ratio for metallized propellants, 500:1.				
O_2/H_2	124 058	69 448	1 124 000	1 052 000
NTO/MMH/Al	190 063	81 363	1 382 000	1 096 000
O_2/MMH/Al	164 865	77 763	1 283 700	1 082 600
O_2/CH_4/Al	175 521	79 025	1 325 300	1 087 600

evolution vehicles would be needed (each delivering 30 000 kg). With conventional O_2/H_2 six such vehicles would be needed.

The schedule savings and cost savings of reduced launch requirements can be significant. Sixteen launches to LEO are required for each Mars vehicle. A maximum of six launches per year may be achieved with either the STS–C or the advanced launch system (ALS) (refs. 1, 4, and 13). This translates into an average rate of one launch every 2 months. Thus, for 16 launches, 32 months (or 2.7 years) are needed for the assembly of each Mars vehicle in LEO. Using metallized propellants reduces the time needed for assembling these elements of a 150 000-kg Mars base by 2.7 years (one fewer vehicle required). The reduction in launch vehicle procurement costs and the reduction in launch operations associated with fewer launches is, of course, also a major cost saving.

Storable Propellant Options

Another possible advantage of metallized propellants may be the use of advanced Earth- or space-storable propellants for the Mars ascent (ref. 7 and personal communication with B. Donahue). Because the time on the Mars surface may be long (20 to more than 600 days), a cryogenic propulsion system may have an extremely high propellant boiloff mass. Therefore, other alternatives to using hydrogen as a fuel for a planetary excursion vehicle are being considered. Metallized propellant combinations using oxygen/methane, oxygen/monomethyl hydrazine, or nitrogen tetroxide/monomethyl hydrazine are possible alternatives. These storable, or "soft," cryogenic propellants can lower the propellant boiloff rate and potentially simplify the excursion vehicle's thermal design.

Tables IX compares the masses of excursion vehicles using non-O_2/H_2 ascent propulsion for expansion ratios of 200:1 and 500:1. Each lander delivers the baseline 25 000 kg to the Mars surface. The MEV mass penalty for using this type of propulsion is relatively small for the expedition vehicles: 8000 to 14 000 kg over those using O_2/H_2. This is not true for evolution vehicle cases. The mass penalties for the evolution cases are much larger and range from 40 000 to 90 000 kg. Also in the tables the corresponding LEO initial masses for the different excursion vehicle options are provided. Again, for the expedition mission the LEO mass penalties are small: 30 000 to 56 000 kg, or 2.9 to 5.3 percent. Thus, only a small LEO mass penalty must be paid to benefit from simplifying the storage of cryogenic propellants by using only a "soft" (90 K O_2) cryogen versus a 20 K propellant (H_2).

System Design Issues

Engine Efficiency

Engine efficiency is critical to achieving the performance advantages of metallized propellants. Without the predicted increases in I_{sp} the advantages of these propellants are significantly reduced. Numerical modeling, propellant rheology experiments, and hot-fire engine testing are under way to determine potential engine efficiency with metallized propellants (refs. 14 to 17). All these areas of research are focused on applying metallized propellants to launch vehicles, upper stages, and planetary missions.

Tank Configurations

If the benefits of reduced LEO mass or increased payload are not desired or significant, increased propellant density can still benefit the Mars missions. Because of the increased density the propellant tank size can be reduced, potentially offering better and smaller tank configurations. Also, the on-orbit assembly of the Mars vehicle may be easier with smaller tankage. Less MEV propellant tank volume is required for O_2/MMH/Al than for O_2/MMH (16.7 m^3 versus 18.66 m^3). This volume is also substantially smaller than that required for the O_2/H_2 (34.66 m^3).

Although, in the O_2/MMH/Al case, the tankage volume decreased, other applications will show a propellant volume increase. As an example, in the expedition mission the total O_2 tank volume for the trans-Mars injection can be reduced from 509 m^3 (O_2/H_2) to 366 m^3 with metallized propellants (O_2/H_2/Al). The H_2 tank volume, however, increases from 1396 m^3 to 1560 m^3 with metallized propellants. Overall, the total tank volume increases from 1905 m^3 to 1926 m^3 (a difference of only 21 m^3, or 1.1 percent). This example is for the case where the LEO mass is held constant (at 1 052 000 kg) for both the metallized and the nonmetallized O_2/H_2 systems using spherical tankage. Though the propellant tank volume increases, the higher I_{sp} of metallized propellants allows 22 percent more payload to Mars.

Pump-Fed and Pressure-Fed Feed Systems

The high-performance O_2/H_2 systems being considered for Mars exploration require a pump-fed engine, which typically needs less mass for propellant tankage and pressurization systems than pressure-fed propulsion systems. The propellant feed system must be designed to provide the non-Newtonian, thixotropic metallized propellant with the same reliability as the nonmetallized H_2. Metallized propellants are currently fed to smaller propulsion systems with positive-displacement propellant expulsion devices such as diaphragms (ref. 18). These devices are also considered too impractical for large propellant tanks. For the extremely large propellant loads needed on the Mars missions, a different expulsion device will be required. The propellant flow properties are being studied both experimentally and analytically. These studies will help determine the best propellant acquisition and feed system for these large propulsion systems.

Conclusions

The primary advantage of metallized propellants for the NASA Mars missions is their ability to increase the surface payload delivery capability. With $O_2/H_2/Al$ on the evolution and expedition missions the payload to the Mars surface is increased by 20 to 22 percent over O_2/H_2 propulsion. For sprint missions the payload mass increases can be up to 33 percent. With this added payload additional science experiments can be brought to the surface or more crew consumables can be delivered to Mars for a longer stay time on the planet.

This increase in payload also enables a faster delivery and assembly of the elements of a Mars base. With the 20-percent payload increase per mission, the number of STS-C launches needed to deliver 150 000 kg to the surface can be reduced from 96 to 80. This corresponds to reducing the number of Mars vehicles from 6 to 5. This reduction in the number of Mars vehicles can significantly reduce the cost and schedule challenges.

With metallized propellants the initial mass in LEO can be modestly reduced. For the Mars evolution mission the initial mass in LEO can be reduced by 3.3 percent of the mass required with O_2/H_2 propulsion. This modest reduction does not significantly reduce the number of launches needed for each vehicle. The mass reductions enabled by metallized propellants are therefore more effective if they are translated into added payload delivered to Mars.

Earth- and space-storable propellants for the Mars ascent can provide an alternative to O_2/H_2 propulsion. The most-promising candidate that allows the lowest storable propulsion mass for the ascent system is O_2/MMH/Al. The LEO initial mass penalty for using metallized O_2/MMH/Al is only 3 to 5 percent over an all-cryogenic system for the expedition missions. These space-storable propellants have lower propellant boiloff rates and can potentially simplify the excursion vehicle thermal design.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, July 2, 1990

Appendix—Glossary

ALS	Advanced Launch System
LEO	low Earth orbit
MEV	Mars excursion vehicle
NASA	National Aeronautics and Space Administration
NTO/MMH	nitrogen tetroxide/monomethyl hydrazine
STS-C	Space Transportation System-Cargo

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16. Abstract

Advanced chemical propulsion using metallized propellants can lead to significant reductions in launch mass for piloted Mars missions. Metallized propellants allow the propellant density or the specific impulse I_{sp} of the propulsion system, or both, to increase. Increasing propellant density and I_{sp} can reduce the propellant mass and the propulsion system dry mass. These effects are discussed and analyzed in this report. Detailed mass-scaling equations and estimates of the I_{sp} for several metallized propellant combinations are presented. The most significant savings with metallized propellants are derived from increasing the payload delivered to Mars. For the mass in low Earth orbit (LEO), a metallized Mars transfer vehicle can deliver 20 to 22 percent additional payload to the surface of Mars. Using metallized propulsion can accelerate the delivery and construction of a Mars base or outpost. This 20-percent payload increase reduces the total number of Mars flights and therefore significantly reduces the number of Space Transportation System–Cargo (STS–C) launches for the entire Mars architecture. Using metallized propellants to reduce the mass in LEO per flight is not as effective as increasing the payload delivery capacity. Although over 20 percent more payload can be delivered to Mars per mission, the mass saving per flight (while delivering the same payload with a higher-I_{sp} system) is much smaller. Using metallized propellants in all of the Mars propulsion systems would produce a modest 3.3-percent LEO mass saving. This translates into a saving of 38 000 kg over the mass required with oxygen/hydrogen (O_2/H_2) propulsion. A Mars excursion vehicle using Earth- or space-storable propellants for the ascent can be an alternative to storing cryogenic H_2 on Mars. There will be a mass penalty for using these alternatives because of the lower I_{sp} of their propulsion systems. A space-storable system using oxygen/monomethyl hydrazine/aluminum (O_2/MMH/Al) would deliver the lowest mass penalty over O_2/H_2. For lower-energy expedition missions the LEO mass penalty for using metallized O_2/MMH/Al would be only 3 to 5 percent.

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