Benefits of Using Hall Thrusters for a Mars Sample Return Mission

IEPC-2009-217

Presented at the 31st International Electric Propulsion Conference,
University of Michigan • Ann Arbor, Michigan • USA
September 20 – 24, 2009

David Y. Oh[*], Richard R. Hofer[†], Ira Katz[‡], Jon A. Sims[§], Noah Z. Warner[**], Thomas M. Randolph[††], Ronald T. Reeve[‡‡], and Robert C. Moeller[§§]
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109, USA

Concept architectures for the proposed Mars Sample Return (MSR) mission have long relied on chemical propulsion to provide on-board Δv capability, and recently proposed architectures are complex and expensive, requiring multiple launch vehicles to return a single sample to Earth. In this study, we consider the use of a solar electric propulsion (SEP) system using off-the-shelf commercial BPT-4000 Hall thrusters as primary propulsion for MSR. The proposed system uses a solar array that generates 20 kW of power at Earth, a size that is routinely flown on large GEO communications satellites. It is found that the high specific impulse of Hall thrusters (2060 seconds) when compared to chemical thrusters (325 seconds) reduces propellant mass to a level that would potentially allow the use of a single launch vehicle to carry both the orbiter and the lander for the proposed MSR mission. This has the potential to greatly simplify the proposed MSR mission architecture. At the same tisme, the reduction of specific impulse compared to ion thruster systems allows for total trip times that are comparable to all-chemical missions. Based on these results, commercial Hall thrusters appear to be an attractive candidate for an electric propulsion based MSR mission, warranting further study to identify optimized solutions.

I. Introduction

Mars Sample Return (MSR) is a scientifically interesting mission that has been considered by NASA in various forms since the 1960s. Concept architectures for MSR have long relied on chemical propulsion to provide the ΔV necessary to accomplish this challenging mission,[1,2] and recently proposed architectures are complex and expensive, requiring multiple launches to return a single sample to Earth. An alternative to chemical propulsion that has the potential to simplify the proposed MSR's mission architecture is solar electric propulsion (SEP). Solar electric propulsion, in the form of ion and Hall effect thrusters powered by solar arrays, is a form of propulsion widely used on commercial communications satellites constructed in the United States, Europe, and Russia. Figure 1 shows over 100 currently operating spacecraft that use solar electric propulsion of all types (resistojets, arcjets, Hall thrusters, and ion thrusters) for primary propulsion and stationkeeping. Of this total, there are approximately 36 Western satellites and 42 Russian satellites flying today that use Hall and ion thrusters, including satellites that carry XM

[*] Senior Systems Engineer, Surface Systems Engineering, David.Y.Oh@jpl.nasa.gov
[†] Senior Engineer, Electric Propulsion Group, richard.r.hofer@jpl.nasa.gov.
[‡] Supervisor, Electric Propulsion Group, Ira.Katz@jpl.nasa.gov
[§] Principle Member of Engineering Staff, Guidance Navigation and Control.
[**] Systems Engineer, Surface Systems Engineering, Noah.Z.Warner@jpl.nasa.gov
[††] Project Element Manager, Propulsion and Materials Engineering, Thomas.M.Randolph@jpl.nasa.gov
[‡‡] Ronald Reeve, Program Manager, JPL Propulsion Technology Program, Ronald.reeve@jpl.nasa.gov
[§§] Senior Systems Engineer, Advanced Design Engineering.

satellite radio and broadcast cable television in the United States.[3,4,5] SEP is a well developed, mature, and widely used technology that is a part of our everyday communications infrastructure. This technology offers the potential to simplify the proposed MSR mission by increasing delivered payloads on the Earth Return Vehicle (ERV) and reducing the number of launch vehicles required for the mission.

Electric propulsion has been proposed in recent years as a means to offset the high propellant loadings that would be required for a potential MSR mission when using chemical rockets. Brophy proposed an advanced NSTAR ion thruster in 2000, Oh considered the benefits of the NEXT ion thruster in 2004, and Donahue considered the use of NEXT and high specific impulse Hall thrusters in 2006.[6,7,8] All of these concepts have utilized SEP thrusters operating at a specific impulse in excess of 3000 seconds. Generally speaking, these studies have shown significant payload mass benefits and the likelihood of decreasing the number of launch vehicles from the two required for an all-chemical system to a single vehicle. Removing a launch vehicle results in a simpler and less expensive MSR architecture. The primary drawback of SEP has been an increase in total trip time, mainly due to longer interplanetary transit times that can require in excess of 30 months compared to 8-9 months for chemically-propelled trajectories.

In this study, we consider the use of a SEP system using off-the-shelf commercial Hall thrusters for the proposed MSR mission. The system examined utilizes the BPT-4000 thruster and a space qualified electric propulsion system currently used by Lockheed on their A2100 satellite bus. The BPT-4000 system is scheduled for launch on the Advanced-EHF satellite in 2010.[9] The proposed spacecraft uses a solar array that generates 20 kW of power at Earth (distance 1 AU from the sun), a size that is routinely flown on large GEO communications satellites. This array would generate approximately 10 kW of power at Mars. Even larger 25 kW solar power systems are planned for launch on commercial satellites in the near future. We find that the higher thrust resulting from the reduction of specific impulse compared to ion thrusters would allow for one-way interplanetary transit times of twelve months. This in turn would enable total trip times that would be comparable to all-chemical missions while reducing propellant mass to a level that potentially would allow the use of a single launch vehicle to carry both the orbiter and the lander for the proposed MSR mission. Based on these results, commercial Hall thrusters appear to be an attractive candidate for an EP based MSR mission, warranting further study to identify optimized solutions.

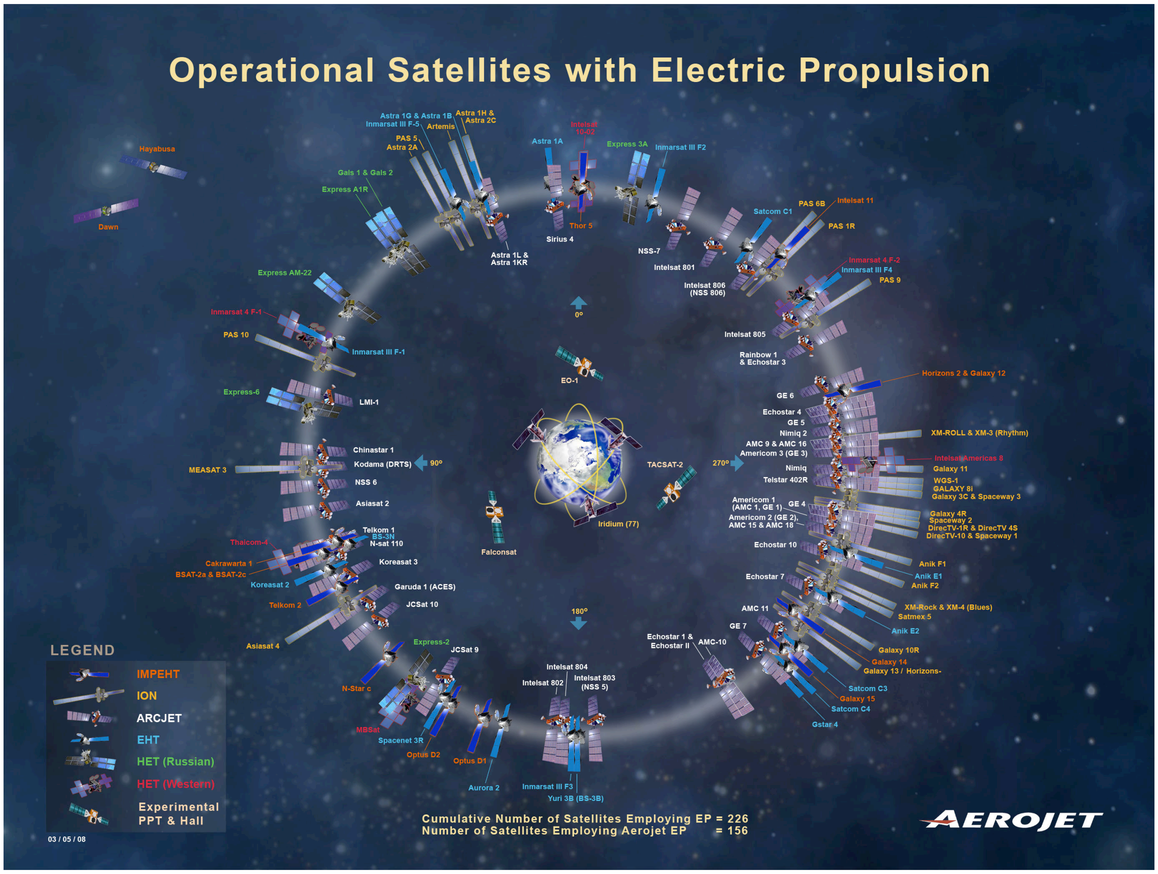

Figure 1: Electric Propulsion is a Mature, Well Developed Technology. Over 100 Spacecraft Currently Use Electric Propulsion for Stationkeeping or Primary Propulsion[10]

II. Overview of Hall Thruster Systems

The state-of-the-art 2.3 kW NSTAR ion thruster that is currently operating on NASA's Dawn mission and the commercial 4.5 kW BPT-4000 from Aerojet are shown in Figure 2. Several important similarities and differences exist for ion and Hall thrusters that are discussed in detail in ref 11. Performance and life characteristics of typical Hall and ion thrusters are compared in Table 1. At constant power, Hall thrusters generally have lower specific impulse, efficiency, and total impulse capability (lifetime) than ion thrusters, but have higher thrust-power ratios. If a de-rating approach is taken, Hall thruster lifetime can approach or exceed that of an ion thruster. For instance, an erosion model of the nominally 4.5 kW BPT-4000 has predicted an impulse capability of 11.3 MN-s,[12] which far exceeds the 7.2 MN-s demonstrated by the 2.3 kW NSTAR ion thruster during wear testing. By using an overpowered Hall thruster for NSTAR-class applications, additional total impulse capability is gained that would not be possible if a Hall thruster of equivalent power were instead used. This approach trades the mass advantage Hall thruster systems have over ion thruster systems for additional life.

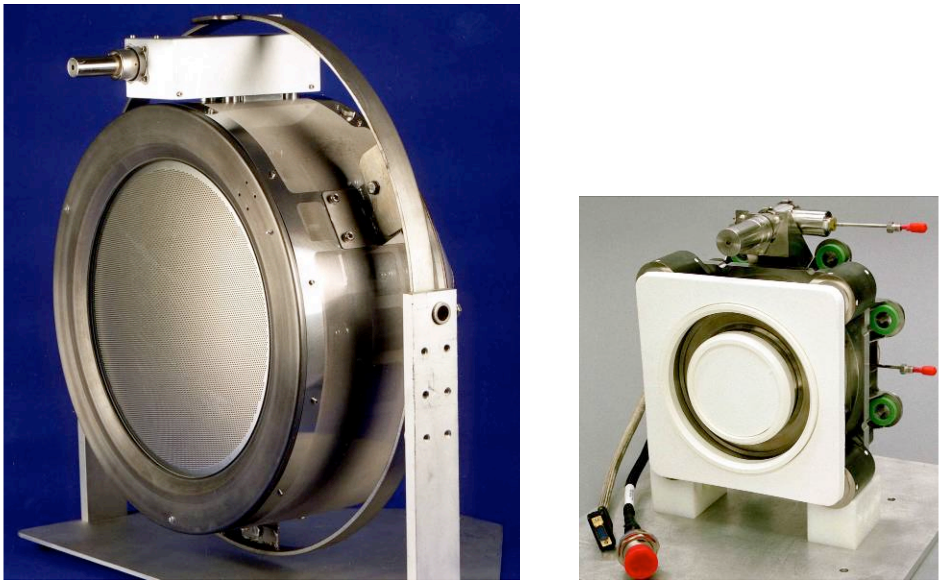

Figure 2: The 2.3 kW NSTAR ion thruster and the 4.5 kW BPT-4000.

Table 1: Comparison of typical Hall and ion thruster performance and life characteristics.

	Hall Thruster	Ion Thruster
Specific Impulse	1000-3000 s	2000-4000 s
Thrust/Power	40-80 mN/kW	20-40 mN/kW
Efficiency	50-60%	60-70%
Impulse Capability	5-11 MN-s	7-17 MN-s

From a systems perspective, Hall thruster systems are generally less complex than ion thruster systems, which can translate into mass and cost reductions. Additionally, in the US and abroad, Hall thrusters are being widely adopted by nearly every major commercial satellite manufacturer. This trend significantly increases the probability that commercial Hall thrusters will be available in the long-term for procurements from existing product lines.

Given the wide range of applicability to NASA science missions for Hall thrusters with throttling ranges from a few hundred watts to several kilowatts, several commercial options exist to fulfill these requirements. These options include thrusters with flight heritage such as the Fakel SPT-70 and SPT-100, TsNIIMASH D-55, and the SNECMA PPS-1350. Additional options have made substantial progress in development including the Aerojet BPT-4000, Fakel SPT-140, Busek BHT-200 and BHT-600, and SNECMA PPS-5000. For application to potential Mars Sample Return missions, the BPT-4000 was chosen, as it was the most mature design that could fit the mission requirements. By selecting the BPT-4000 in combination with the system architecture described below, the amount of system component development and qualification effort is substantially reduced.

Shown in Figure 2, Aerojet's BPT-4000 Hall thruster has been identified as a candidate for near-term use on NASA science missions. [11,12,13] The BPT-4000 Hall thruster propulsion system (HTPS) was developed through a joint effort between Lockheed Martin Space Systems and Aerojet as a 4.5 kW electric propulsion system for GEO satellite applications. At 4.5 kW discharge power and 400 V discharge voltage, the mission-average performance of the BPT-4000 provides a thrust of 252 mN and specific impulse of 2060 s. The first flight of the BPT-4000 is scheduled for 2010 on the Advanced EHF spacecraft.[9]

Detailed reviews of the qualification status of a Hall thruster system based on the BPT-4000 for NASA science missions have shown no substantial risk items.[11,12,13] In most cases, the completed qualification programs for the commercial system equals or exceeds science mission requirements. For those requirements not currently met by commercial components, a low risk delta-qualification has been planned and the cost and risks are manageable.

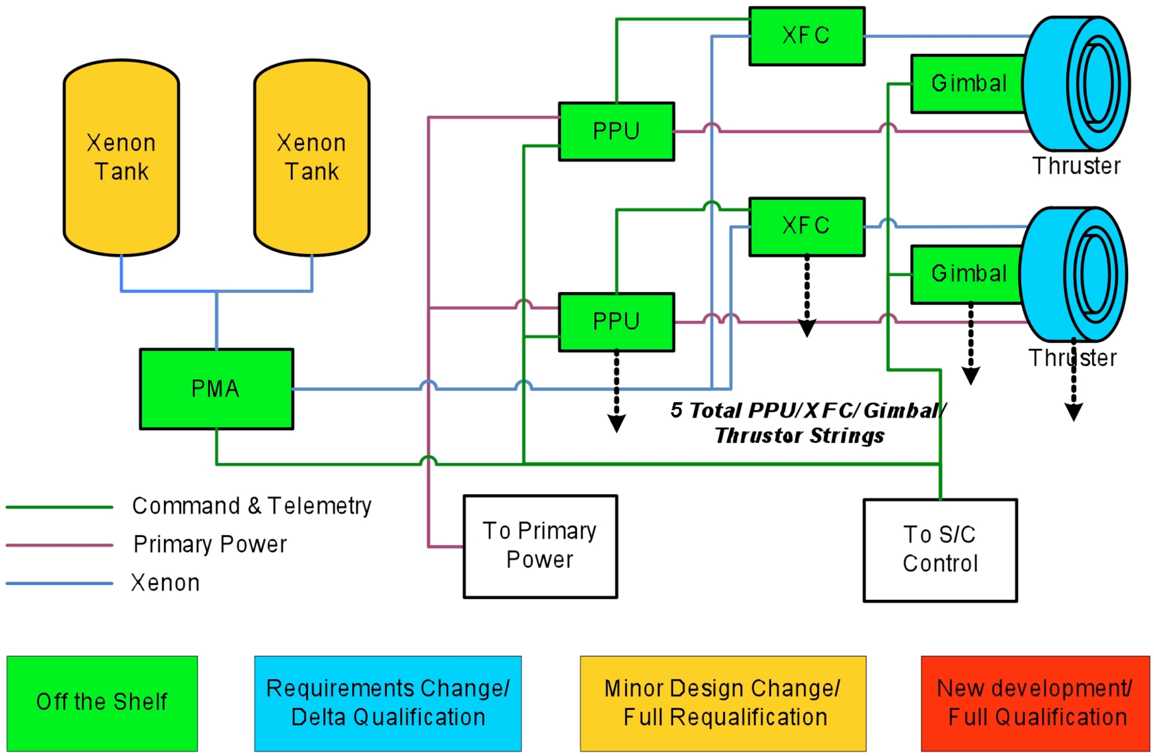

Figure 3: Hall thruster propulsion system (HTPS) block diagram.

The system architecture selected for this study, shown in Figure 3, provides single string thruster, gimbal, xenon flow controller (XFC), and Power Processing Unit (PPU) combinations. This architecture maximizes commonality with commercial systems in order to minimize changes necessary to accommodate NASA science missions. A single upstream propellant management assembly (PMA) allows both the distribution of propellant at low pressures and a simplified interface with the spacecraft electronics. For the very large xenon loads that would be required for this proposed mission, xenon tanks could be manifolded together or a new tank could be developed. The final system used in the analysis below consists of five thruster/XFC/Gimbal/PPU strings, a single PMA, and five xenon tanks. This would correspond to a propellant throughput of 600 kg per thruster for four thrusters over the life of the proposed mission, plus one additional thruster for redundancy.

III. Analysis of Possible Mars Sample Return Mission Architectures using Hall thrusters

The proposed MSR would be an extremely complex multi-element mission, and a detailed analysis of a complete MSR mission architecture is beyond the scope of this paper. This study primarily considers the use of SEP with Hall thrusters for the ERV and discusses the resulting benefits and impacts on the overall mission. A comparative analysis of chemical, Hall, and ion thrusters options is presented in three sections. First, we compare the performance of chemical propulsion, SEP using ion thrusters, and SEP using Hall thrusters on a single leg of the proposed MSR mission. This provides a quick-look at the general transit time tradeoffs associated with these options. Second, we compare the performance of chemical propulsion vs. SEP using Hall thrusters on a specific MSR mission architecture baselining an Atlas 521 launch vehicle and a 2018 launch opportunity. This provides a direct comparison of the mass performance of these two options. Third, results from the 2018 mission comparison are scaled to larger launch vehicles using a previously developed Mars Sample Return mass-tracking tool. This allows us to identify cases in which electric propulsion might enable a single launch MSR mission.

A. Simplified Analysis of Propulsion Options on Earth-Mars Transit Leg

The general tradeoff between flight time and specific impulse is illustrated by comparing trajectories for a single leg of the overall baselined mission: the Earth-Mars transit. Table 2 and Figure 4 compare the transit time for chemical, Hall, and ion propulsion systems on the initial Earth-Mars transit leg. Chemical propulsion missions are limited to ballistic trajectories with launch windows limited by planetary alignment to approximately once every 2.1

years. A 2018 launch opportunity was selected for this comparison, but the flight times are similar for all launch opportunities. Electric propulsion missions use trajectories where constant thrust is applied continuously over a period of several months or years. These missions are less constrained by planetary alignment and can utilize much longer launch windows. The Hall thruster used in this analysis is the BPT-4000 and the ion thrusters used are a modified the NASA Solar Technology Application Readiness (NSTAR) ion thruster and NASA's Evolutionary Xenon Thruster (NEXT) ion thruster. For this comparison, a 2018 launch opportunity was used for the Hall system, a 2007 launch opportunity was used for the modified NSTAR ion system, and a 2013 launch opportunity used for the NEXT ion system. The chemical propulsion system is a high performance bipropellant system. The power level assumed for the trajectories is 20 kW at 1 AU for the Hall system, 30 kW for the NEXT ion system, and 17 kW with the NSTAR system. The launch vehicle is an Atlas 521 for the chemical and Hall options, an Atlas 531 for the NSTAR option, and a Delta IV-Heavy for the NEXT option. In all cases, the spacecraft is assumed to launch directly to Earth departure on a positive C_3 trajectory.

Propulsion Type (Specific Impulse)	Earth to Mars Transit		Transit Time
	Depart	**Arrive**	**(months)**
Chemical (325 sec)	5/10/2018	1/7/2019	8
Hall (1900 sec)	3/20/2018	3/23/2019	12
Ion, NEXT (4100 sec)[6]	July 2013	Jan 2016	18
Ion, NSTAR improved (3800 sec)[7]	1/8/2007	7/26/2009	31

Table 2: One way Earth-Mars Transit times using Chemical and Electric Propulsion (2018 launch opportunity, Atlas 521 launch vehicle, 20 kW at 1 AU)

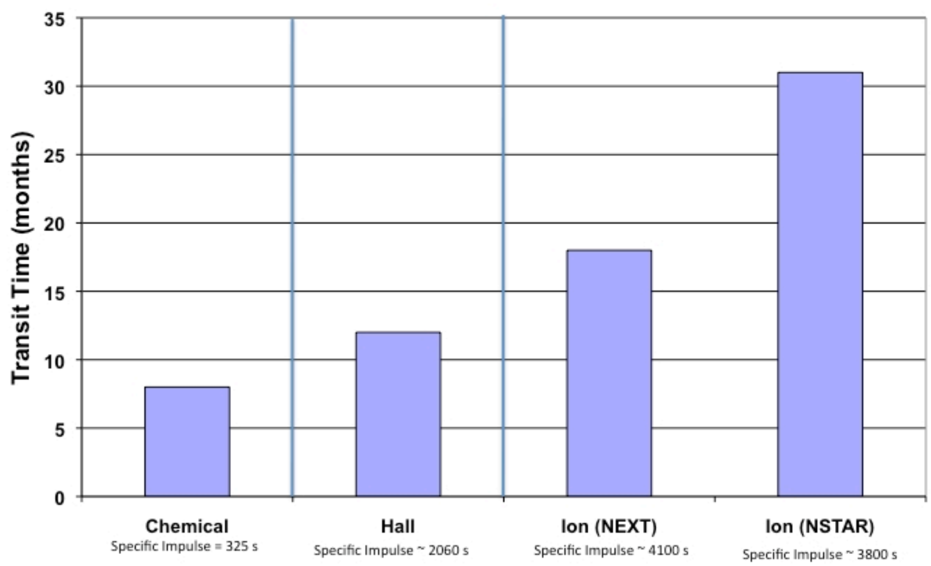

Figure 4: Hall Thrusters Provide An Ideal Combination of High Specific Impulse and Low Transit Time for Earth-Mars Transits

Table 2 and Figure 4 show the trip time tradeoffs for each option. Chemical propulsion provides the shortest trip time, but requires the most propellant because it operates at a specific impulse of only 325 seconds. The ion system operates at a specific impulse over ten times higher, but requires two to four times longer to complete the transit because of the low thrust generated by the system. The Hall thruster system operates at a specific impulse six times higher than chemical, but with only a moderate increase in one-way flight time. This is because the lower specific impulse allows the system to provide more thrust than an ion thruster at a given power level. As we will see in the next section, the specific impulse of the Hall system is high enough to greatly increase delivered payload mass while the thrust is high enough to provide acceptable trip times for this proposed mission.

B. Direct Comparison of an MSR Using Chemical Propulsion vs. an MSR Using SEP with Hall Thrusters

To perform a direct comparison of the mass delivered by these systems, we compare the performance of chemical propulsion vs. SEP with Hall thrusters on a possible MSR mission architecture baselining a 2018 launch opportunity. A representative proposed dual launch MSR architecture utilizing chemical propulsion is used as the baseline mission in this analysis. This architecture is one of several possible options and has following sequence of events. [14]

1) The Orbiter/ERV would be launched on a type II ballistic trajectory to Mars using an Atlas 521 launch vehicle. The spacecraft would be launched directly to an Earth escape trajectory and have a nominal flight time of 10 months.
2) A lander with rover, supported by a cruise stage, would be launched on a type II ballistic trajectory to Mars on an Atlas 511 launch vehicle. This spacecraft would also be launched on an Earth escape trajectory and would be targeted to arrive at about the same time as the Orbiter/ERV.
3) The Orbiter/ERV would use a high performance bipropellant chemical thruster to conduct a Mars Orbit Insertion burn that would place the spacecraft in an elliptical orbit.
4) Aerobraking would be used to circularize the orbit over a 6 month period.
5) The lander would enter the Martian atmosphere using a direct entry trajectory and land on the surface.
6) The rover would collect samples or a sample cache, deliver them to the Mars Ascent Vehicle (MAV), and the MAV would launch the sample canister into a 300 km circular orbit about Mars.
7) The MAV and the Orbiter would rendezvous, transferring the sample canister to the Orbiter/ERV
8) The Orbiter/ERV would use a high performance bipropellant chemical propulsion system to escape Martian orbit and establish an Earth return trajectory.
9) Once in Earth vicinity, the Earth Entry Vehicle (EEV) would be released for direct entry into the Earth's atmosphere.

For comparison, we use a hypothetical dual launch electric propulsion architecture with the following timeline of events for the ERV. Other elements of the architecture remain the same as the baseline case.

1) The Orbiter/ERV would be launched directly to escape velocity using an Atlas 521 launch vehicle, deploy a 20 kW solar array, and proceed to Mars using BPT-4000 Hall thrusters to follow a powered solar electric propulsion (SEP) trajectory
2) The Orbiter/ERV would use SEP to spiral down to low Mars Orbit
3) The MAV and the Orbiter/ERV would rendezvous using a simple monopropellant system for rendezvous maneuvers. The sample canister would be transferred to the Earth Return Vehicle (ERV).
4) The Orbiter/ERV would use SEP to spiral up and reach escape velocity.
5) A powered SEP trajectory would be used to return to Earth vicinity
6) Once in Earth vicinity, the Earth Entry Vehicle (EEV) would be released for direct entry into the Earth's atmosphere.

A 2018 launch opportunity is assumed for both mission variants. The total mass returned to Earth vicinity is calculated using low trajectories optimized using MALTO and includes the assumed mass of the sample, the Earth Entry Vehicle, and the dry mass of the Earth Return Vehicle. The calculated masses are approximate and the overall architecture is un-optimized. No effort was made to identify the optimum flight time or power level for this mission.

As shown in Table 3, the use of Hall thrusters would increase the mass delivered to Earth substantially, by over 900 kg. However, calculating the true net mass benefit requires accounting for mass added by the addition of a 20 kW solar array and an electric propulsion system and mass subtracted by the removal of the chemical bipropellant system. Note that the solar array is sized to generate 20 kW at Earth, but generates much less power at Mars. This effect is modeled as part of the trajectory performance calculations.

Table 4 shows a calculation of the net mass benefit from adding Hall Thrusters to the ERV. The net mass benefit is calculated by removing mass associated with a small solar array, the bipropellant propulsion system (including propellant tanks) and aerobraking mechanisms and adding mass associated with a 20 kW solar array, a monopropellant attitude control system, and a five thruster BPT-4000 Hall thruster system. Mass margin of 30% is included in all of these values.

Atlas 521: ERV Only	Mass (kg)
Chemical - Back to Earth	1160
Hall - Back to Earth	2060
EP System and Solar Arrays	500
Payload Increase	**400 kg**

Table 3: Net Delivered Mass to Earth for Chemical and Hall Thruster missions, 2018 launch opportunity

	Mass (kg)		
Component	**CBE**	**CBE + Contingency**	**Comments**
Elements Removed from ERV			
Cruise Solar Array	-23.9	-31.1	Remove original solar array single wing Ultraflex design (95W/kg)
Aerobraking Panel and Release Mechanism	-8.6	-11.2	No aerobraking required
Bipropellant Chemical Propulsion	-122.7	-152.5	Bipropellant chemical propulsion system dry mass (does not include propellant)
	Total Mass Removed:	**-194.7**	
Elements Added to ERV			
Electric Propulsion System	+352.9	+409.7	5 BPT-4000 thrusters, 5 PPUs, 2345kg Xe at 600kg throughput, 1 redundant, plus margin to accommodate 2 more thrusters
Monoprop ACS Chemical Propulsion	+40.0	+52.0	Chemical propulsion for secondary propulsion
Large Solar Array	+181.8	+236.4	20kW array scaled at 110W/kg
	Total Mass Added:	**+698.1**	
Net change in ERV Dry Mass	+419.5	+503.3	Net mass required to switch from chemical to Hall Thrusters for earth return vehicle
Propellant Mass Saved by Using Electric Propulsion	-904.0	-904.0	Propellant change assuming we still deliver the original ERV mass allocation
Net Mass Available for Additional ERV Payload:	***+484.5***	***+400.7***	Net payload mass benefit from use of electric propulsion

Table 4: Calculation of Net Mass Benefit from use of Hall thrusters on the Earth Return Vehicle (ERV)
CBE = current best estimate. CBE + contingency = current best estimate + contingency mass margin.

Table 4 shows that after accounting for the mass of the electric propulsion system, there is still a very substantial 400 kg increase in the mass available for the ERV's payload. Note that the chemical mission architecture assume aerobraking would be used to increase payload mass while the SEP architecture assumes electric propulsion would be used to spiral up/down in Mars orbit. Aerobraking could also be used with SEP to further increase available payload mass.

Figure 5 compares the mission timeline for the chemical propulsion and SEP with Hall thrusters options. This proposed timeline includes interplanetary transit time, aerobraking time, EP spiral time, and time spent in the science orbit and rendezvous orbit.

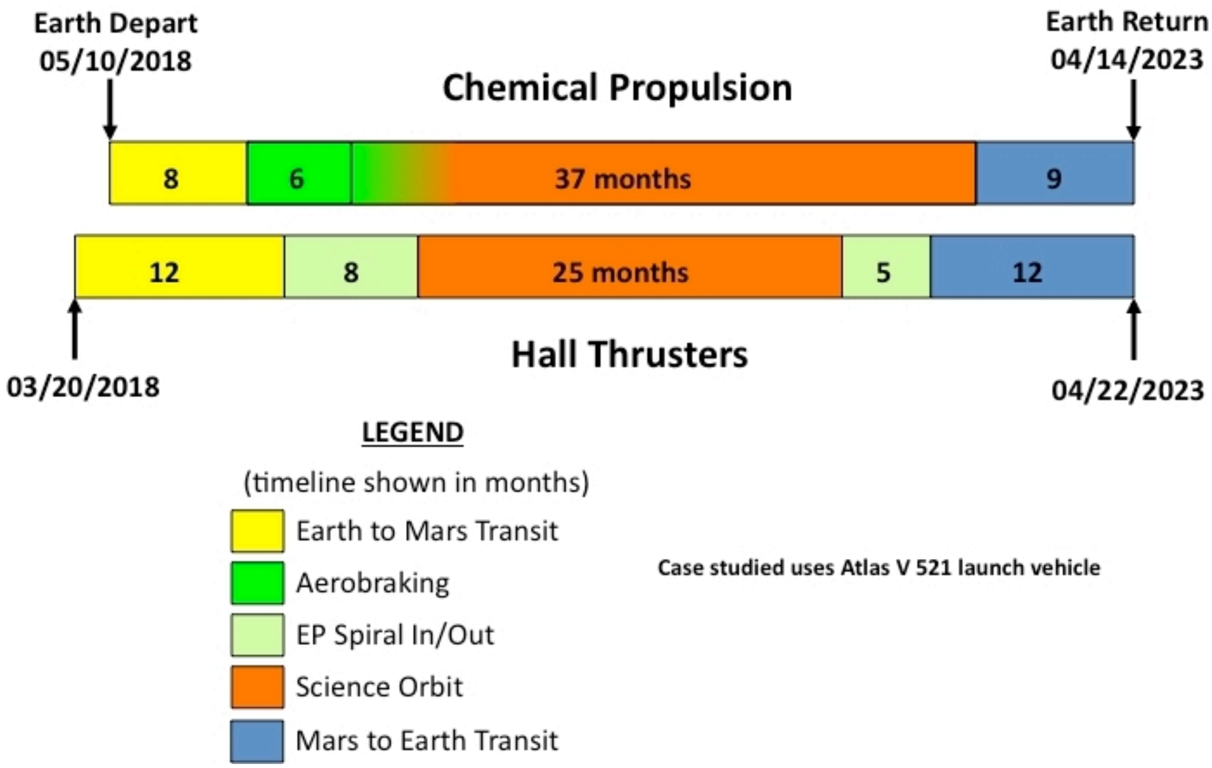

Figure 5: Hall Thruster Mission Timeline is Competitive with Chemical Propulsion for end-to-end Proposed Mars Sample Return Mission (Assumes MSR 2018 Launch Opportunity, 20 kW SEP system)

Figure 5 shows that the overall end-to-end flight time for the Hall thruster option would only be 2 months longer than the chemical option. Although the chemical system would use faster transits, the launch and return windows for the chemical options are limited to fixed dates by planetary alignment. The Hall thrusters would allow the ERV more flexibility in selecting departure and arrival windows, so the mission design could compensate for longer transit times by departing earlier from Mars. Overall, we see that in a one-to-one comparison of chemical and SEP with Hall thruster mission architectures, Hall thrusters would substantially increase the ERV's net delivered mass while maintaining a mission duration similar to that of an all-chemical system. While the increase in delivered mass would be substantial, it is not immediately clear how this extra mass could benefit the overall proposed MSR mission. The greatest potential benefit to the proposed MSR mission would come from using SEP to reduce the total number of launch vehicles from two to one. The next section will examine simple launch options for the proposed MSR mission using electric propulsion.

C. Analysis of Potential Single Launch MSR Architectures using Electric Propulsion

To examine potential single launch options, the delivered masses presented in the previous section are scaled up to a series of larger launch vehicles using an "MSR Mass-tracking Analysis" tool developed in previous work.[15] The feasibility of carrying a lander together with the ERV in a single launch vehicle was examined by limiting the potential mass returned to Earth to a mass allocation sufficient to return an ERV, Earth Entry Vehicle, and sample canister to Earth. The mass allocation was derived from a quasi-grass roots mass budget for an ERV using chemical propulsion originally generated by JPL's Advanced Projects Design Team ("Team X"). The Team X mass budget was modified using the values shown in Table 4 to calculate the dry mass of an ERV using Hall Thrusters. Any available surplus mass would be used to deliver a lander to Mars for dropoff just prior to the spiral down to low Mars orbit. This results in the following proposed single launch MSR architecture using SEP:

1) The Orbiter/ERV and Lander with rover would be launched directly to escape velocity on a single launch vehicle.
2) The Orbiter/ERV and Lander would proceed to Mars together using BPT-4000 Hall thrusters to follow a powered SEP trajectory.

3) As the Orbiter/ERV would arrive at Mars with an approach C3 ~ 0 km^2/s^2, the lander would be released and enter the Martian atmosphere on a direct entry trajectory.
4) The Orbiter/ERV would use SEP to spiral down to low Mars Orbit.
5) Optional step: the Orbiter/ERV would use aerobraking to supplement the SEP spiral down and establish a 300 km circular orbit.
6) The rover would collect a sample or sample cache, return it to the MAV, and the MAV would launch it into a 300 km circular orbit about Mars.
7) The MAV and the Orbiter would rendezvous, transferring the sample to the ERV
8) The Orbiter/ERV would use SEP to spiral up and reach escape velocity
9) A powered SEP trajectory would be used to return to Earth vicinity
10) Once in Earth vicinity, the Earth Entry Vehicle (EEV) would be released for direct entry into the Earth's atmosphere.

The results generated by applying this architecture to the proposed MSR with Hall thrusters are summarized in Table 5.

	Total Mass Returned to Earth* (kg)	Dropoff Entry System Mass at Mars (kg)
Calculated Delivery Capability, ERV using Hall Thrusters		
Atlas V 521		
Single Launch (ERV+Lander) no Aerobraking	1300	1270
Single Launch (ERV+Lander) w/Aerobraking	1300	1585
Atlas V 551		
Single Launch (ERV+Lander) no Aerobraking	1300	2638
Single Launch (ERV+Lander) w/Aerobraking	1300	***2953****
Delta IV-Heavy		
Single Launch (ERV+Lander) no Aerobraking	1600	***4407****
Single Launch (ERV+Lander)w/Aerobraking	1600	***4794****
Reference Masses		
MSR Earth Return Vehicle with Chemical Propulsion and Aerobraking (Team X estimate)	802	
MSR Lander with Fetch Rover (Team X estimate)	802	2830
MSL Mass at Mars Entry (Planned)		3400

* Viable launch options for single launch MSR architecture

Table 5: MSR Earth Return Mass and Lander Entry Mass Estimates for SEP using Hall Thrusters

The top half of Table 5 shows the initial entry mass ("drop off mass") that could be delivered to Mars by the proposed single launch MSR architecture using SEP with Hall thrusters. Both cases that would use SEP-only for the spiral down at Mars and cases that combine SEP + aerobraking for the Mars approach are shown in the table. The bottom half of Table 5 shows estimated masses for an all chemical ERV and an MSR lander with fetch rover as generated by "Team X". Table 5 also shows a recent estimate of the entry mass of the Mars Science Laboratory, the largest system that can be landed on Mars using currently available EDL technologies.[16]

The results show that there are a number of launch options that could potentially support a single launch MSR architecture. The Atlas V 551 with aerobraking could support the 2830 kg entry system mass estimated by "Team X" with approximately 100 kg of margin. The Delta IV-Heavy options could support much larger entry systems, including an MSL class vehicle, with over a metric ton of mass margin. Note that the margins listed in this paragraph are in addition to substantial contingency mass margins already included in the reference mass estimates shown in Table 5.

It should be noted that the increased launch mass associated with use of a Delta IV Heavy would lower the initial thrust to mass ratio of the ERV, resulting in longer trip times on the initial Earth to Mars transit. This could be compensated for by increasing the size of the solar array, or by allowing the overall trip time to increase. The transit time on the other legs of the proposed mission (SEP spiral down/up and Mars to Earth transit) would be unaffected by the mass increase, as the lander would be released prior to the initial spiral down maneuver.

In summary, we find that the use of SEP with Hall Thrusters for the ERV might be enabling for a single launch MSR architecture in which the Orbiter/ERV and the landed elements would be carried on a single launch vehicle. As in the previous section, the calculated masses are approximate and the overall architecture is un-optimized. Further work is needed to establish the viability of the full MSR architecture.

D. Risks and Benefits of Electric Propulsion for MSR Architecture

In addition to the mass benefits discussed above, the use of electric propulsion for the proposed MSR mission has the potential to benefit the overall architecture in a variety of different ways.

- The use of low thrust would mitigate some MSR mission risks by eliminating up to three time-critical maneuvers present in the chemical mission plan: the Mars orbit insertion, the trans-Earth injection, and the aerobraking maneuver sequence.
- The use of low thrust would provide flexibility in the selection of launch and return windows for the interplanetary legs of the missions when compared to chemical propulsion, and would lower the impact of missing the launch or return dates originally planned for the mission.
- SEP trajectories could be designed to lower the arrival V-infinity at Earth, reducing the risk and/or mass of the heat shield on the Earth Entry Vehicle
- SEP trajectories could be designed to lower the arrival V-infinity at Mars, reducing the risk and/or mass of the heat shield on the Mars lander.
- Hall thrusters on the ERV could provide high ΔV for maneuvering at Mars. This would give the ERV flexibility to maneuver through substantial altitude and plane changes to rendezvous with the MAV and could allow the use of an unguided MAV for the Mars ascent. This in turn would help minimize the landed mass on Mars. The use of lower rendezvous orbits for the orbiting sample could further reduce the mass of the MAV with relatively little penalty to the mass of the ERV.
- The 20 kW solar arrays used in this analysis would provide a large drag area that might reduce aerobraking time compared to chemical architectures.

At the same time, the use of electric propulsion for the proposed MSR mission has the potential to add some risk to the overall mission.

- The need to release the lander at an approach $C_3 \sim 0$ km^2/s^2 might affect landing accuracy.
- The flexibility of large solar arrays might affect guidance accuracy when approaching and capturing the sample
- The overall complexity of the propulsion system would be increased by the use of electric propulsion, though this risk would be partially offset by the replacing the bipropellant chemical system with a much simpler monopropellant chemical system for attitude control only.

Further work is needed to understand and quantify these risks and determine the overall risk-benefit trade for the end-to-end proposed MSR mission architecture.

IV. Conclusions

Concept architectures for the proposed MSR mission have long relied on chemical propulsion to provide the ΔV necessary to accomplish this challenging mission. Recently proposed MSR architectures are complex and expensive, requiring multiple launch vehicles to return a single sample to Earth. In this study, we consider the use of Solar Electric Propulsion (SEP) with space qualified, off-the-shelf commercial Hall thrusters to provide a simplified MSR mission architecture. Unlike previous studies of SEP systems based on ion thrusters, Hall thrusters would provide sufficient thrust to allow total trip times comparable to all-chemical missions. At the same time, Hall thrusters would reduce propellant mass sufficiently to potentially allow the use of a single launch vehicle to carry both the Orbiter/ERV and the lander for the proposed MSR mission. Overall, we have shown that:

1) Hall thrusters would provide for overall MSR mission durations that would be competitive with chemical propulsion

2) With an un-optimized dual launch MSR architecture, the use of a 20 kW Hall Thruster system could increase the net payload mass returned to Earth (as compared to launch on an Atlas 521) by ~400 kg

3) With an un-optimized single launch MSR architecture, the use of Hall Thrusters might enable the use of a single launch vehicle (Atlas 551 or Delta IV-Heavy) to carry both the lander and the Orbiter/ERV

4) Using Hall thrusters for primary propulsion, a Delta-4 Heavy vehicle could potentially carry an Orbiter/ERV plus a landed system with an entry mass equal to that of the Mars Science Laboratory (MSL) on an MSR mission. MSL is the largest mass we can land on Mars using existing technologies.

This study has shown that solar electric propulsion with Hall Thrusters is a potentially viable candidate for primary propulsion on a potential Mars Sample Return mission. Hall thrusters are an off-the-shelf technology that would potentially be enabling for a single launch MSR architecture. Higher fidelity studies are recommended to demonstrate the full viability of this technology for potential MSR missions.

Acknowledgments

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

We would like to thank Joe Cassady and Fred Wilson at the Aerojet corporation for providing Figure 1, and Kristi de Grys at the Aerojet corporation for her help providing information on the BPT-4000 Hall effect thruster.

References

[1] Mattingly, R. "The Many Faces of the Mars Sample Return Mission Architecture," AAS-05-066, 27th Annual AAS Guidance and Control Conference, February 2005.

[2] Mattingly, R., Matousek, S., and Jordan, F. "Continuing Evolution of Mars Sample Return," IEEEAC paper #1238, *2004 IEEE Aerospace Conference, March 2004*, Paper #1392.

[3] Pidgeon, D., Corey, R., Sauer, B. "Two Years of On-Orbit Performance of SPT-100 Electric Propulsion," AIAA 2006-5353, 24th AIAA International Communications Satellite Systems Conference (ICSSC), June 2006, San Diego, CA.

[4] Goebel, D., Martinez-Lavin, M., Bond, T. and King, A. "Performance of XIPS Electric Propulsion in On-Orbit Stationkeeping of the Boeing 702 Spacecraft," AIAA-2002-4348, 38th Joint Propulsion Conference and Exhibit, Indianapolis, Indiana, July 2002.

[5] V. Khayms, L. Werthman, K. Kannenberg, S. Hu, B. Emgushov, J. W. Meyer, "Status of Hall Thruster Integration Activities at Lockheed Martin Space Systems Company", AIAA-20-03-5261, 39th Joint Propulsion Conference, Huntsville, Alabama, July 2003.

[6] Brophy, J. R. and Rodgers, D. H., "Ion Propulsion for a Mars Sample Return Mission," AIAA Paper 2000-3412, July 2000.

[7] Oh, D. Y., Benson, S. W., Witzberger, K., and Cupples, M., "Deep Space Mission Applications for NEXT: NASA's Evolutionary Xenon Thruster," AIAA Paper 2004-3806, July 2004.

[8] Donahue, B. B., Green, S. E., Coverstone, V. L., and Woo, B., "Chemical and Solar-Electric-Propulsion Systems Analyses for Mars Sample Return Missions," Journal of Spacecraft and Rockets 43, 1, 170 (2006).

[9] http://spacefellowship.com/2009/06/17/lockheed-martin-begins-critical-environmental-test-of-first-advanced-ehf-military-communications-satellite/

[10] Figure credit: Aerojet corporation.

[11] Hofer, R. R., Randolph, T. M., Oh, D. Y., Snyder, J. S., and De Grys, K. H., "Evaluation of a 4.5 kW Commercial Hall Thruster System for NASA Science Missions," AIAA Paper 2006-4469, July 2006.

[12] Randolph, T. M., "Qualification of Commercial Electric Propulsion Systems for Deep Space Missions," Presented at the 30th International Electric Propulsion Conference, IEPC Paper 2007-271, Florence, Italy, Sept. 17-20, 2007.

[13] Hofer, R. R., Mikellides, I. G., Katz, I., and Goebel, D. M., "BPT-4000 Hall Thruster Discharge Chamber Erosion Model Comparison with Qualification Life Test Data," Presented at the 30th International Electric Propulsion Conference, IEPC Paper 2007-267, Florence, Italy, Sept. 17-20, 2007.

[14] JPL Advanced Projects Design Team report "MSR Fetch Rover II Pinpoint Lander 2004-09," Team X report #742.

[15] Oh, D., Easter, R., Heeg, C., Sturm, E., Wilson, T., Woolley, R. and Rapp, D. "An Analytical Tool for Tracking and Visualizing the Transfer of Mass at each Stage of Complex Missions," AIAA-2006-7254, Space 2006, San Jose, CA, September 2006.

[16] Braun, R. and Manning, R., "Mars Exploration Entry, Descent, and Landing Challenges," 2006 IEEE Aerospace Conference, IEEEAC paper #0076, Big Sky, Montana, March 2006.