In-Flight Propulsion System Characterization for Both Mars Exploration Rover Spacecraft

Todd J. Barber* and Frank Q. Picha†
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

Two Mars Exploration Rover spacecraft were dispensed to red planet in 2003, culminating in a phenomenally successful prime science mission. Twin cruise stage propulsion systems were developed in record time, largely through heritage with Mars Pathfinder. As expected, consumable usage was minimal during the short seven-month cruise for both spacecraft. Propellant usage models based on pressure and temperature agreed with throughput models within a few percent. Trajectory correction maneuver performance was nominal, allowing the cancellation of near-Mars maneuvers. Spin thruster delivered impulse was 10-12% high vs. ground-based models for the initial spin-down maneuvers, while turn performance was XX-XX% high/low vs. expectations. No clear indications for pressure transducer drift were noted during the brief MER missions.

I. Introduction

TAKING advantage of the closest Earth-Mars approach in nearly sixty millennia, twin Mars Exploration Rovers with their attached cruise stages set forth for the red planet in the late Spring of 2003. The MER mission was conceived as a scientifically ambitious follow-up to the highly successful Mars Pathfinder mission, which was largely an engineering demonstration for low-cost planetary landing techniques. The double failures of the 1999 Mars Climate Orbiter (MCO) and Mars Polar Lander (MPL) missions led to a revamping of the entire robotic Mars exploration program. One casualty of this change in direction was the Mars lander scheduled for a 2001 launch. Fittingly, this hardware has "risen from the ashes" as the backbone of the recently selected Phoenix mission, a Mars Scout mission planned for 2007. Another consequence of redirection was an extremely compressed (34-month) development schedule to exploit a superb Earth-Mars opportunity in 2003. Despite the woefully inadequate available timetable, the MER mission (with two cruise stages and two rovers) was successfully conceived, developed, built, tested, and launched to Mars between 2000-2003.[1] The MER propulsion system was a JPL in-house effort, and the propulsion team was led by Barry Nakazono of the Propulsion Flight Systems Group.

Each MER cruise stage successfully traversed 300 million miles of interplanetary space in the seven months before the twin January, 2004 landings of the Spirit (MER-A) and Opportunity (MER-B) rovers on opposite sides of the red planet. Just before atmospheric entry, the landed package was jettisoned from each cruise stage in preparation for Entry, Descent, and Landing (EDL). Both MER cruise stages were subsequently destroyed in the Martian atmosphere, having served their purpose in ferrying a rich scientific payload for *in situ* exploration of the diverse Martian surface. The EDL design borrowed heavily from Mars Pathfinder, including a Viking-derived heat shield and backshell, a supersonic parachute, a protective cocoon of airbags, and solid rocket motors to limit the vertical and horizontal impact speeds upon touchdown.

The MER landing sites were selected as part of NASA's "follow the water" strategy for Mars exploration. Spirit touched down successfully on January 4, 2004 (UTC) within Gusev Crater, likely the site of a former Martian lake, given an inflow channel readily seen from low-Mars orbit. Three weeks later, Opportunity scored an interplanetary "hole-in-one" by bouncing and rolling to a stop within diminutive Eagle Crater on the flat expanse of Meridiani Planum. The MER-B landing site was selected because the plains of Meridiani boast an Oklahoma-sized signature of hematite, a mineral that nearly always forms in liquid water on Earth.

Following each EDL and the successful egress of Spirit and Opportunity from their airbag-encased landing platforms, the twin rovers prepared for 90-sol (~92-Earth-day) primary missions of unbridled exploration.[2] An unfortunate computer-memory resource issue sidelined Spirit for a few weeks, coincidentally right around the time of the Opportunity landing. This temporary setback has done little to hamper Spirit's progress; as of April 5, 2004,

* Member, Technical Staff, 4800 Oak Grove Dr. MS 230-104, Pasadena, CA, 91109
† Member, Technical Staff, 4800 Oak Grove Dr. MS 179-205, Pasadena, CA, 91109

all Spirit mission success criteria have been met, including the daunting challenge of traversing at least 600 meters (1968.5 feet) on the Martian surface. The proof of Gusev Crater's watery past is proving to be much more elusive, even with a view into Bonneville Crater, a naturally provided excavation of Gusev's past a mere few hundred meters from the Spirit landing site. The Spirit extended mission is proceeding as planned, including extended drives towards the Columbia Hills over a mile to the southeast of Bonneville Crater. These seven peaks, named in honor of the STS-107 crew, may show layering consistent with an ancient aqueous environment.

The water history at the MER-B landing site has been much easier to decipher, thanks to a fortuitous landing within a few meters of bedrock, the first discovered on Mars. In fact, Opportunity has spent over half of its primary mission within the narrow confines of Eagle Crater, teasing out the liquid water history of this region. The rover instrument suite has worked beautifully, teaming up to untangle the geologic history of this site. The scientific consensus is the bedrock in Eagle Crater was set down in a gently undulating, surface-water environment. This has enormous implications for exobiology, the 2009 Mars Science Laboratory landing site selection, and the impetus for a Mars Sample Return mission. Opportunity has begun to explore the immense plains of Meridiani Planum, with a near-term goal of seeking layered bedrock in nearby Endurance Crater. The prospects for lengthy extended missions for both Spirit and Opportunity remain excellent, thanks to ample thermal and power margins, lower-than-expected dust accumulation on the solar panels, and recently approved funding. Public interest in the MER mission has been nothing short of phenomenal; in the few months since landing, NASA has logged over ten billion web hits. This is an order of magnitude larger than the number of hits recorded in all of 2003 by any government agency, including NASA.

II. The Spacecraft

Each MER spacecraft consists of four separate elements, all of which must work in concert for mission success. The rover is encased within a lander, though unlike Mars Pathfinder, the MER landers have no science function on the Martian surface. The lander and rover are attached to the Entry, Descent, and Landing (EDL) system for Spirit and Opportunity. Finally, the EDL, lander, and rover package is ferried to Mars with an attached propulsive cruise stage. The MER cruise stage is quite similar to the Mars Pathfinder design, much more so than the other three spacecraft elements.

The MER rover was designed to be a fully capable robotic geologist on the surface of the red planet, building on the success of Sojourner. At 174 kg (384 pounds) and a length of 1.6 meters (5.2 feet), Spirit and Opportunity dwarf their diminutive predecessor. The core structure consists of a composite honeycomb warm electronic box lined with aerogel for thermal insulation. Three antennas and nine cameras adorn each MER rover, along with 1.3 m^2 (14 ft^2) of top-mounted solar panels. These arrays produce around 900 Watt-hours of energy at the beginning of the MER landed mission, though dust accumulation on the solar panels reduces the available power significantly during the mission. Two lithium ion batteries are charged for supplementary power, using excess energy from the solar arrays. The six-wheeled rocker-bogie suspension system is analogous to Sojourner, allowing the rovers to tilt up to 45° without toppling. Spirit and Opportunity have some autonomous driving capability, using on-board navigation software and hazard-avoidance logic. In the best of circumstances, the maximum rover traverse speed is about 5 cm/s (2 in/s). The geological "heart" of each MER rover is the Instrument Deployment Device (IDD), or instrument arm. The IDD contains four "fingers" mounted at right angles to one another: a Mössbauer spectrometer, Alpha Proton X-Ray Spectrometer (APXS), Microscopic Imager (MI), and Rock Abrasion Tool (RAT). These high-tech equivalents to the geologist's hammer and hand lens have already rewritten the textbooks of Martian science. Figure 1 is a line drawing of the MER rover.

The lander primarily consists of four triangular, graphite-epoxy composite petals, three of which are hinged on the fourth base petal. When folded in its launch through landing configuration, it forms a tetrahedron essentially identical (in size and shape) to the Mars Pathfinder lander. Its duties during EDL and egress include EDL communications, deploying airbags, radar altimetry of the Martian surface, righting the rover if the package does not land base-petal down, and airbag retraction.

The EDL system design borrowed heavily from Mars Pathfinder experience, but the 50% increase in landed mass for MER led to a large redesign and qualification effort. Largely, the EDL package consists of a two-part aeroshell (forward-facing heat shield and rear-facing backshell), a supersonic parachute, tether/bridle, airbags, and solid rocket motors to reduce vertical and horizontal impact speeds to manageable levels. All EDL hardware had legacy with NASA's Viking mission of the mid 1970's or the Mars Pathfinder mission of 1997. The 15-m (49-ft) diameter parachute initially failed during Earth-drop tests, due to excessive loads. In addition, parachute "squidding" (a failure of the parachute bell to properly inflate) was noted during tests in the world's largest wind

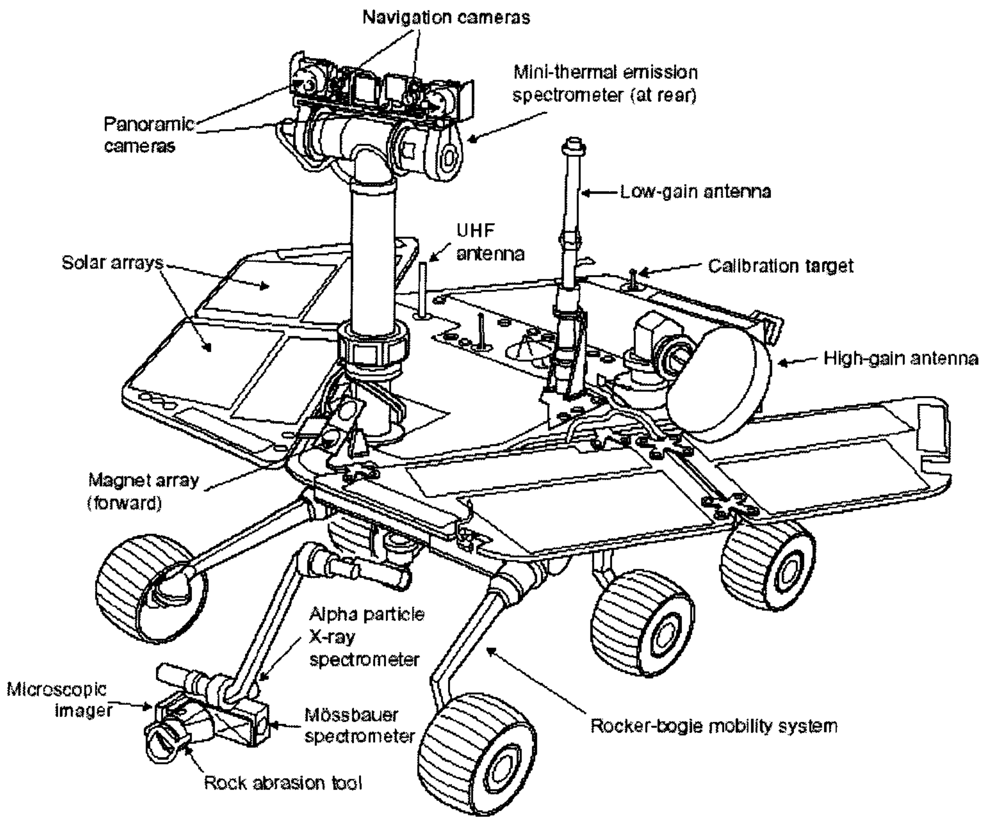

Figure 1: Mars Exploration Rover

tunnel, at NASA Ames near Mountain View, California. These snafus were identified and overcome, thanks to a rigorous testing program before launch, leading to parachute redesign.

As with Mars Pathfinder, the backshell contains an accelerometer, used to select the proper time for parachute deployment. Updates were made to the deceleration level for parachute deployment in the last few days before EDL, based on assessments of Martian atmospheric density from the orbiting Mars Odyssey and Mars Global Surveyor spacecraft. The final impact speed of the landed package was reduced using three solid rocket motors provided by ATK, also mounted to the backshell. The solid Rocket Assisted Descent (RAD) motors were essential for a safe landing, reducing the vertical impact speed from about 85 m/s (nearly 200 mph) to a much more palatable 10 m/s (22 mph). The MER mid-afternoon landings (with associated Martian winds) necessitated horizontal impact speed mitigation as well. This was not required for Mars Pathfinder, which touched down around 3 am local Mars time. Therefore, a new development effort was undertaken to combat excessive horizontal touchdown velocities. A Transverse Impulse Rocket System (TIRS) was designed for MER, consisting of three solid rocket motors, each pointed 120° to its two neighbors. On-board inertial measurements determined the optimal firing configuration (with one or two rockets allowed to fire) for each EDL package during final approach. Spirit's successful landing necessitated the use of TIRS, thanks to an inopportune wind gust within 150 meters (500 feet) of the ground inside Gusev Crater, while the comparatively benign Opportunity landing on Meridiani Planum required only RAD firings.

The MER airbags, based heavily on Mars Pathfinder experience, offered the final protection against the blow of impacting the surface. Each side of the lander tetrahedron was equipped with a collection of six airbags stitched together. Internal airbag pressure was provided by explosive gas generators, with internal pressures of about 6900 Pa (roughly 1 psia). Comprised of double bladders and six layers of Vectran, the MER airbags were considerably strengthened vs. Pathfinder, largely due to test failures in the world's largest vacuum chamber in Ohio. Vectran is a synthetic fiber, five times stronger than steel, and it has found extensive use in the sporting goods industry in the strings of tennis racquets and archery bows. It is roughly twice as strong as a similar but more familiar fabric, Kevlar, and it offers better low temperature characteristics. EDL is often referred to as "six minutes of terror," as elucidated in Figure 2. Many dozens of pyrotechnic devices had to fire perfectly within this brief window of intense activity. Otherwise, the mission would have been unsuccessful, a new member of Mars' interplanetary graveyard.

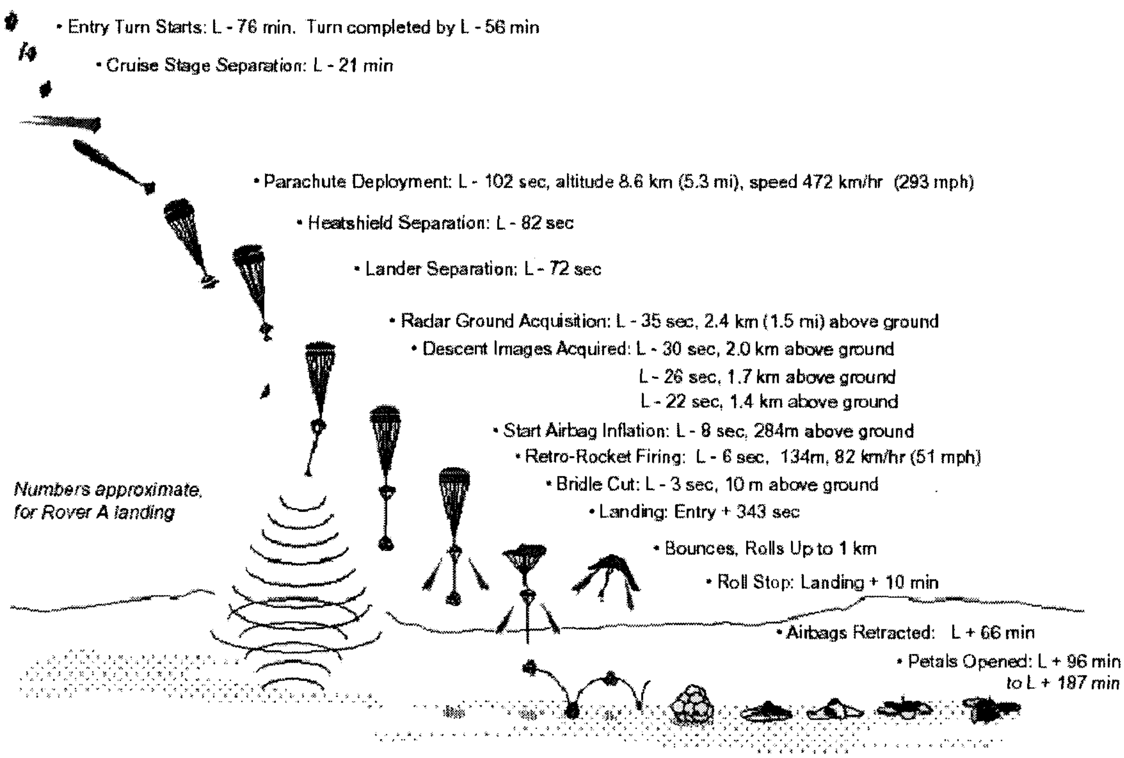

Figure 2: Entry, Descent, and Landing (EDL) Timeline

The cruise stages for Spirit and Opportunity resemble the Mars Pathfinder cruise stage very closely. They provided all vehicle functions for the seven-month, 300-million-mile cruise to Mars, including telecommunication, thermal control, attitude control, and propulsion. Each cruise stage approximates a cylinder about 2.6 m (8.5 ft) in diameter and 1.6 m (5.2 ft) tall. The top face of the cruise stage is dominated by solar arrays and antennas for communication with Earth, while the bottom face attaches to the aeroshell. The circumference of each cruise stage includes a star scanner, sun sensor, and a Heat Rejection System (HRS), which transfers excess rover computer heat to rim-mounted radiators through a pumped freon loop.[3] In addition, each cruise stage includes two titanium hydrazine tanks and eight 4.5-N (1.0-lb_f) thrusters, along with peripheral propulsion hardware. The cruise stage propulsion systems will be described in greater detail in the next section. Figure 3 is an exploded view of the entire MER flight system, including cruise stage, backshell, rover and lander, and heat shield. The Spirit and Opportunity heliocentric trajectories are represented in Figs. 4 and 5, respectively. Both paths from Earth to Mars were standard Type I trajectories; as mentioned above, the proximity of Mars during 2003's opposition made this launch window particularly favorable.

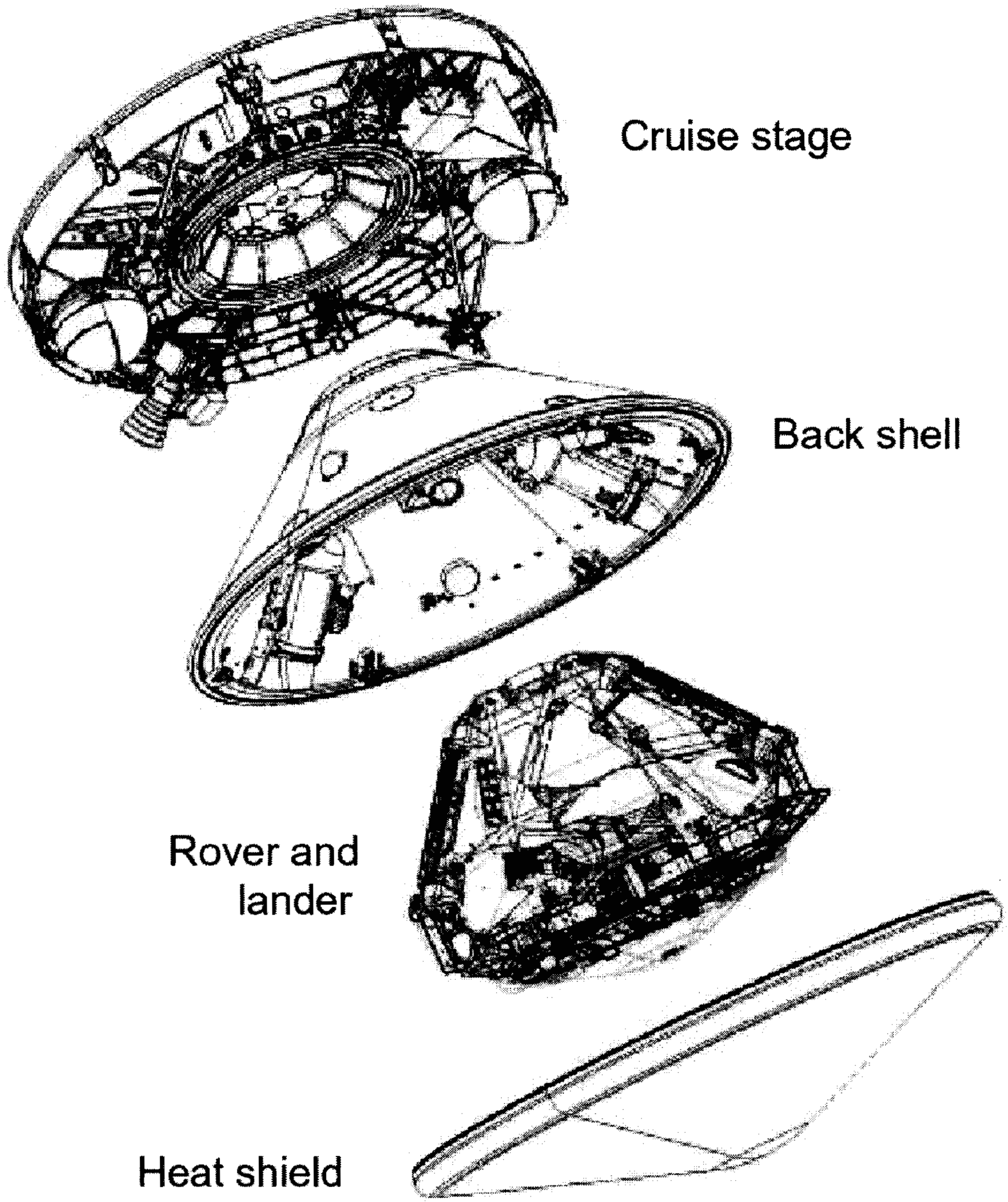

Figure 3: MER Spacecraft Flight Configuration (Exploded View)

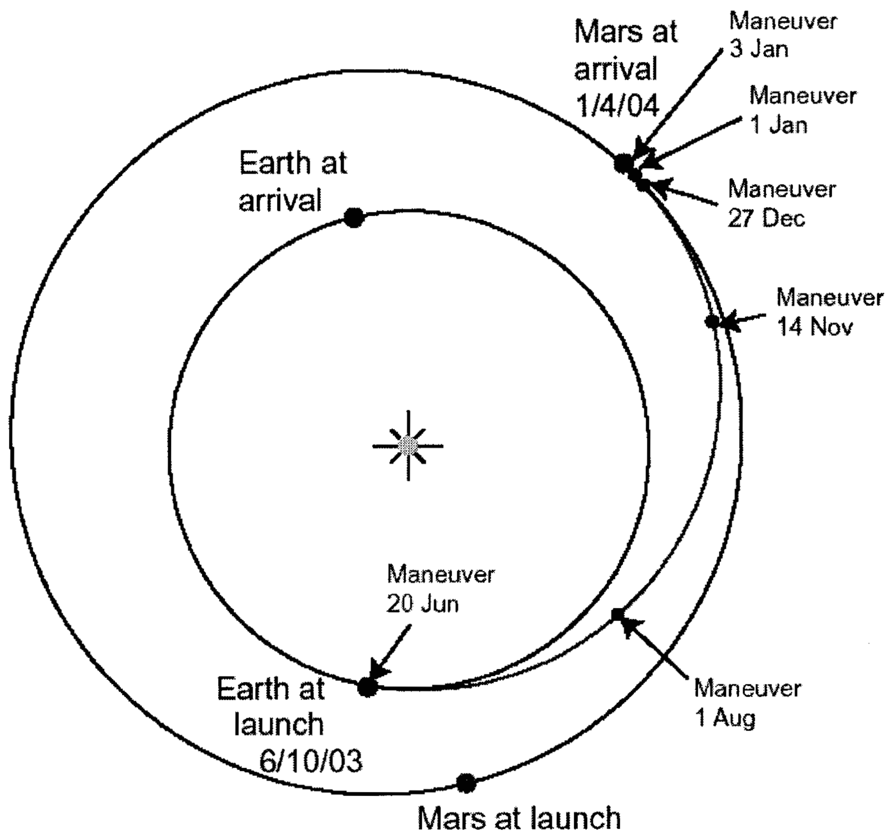

Figure 4: Spirit (MER-A) Heliocentric Trajectory

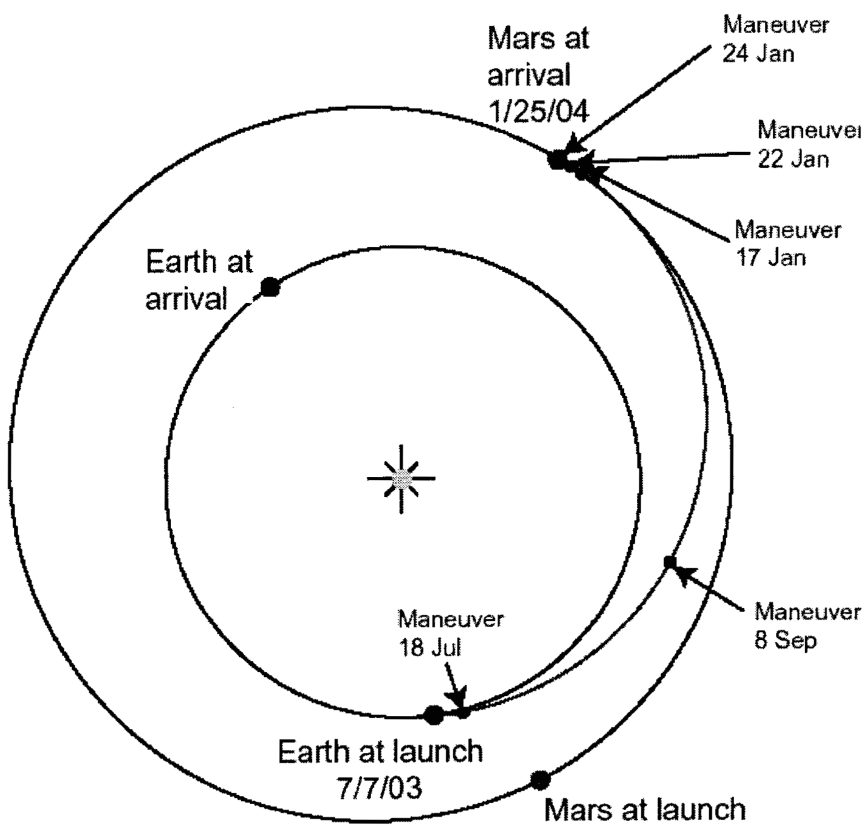

Figure 5: Opportunity (MER-B) Heliocentric Trajectory

III. Cruise Stage Propulsion System

The MER propulsion systems consist of a simple, monopropellant, blow-down system based on successful Mars Pathfinder (MPF) flight heritage. The design was simplified from MPF by reducing the number of propellant tanks from four to two, thereby reducing associated valves and tubing. A line drawing of the propulsion subsystem is displayed in Figure 6. The spacecraft was spin stabilized, allowing attitude control maintenance with a mere eight thrusters in two clusters of four. In typical two-cluster operation, all maneuvers are executed in coupled pairs, thereby imparting no axial or lateral delta-V. An interesting feature of the MER propulsion system is that it could perform its functions after single failures, unlike most other MER spacecraft subsystems. The thrusters, catalyst bed heaters, tank pressure transducers, and latch valves were all redundant. Each cluster had an associated latch valve. The attitude control software, fault protection software, and wiring were arranged so that all propulsion functions could still be performed in a degraded fashion by one thruster cluster. This would have been required, for example, after one cluster was isolated because of a malfunctioning thruster or a failed-closed latch valve. Naturally, a maneuver performed with a single cluster no longer has the benefits of coupled-pair thruster firing.

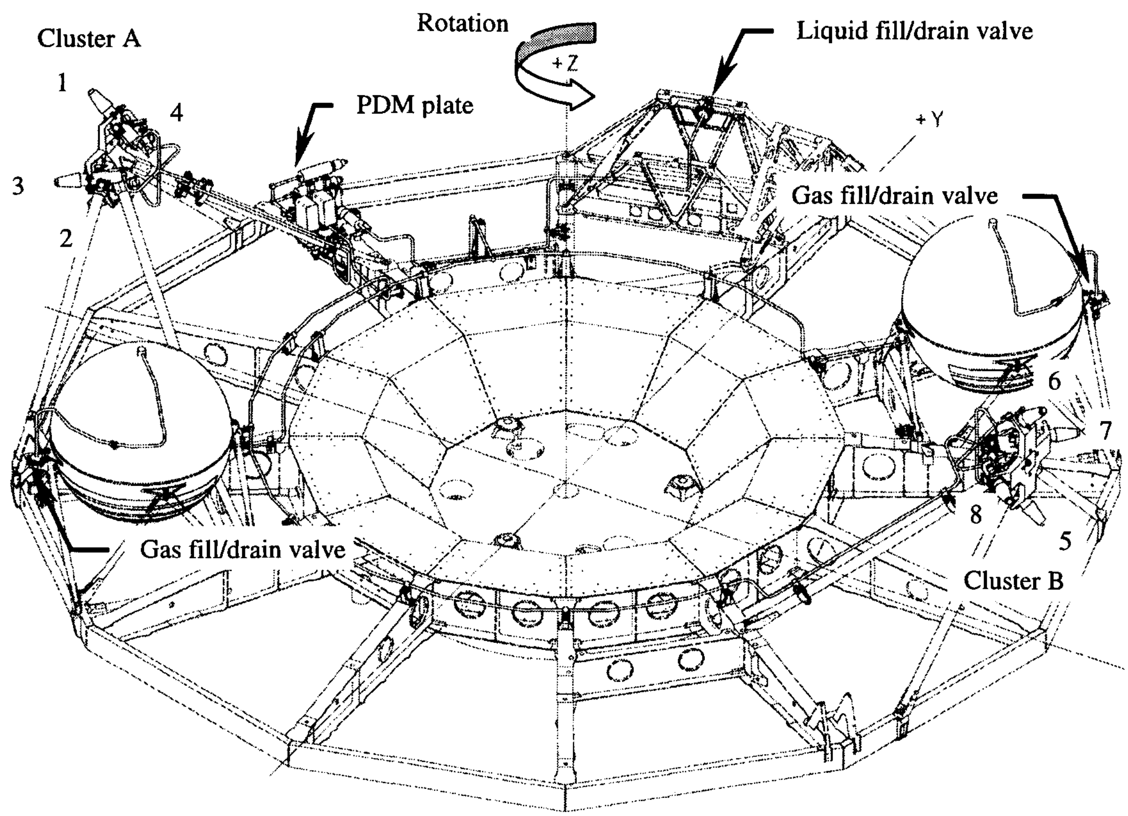

Figure 6: MER Cruise Stage Propulsion Subsystem Line Drawing

Each cruise stage propulsion subsystem included two 0.42-m (16.5-in) diameter spherical, skirt-mounted, 6Al-4V titanium-wall propellant tanks, with an AF-E-332 elastomeric diaphragm positive-expulsion device. Helium was utilized for the pressurant gas, at an initial pressure of 392 psia. Dual-mechanical-seal gas service valves capture the pressurant within each propellant tank. The tank exit ports were connected together through the propellant manifold, feeding into the Propellant Distribution Module (or PDM) plate. The entire propellant manifold consisted of all-welded construction using 6.35-mm (0.25-in) diameter 304L, 316L, and 347 stainless steel tubing. Integral to the PDM plate was a 10-micron absolute propellant filter, redundant pressure transducers, and single-seat, torque motor latch valves separating each cluster branch. The clusters contained four 4.5-N (1.0-lb_f) Rocket Engine

Assemblies (REAs) pointed along either the ±X or ±Y axis. Both cluster mounting brackets cant the REAs at a 40-degree angle measured from normal to the ±X axis. The cruise stage (and spacecraft) axes are defined in Figure 3. Each REA has two mechanically separate, normally closed, propellant valve seats in series to provide fault tolerance against leakage. A MER cruise stage propulsion schematic is included as Figure 7.

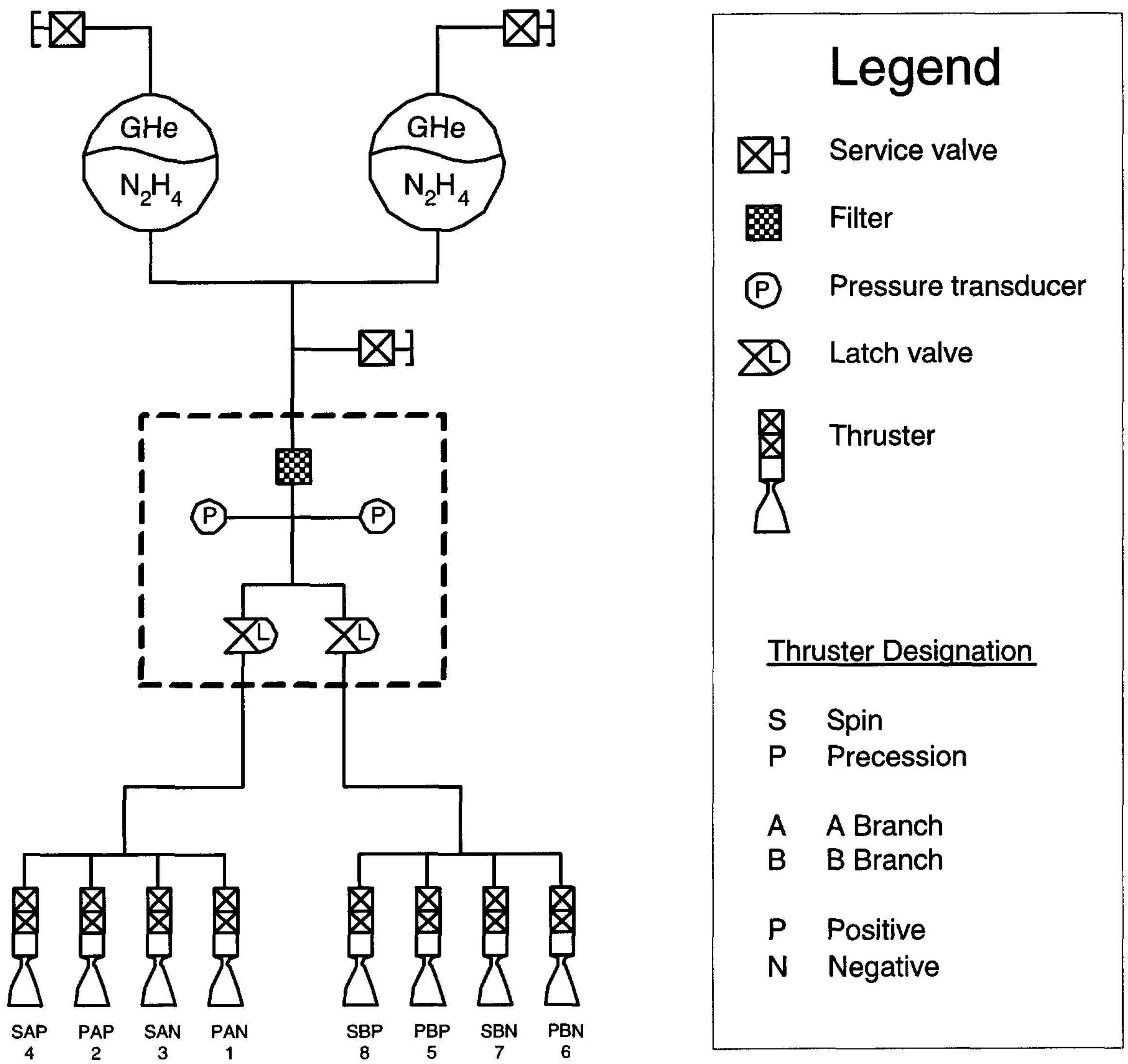

Figure 7: MER Cruise Stage Propulsion Subsystem Schematic

Thermal control for thruster valves, the PDM plate, and tanks was provided using primary and redundant thermostatically controlled heaters, without using software control. The propellant lines were separated into six zones containing redundant heaters, utilizing software control. Software-controlled line heaters turned out to be a blessing for both MER-A and MER-B. The control transducer for zone two was placed on a portion of propellant line with flowing propellant, though it also maintained the temperature on the dead-end portion of the fill line. During TCM-A1, the line temperature spiked in the "dead" line as the control tried to heat the flowing propellant from the tanks, which ran 10°C cooler. Although no flight rules were violated, and the temperature never exceeded

70°C (well below the detonation temperature of hydrazine under these conditions), the software setpoints were changed in that zone for all subsequent propulsion activities.

Catalyst bed heaters for each thruster were redundant as well on MER. There were two heaters on each thruster wired in parallel; both were powered on ninety minutes before any thruster activity. Either heater could raise the catalyst bed temperature to a safe operating level. The thruster temperatures were observed during each in-flight propulsive event, and there were no catalyst bed heater failures. It also turned out the thrusters remained warm enough without their catalyst bed heaters on such that they probably would have survived cold starts. The complete list of propulsion hardware, suppliers, and heritage is provided in Table 1.

Table 1: Propulsion System Hardware Summary

Propulsion Component	Supplier	Flight Heritage / Similarity
Monopropellant Tanks (MTA)	Pressure Systems Inc. (PSI)	MPF
Rocket Engine Assemblies (REA)	Aerojet	MPF, Mars Observer (4.5-N thruster with Perkin Elmer valve)
Latch Valves	Vacco	DS1 (Delta Qualified)
Filter	Vacco	Numerous spacecraft
Service Valves	Vacco	MPF, DS1
Pressure Transducers	Tavis	Mars Odyssey, MGS, Stardust
Temperature Sensors (tanks, PDM plate, engine valves, propellant lines)	Rosemount	MPF, Numerous spacecraft
Thermostats (tanks, PDM plate, engine valves)	Elmwood	MPF, Numerous spacecraft
Heaters (tanks, PDM plate, engine valves, liquid service valve, propellant lines)	Tayco	MPF, Numerous spacecraft

A final interesting feature of the MER propulsion system is that both were launched containing a large excess of propellant over their estimated propellant requirements. The propulsion systems were designed to carry a maximum of 52 kg of propellant in the tanks. (There was an additional 0.3 kg of unusable propellant in the lines, latch valves, and filters.) The estimate before launch was that a maximum of 30 kg would be required for TCMs and attitude control during the missions. Both spacecraft were launched with the full 52 kg of usable propellant on board, however, because it turned out both spacecraft were light enough that the launch vehicles could accommodate full tanks.

The MER propulsion system design and construction generally occurred according to plan, being completed in just over two years. Several difficulties did occur during design and development, however. First, a 15-month effort was undertaken to design, build, and qualify composite propellant tanks. It was recognized from the beginning that this was a high-risk development, but it was thought to be worthwhile because it would have saved approximately 10 kg on each MER cruise stage (and at one point there was a serious cruise stage weight problem). In parallel with the composite tank development, long-lead items for titanium tanks were procured so titanium tanks could be used if the composite tanks could not be obtained. It was not possible to finish the composite tank program in the time available, so the titanium tanks were finally baselined for the cruise stages. Fortunately, the weight problem was resolved such that there was enough weight margin to successfully plan for launch with heavier titanium tanks. A second problem was noted when pressure transducers were procured which had an output voltage range of 5 volts vs. the 3 volts typically used in spacecraft electronics. This problem was resolved by incorporating voltage dividers in the cabling that reduced the pressure transducer output voltage range to 3 volts. This approach solved the problem, and the pressure transducers performed well during the MER mission.

IV. Propulsion Consumables Summary

One of the most critical propulsion consumables on MER is remaining hydrazine mass. The MER tanks were conservatively sized and loaded, largely to account for launch injection errors that did not materialize. As such, the final MER-A and MER-B remaining propellant masses at the time of Martian atmospheric entry were quite large. Three independent methods were used to estimate consumed hydrazine mass as a function of mission time. First, an Attitude and Articulation Control Subsystem (AACS) telemetry channel, A-0009, was used as the first crude estimate. This is an on-board estimate of the hydrazine used, based on thruster on-time and pulse counts and a crude propellant consumption model. The remaining N_2H_4 mass may be determined by subtracting this telemetry value from the launch load of 52.3 kg (including the estimated 0.3 kg of unusable propellant). Second, the remaining hydrazine mass was determined by tabulating in-flight tank temperatures and pressures twice per day and then running a tank thermodynamic model. With a known, fixed helium mass (launch) value, the remaining hydrazine mass can be inferred from this model. Again, this value may be subtracted from the launch load to determine hydrazine consumption. Finally, a more rigorous, ground-based propulsion consumption model was used, essentially a high-fidelity version of the algorithm used to generate telemetry channel A-0009.

Figure 8 displays the Spirit, or MER-A, hydrazine mass consumed as a function of mission time since launch. Note the major propulsive events (e.g., initial spin-down and Trajectory Correction Maneuvers, TCMs) labeled in the plot. The three curves in the figure correspond to the three independent means by which propellant consumption may be estimated. Note the excellent agreement between the three different models. Since tank pressure transducer drift is unlikely on MER (see Section VI below), the most accurate value for hydrazine mass is probably from tank thermodynamic models. Compared to this "standard," the AACS consumption estimate from A-0009 is only 4.7% high, remarkably good agreement for a relatively simple, on-board model. As expected, the propulsion ground-based consumption model is even more accurate; it is only 1.7% high vs. the tank thermodynamic model. The agreement between models is better yet for Opportunity (MER-B), as may be noted in Figure 9. The AACS model is only 2.1% high vs. the tank model, while the propulsion model overpredicts N_2H_4 consumption by a mere 0.6%. Note the final remaining hydrazine masses for Spirit and Opportunity were roughly 31 kg and 38 kg, respectively. That is, the MER-A and MER-B cruise stages were destroyed in the Martian atmosphere with their "gas tanks" 59% and 73% full, respectively.

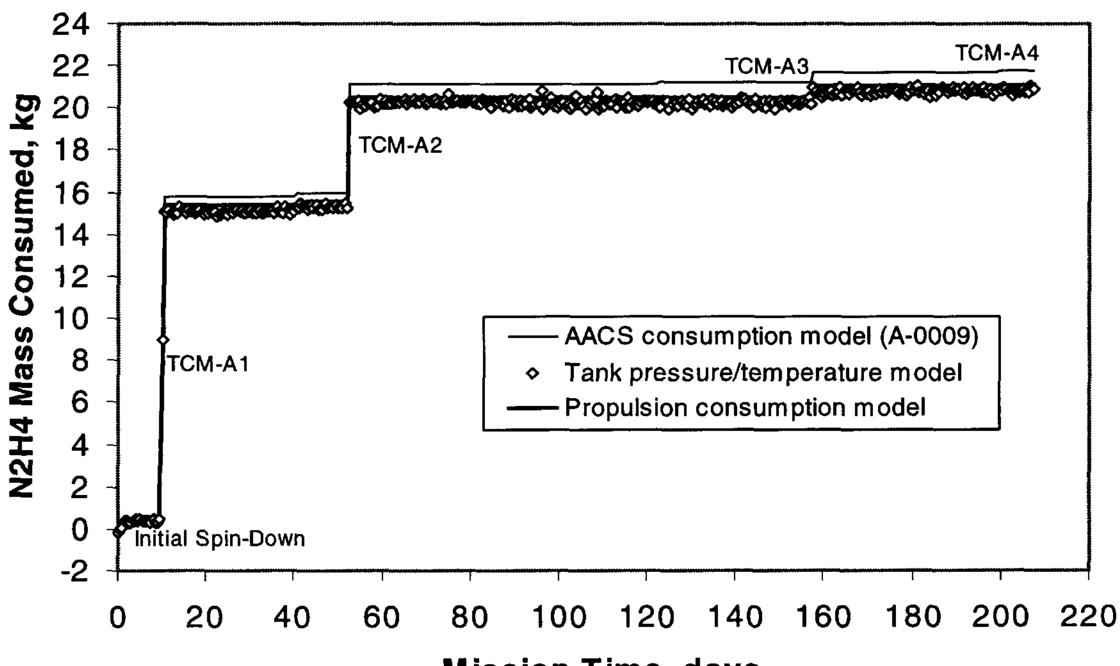

Figure 8: Spirit (MER-A) N_2H_4 Consumption vs. Mission Time

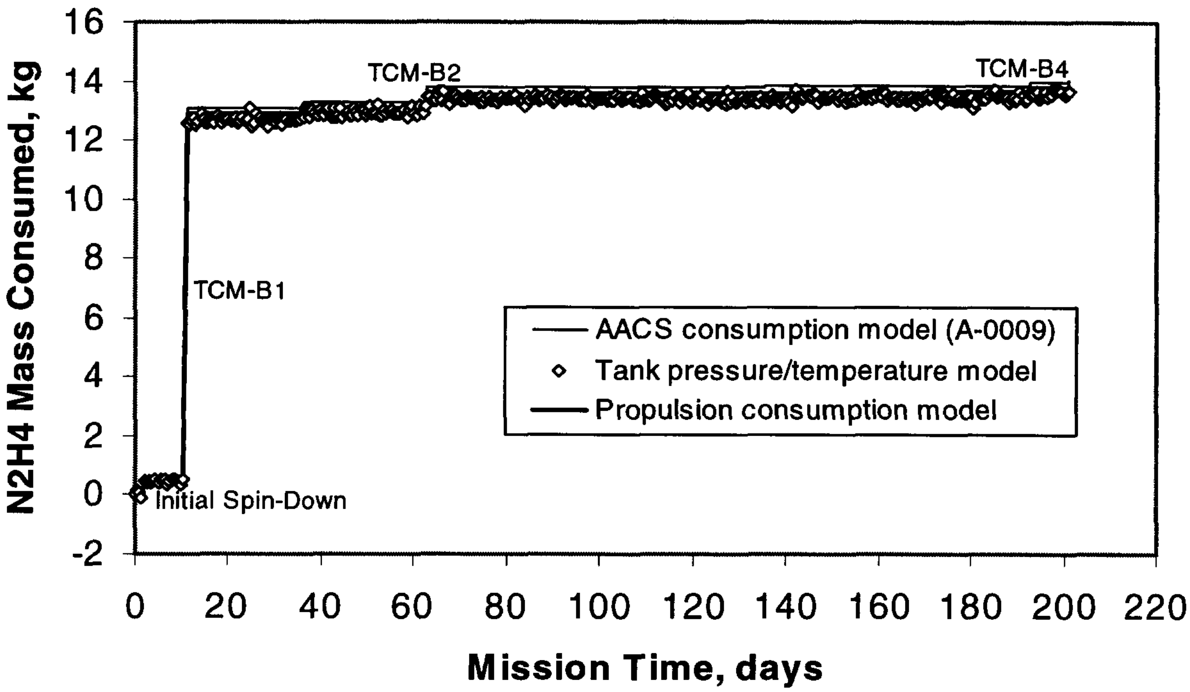

Figure 9: Opportunity (MER-B) N_2H_4 Consumption vs. Mission Time

The propulsion subsystem consumable summaries for the completed mission are presented in Table 2 and Table 3 for MER-A and MER-B, respectively. Thruster valve cycles, latch valve cycles, and propellant throughput were tabulated, as has been done on other projects such as Galileo[4] and Cassini[5]. The thruster valve consumable specification limit of 10,000 pulses was selected to be modest, as ample flight data on other missions suggest this limit is quite conservative. As an example, the Cassini and Voyager thruster valve cycle limit is 273,000 pulses per thruster.

Of additional interest in Table 2 and Table 3 is the notably higher propellant throughput for thrusters 2 and 5 (both negative-Z-axis pointing thrusters) vs. other thrusters. As discussed in more detail in Section V, the higher throughput for these thrusters is mainly a result of the long axial TCM burns required to remove launch biases. It is worth mentioning the highest consumable usage (in percentage) in Tables 2 and 3 is hydrazine propellant, which has already been shown to be conservatively abundant. Lastly, latch valve cycles were tracked, but as noted in the tables, they did not approach the already conservative specification limit of 6600 cycles. It is probably most interesting to note the final cruise stage data products required to complete these tables were actually stored within each rover's computer, later relayed to Earth from the Martian surface. In fact, these tables would have been incomplete without a successful EDL for Spirit and Opportunity.

Table 2: MER-A Propulsion Subsystem Consumables

MER-A Propulsion Subsystem Consumable	Used During Cruise	JPL Spec. Requirement	% Used
N_2H_4 (Monoprop.) Mass [kg]	20.83	52.0	40.1%
PAN (1) Thruster Valve Cycles [ ]	468	10000	4.7%
PAP (2) Thruster Valve Cycles [ ]	451	10000	4.5%
SAN (3) Thruster Valve Cycles [ ]	236	10000	2.4%
SAP (4) Thruster Valve Cycles [ ]	222	10000	2.2%
PBP (5) Thruster Valve Cycles [ ]	471	10000	4.7%
PBN (6) Thruster Valve Cycles [ ]	448	10000	4.5%
SBN (7) Thruster Valve Cycles [ ]	236	10000	2.4%
SBP (8) Thruster Valve Cycles [ ]	222	10000	2.2%
PAN (1) Thruster Throughput [kg]	1.09	40.7	2.7%
PAP (2) Thruster Throughput [kg]	6.77	40.7	16.6%
SAN (3) Thruster Throughput [kg]	2.00	40.7	4.9%
SAP (4) Thruster Throughput [kg]	1.77	40.7	4.4%
PBP (5) Thruster Throughput [kg]	5.38	40.7	13.2%
PBN (6) Thruster Throughput [kg]	0.72	40.7	1.8%
SBN (7) Thruster Throughput [kg]	1.63	40.7	4.0%
SBP (8) Thruster Throughput [kg]	1.47	40.7	3.6%
Latch Valve LV1 Cycles [ ]	16	6600	0.24%
Latch Valve LV2 Cycles [ ]	16	6600	0.24%

Table 3: MER-B Propulsion Subsystem Consumables

MER-B Propulsion Subsystem Consumable	Used During Cruise	JPL Spec. Requirement	% Used
N_2H_4 (Monoprop.) Mass [kg]	13.64	52.00	26.2%
PAN (1) Thruster Valve Cycles [ ]	252	10000	2.5%
PAP (2) Thruster Valve Cycles [ ]	250	10000	2.5%
SAN (3) Thruster Valve Cycles [ ]	9	10000	0.1%
SAP (4) Thruster Valve Cycles [ ]	25	10000	0.3%
PBP (5) Thruster Valve Cycles [ ]	253	10000	2.5%
PBN (6) Thruster Valve Cycles [ ]	249	10000	2.5%
SBN (7) Thruster Valve Cycles [ ]	9	10000	0.1%
SBP (8) Thruster Valve Cycles [ ]	25	10000	0.3%
PAN (1) Thruster Throughput [kg]	0.21	40.7	0.5%
PAP (2) Thruster Throughput [kg]	6.97	40.7	17.2%
SAN (3) Thruster Throughput [kg]	0.19	40.7	0.5%
SAP (4) Thruster Throughput [kg]	0.04	40.7	0.1%
PBP (5) Thruster Throughput [kg]	5.89	40.7	14.5%
PBN (6) Thruster Throughput [kg]	0.15	40.7	0.4%
SBN (7) Thruster Throughput [kg]	0.16	40.7	0.4%
SBP (8) Thruster Throughput [kg]	0.03	40.7	0.1%
Latch Valve LV1 Cycles [ ]	13	6600	0.20%
Latch Valve LV2 Cycles [ ]	13	6600	0.20%

V. TCM Performance

The two MER spacecraft executed a total of seven TCMs (Trajectory Correction Maneuvers) using timer-controlled continuous-axial and pulsed-lateral burns. The propulsion delta-V accuracy requirement was ±3.5% and all maneuvers met this requirement. An additional seven TCMs were provided for but not performed because they were not necessary. These included a late-cruise maneuver on Opportunity (TCM-B3) and the six final targeting maneuvers (TCMs A5, A5X, A6, B5, B5X, and B6). Table 4 summarizes the seven TCMs that were performed. There were no propulsion system hardware failures, all TCMs were performed satisfactorily, and MER navigation, in general, was excellent.

TCMs A1 and B1 were performed to remove launch bias. The Delta II launch vehicles targeted the two spacecraft far enough from Mars that their third-stage solid rocket motor casings, which had been jettisoned from the spacecraft, would not enter the atmosphere. The first TCM on each cruise stage removed this bias. The remaining five TCMs were statistical and gradually decreased in magnitude as the two spacecraft approached Mars until the final TCMs (A4 and B4) were very small, approximately 0.025 and 0.1 m/s, respectively.

The TCMs were designed using a propulsion system simulator (a Fortran program called PROP) designed by the propulsion operations team and operated by the Attitude Control Subsystem (ACS) team. Propulsion personnel provided an input file for each TCM design, containing the predicted tank pressure and predicted thruster performance factors (the ratios of expected thrust to the thrust measured during Flight Acceptance test for each of the eight thrusters). The TCMs were then designed by ACS and Navigation using the output of PROP to provide expected propulsion system performance.

Tank pressures remained nearly constant between TCMs and so were easy to predict, even though tank temperatures fluctuated significantly because of the operation of their thermostats. It turned out that the temperature fluctuations in the two tanks for each cruise stage were out of phase, thus having a negligible effect on the average tank pressures. Almost all of the maneuver errors were due to errors in the predicted thruster performances.

A great effort was made to predict the average performance factors of the thrusters for each TCM based on the expected tank pressure, the observed performances during previous TCMs, and the expected plume impingement losses. There were no thruster chamber pressure transducers provided, so the actual performances of the individual thrusters could not be determined. The maneuver error values in Table 4 show how successful this effort was. As is typical with hydrazine thrusters, the performances varied by a few percent from one TCM to the next, and we were unable to reduce the burn errors below a range of 1-3%. This was certainly good enough; the navigation plan was designed for a 3σ delta-V error of ±3.5%, and the actual flight paths to Mars were sufficiently accurate that the last three TCMs for each spacecraft were canceled.

The final conclusions about thruster performance were that thrusters 1 and 6 provided approximately 99% of their FA thrusts in the negative axial direction, thrusters 2 and 5 provided approximately 96% of their FA thrusts in the positive axial direction (probably due to plume impingement losses), and, when all four thrusters fired together in lateral pulses, they provided approximately 99% of their FA thrusts. These comments hold for both Spirit and Opportunity.

Table XX MER TCM Summary Table (Both Spirit and Opportunity)

TCM	Date	Maneuver ΔV (m/s)	Maneuver Error (%)	Comments
A1	6/20/03	+Axial & Lateral, 16.5 total	Axial, -2.7% Lateral, -0.1% to +2.2% Total, -0.2%	Removed launch bias, 1 +Axial, 14 lateral segments
B1	7/18/03	+Axial, 16.2	-1.4%	Removed launch bias
A2	8/1/03	+Axial & Lateral, 6.0 total	Axial error was -2.8%	Statistical burn, Lateral error not discernable
B2	9/8/03	+Axial & Lateral, 0.533 total	Total, +1.3%	Statistical burn
A3	11/14/03	+Axial & Lateral, 0.577 total	Axial error was -1.5%	Statistical burn
B3	-	-	-	Omitted, unnecessary
A4	12/26/03	Lateral, 0.025	Small	Statistical burn, One pulse
B4	1/16/04	-Axial & Lateral, 0.1 total	Axial, +2.9% Lateral, -1.9%	Statistical burn, the only -Axial burn

VI. Pressure Transducer Drift Assessment

Many JPL missions (Voyager, TOPEX-Poseidon, and Galileo, for example) have experienced linear pressure transducer drift during the course of their multi-year missions. This phenomenon has befuddled attempts to understand pressurization system behavior, propellant consumption, and maneuver performance during mission operations. Great pains were taken on Cassini to provide drift-free pressure transducers. This included modifications to the electronic circuitry, since this was typically implicated as the culprit for sensor drift. Specifically, an operational amplifier (op amp) in the pressure transducer supply electronics was found to drift linearly vs. time. This component instability was sufficient to explain the pressure transducer drifts seen in flight on Voyager, TOPEX, and Galileo. Unfortunately, in a flight environment, there are no independent reference points for the actual pressure, so it is impossible to assess which transducers are drifting.

Pressure transducer drift on prior JPL missions were discovered in flight by differencing the output of two, independent sensors that measure the same pressure. Therefore, missions (such as Deep Space One) that had no redundant pressure measurements were not useful for assessing drift. The maximum drift rate observed in flight was quite consistent among Galileo, Voyager, and TOPEX-Poseidon, roughly 0.24%-0.32% of full scale per year. Cassini has been flying for nearly seven years, with no hints of pressure transducer drift to date. Apparently, the error mitigation efforts paid off handsomely for this flagship mission.

Figure 10 represents the difference of two Spirit (MER-A) hydrazine tank pressure measurements, P(A) and P(B), as a function of mission time between launch and atmospheric entry into Mars. Telemetry data samples were tabulated and differenced twice per day. The difference between P(A) and P(B) is essentially flat vs. time, suggesting the Spirit N_2H_4 tank pressure transducers are not drifting. The slope in Figure 10, +1.90 psia/yr, is 0.38% of full scale per year, which is actually similar to but higher than the worst-case inferred drift rates on Galileo, Voyager, and TOPEX-Poseidon. However, the slope in Figure 10 could easily be zero, within uncertainties. The short (seven-month) cruise mission on MER may be too short to discern pressure transducer drift information.

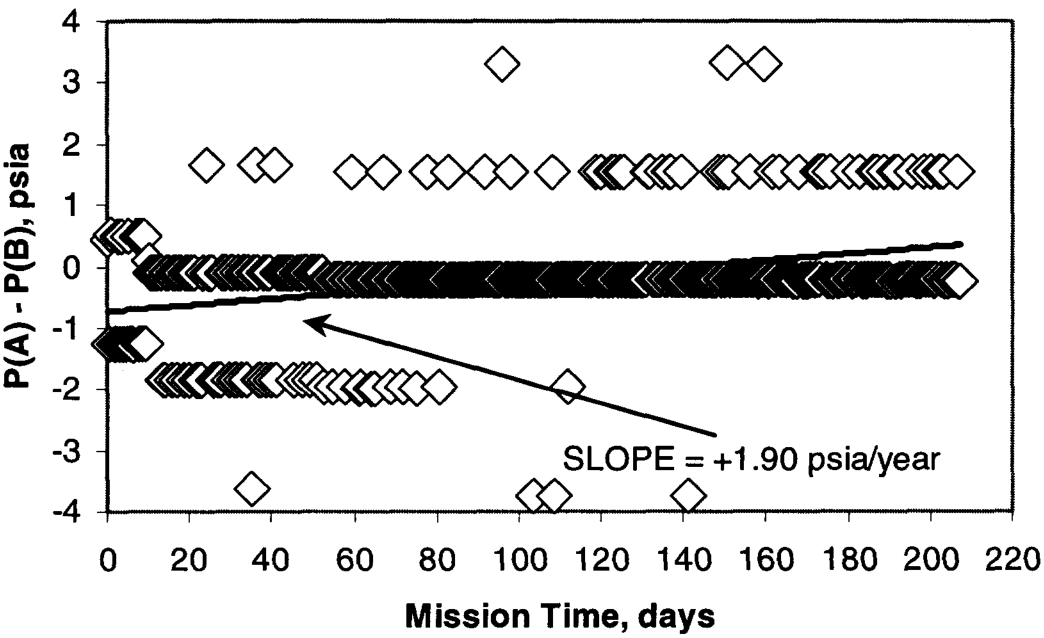

Figure 10: Spirit (MER-A) N_2H_4 Tank Pressure Difference vs. Mission Time

Indeed, at least a year of mission operations was required to detect pressure sensor drift on Galileo, Voyager, and TOPEX-Poseidon. This certainly seems to be, at best, an exercise in noise analysis for short-duration missions like MER (and other Mars missions as well).

The case for Opportunity displaying pressure transducer drift is weaker still. Figure 11 represents the MER-B analogue to Figure 10. The slope in Figure 11 is +1.46 psia/yr, or 0.29% of full scale per year. This number, too, is similar to the worst-case inferred drift rates on Galileo, Voyager, and TOPEX-Poseidon. As before, though, the slope in Figure 11 could easily be zero, within uncertainties.

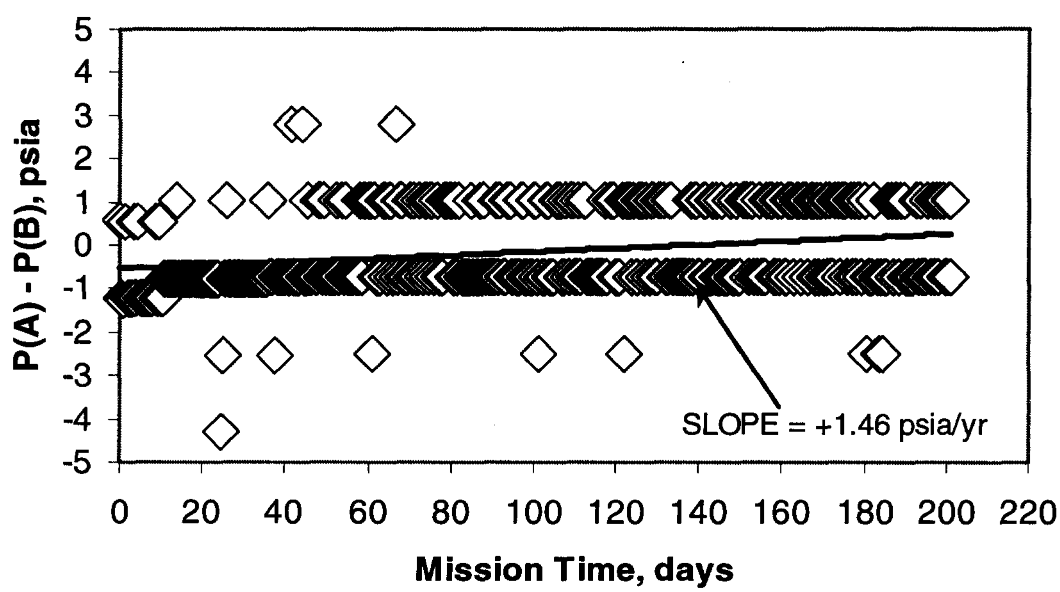

Figure 11: Opportunity (MER-B) N_2H_4 Tank Pressure Difference vs. Mission Time

One distinguishing characteristic noted on Voyager, Galileo, and TOPEX-Poseidon is the invariance of the calculated drift rate as a function of elapsed mission time, even relatively early in the mission. In contrast, the inferred MER drift rates generally decreased during the mission as more data were accumulated. This suggests the "signals" seen in Figs. 10 and 11 are probably not real, and the inferred drift rates would continue decreasing towards zero if the MER mission cruise mission would have continued.

Regardless of how the data of Figs. 10 and 11 are interpreted, transducer drift effects may generally be ignored for direct impact Earth-to-Mars missions such as MER, given their short duration. The worst-case error when averaging the two tank pressure measurements, even at the end of a seven-month mission, is only about 0.5 psia in the case of MER (Spirit). This is three to four times smaller than the digital "quanta" for pressure, called a data number, or DN. That is, the value of any pressure transducer output is only known to ± 0.5 DN, or about ± 0.9 psia, just due to discretization errors. This discretization error may be readily seen in Figs. 10 and 11.

In summary, pressure transducer drift was investigated on the MER mission, and no clear indications for transducer drift were found. Furthermore, a literal interpretation of "drift" rates inferred for MER is well within the uncertainty on true pressure, so this effect was ignored. Even if accounted for, there is no way to determine which transducer is drifting, or in fact if both transducers are drifting but at different relative rates. Gross transducer drift was eliminated from consideration with this study, allowing more confidence in open-loop TCM predictions, which rely on accurate tank pressure predictions.

The pressure and temperature noise "spikes" on MER were higher than usual for JPL missions. The source of this noise was never determined, but it was observed both during Assembly, Test, Launch, and Operations (ATLO) preparations before launch and during the seven-month cruise to Mars. Typically, JPL missions have noise spikes of no more than ±1 DN, whereas Spirit and Opportunity routinely displayed noise spikes of ±2, ±3, or even ±4 DN. The presence of these noise spikes had little effect during the cruise mission, however.

VII. Thruster Performance Assessment During Spin-Downs and Turns

Start here, Frank.

VIII. Conclusion

Despite a highly compressed time schedule, two Mars Exploration Rover spacecraft were designed, built, and launched to red planet early in the first decade of the 21st century. The science results, media and popular interest, and internet frenzy over new images from the red planet have been nothing short of miraculous. Utilizing Mars Pathfinder heritage when possible, propulsive cruise stages were built to ferry two robotic geologists to Mars. Propulsion subsystem development and construction transpired with few snafus, despite the harried timetable.

Propellant usage was calculated via three different models, and the agreement among models was within 5%. Consumable usage was tracked during the mission, though no propulsion consumable approached its specification limit. Each MER cruise stage propellant tank was well over half full at the time of Martian atmospheric impact.

TCM performance was nominal, with errors typically no larger than a few percent for open-loop maneuvers. This predictive capability, coupled with excellent navigation, led to the cancellation of many MER maneuvers, particularly during Mars approach. Pressure transducers were assessed with respect to drift; no drift was readily apparent, as expected.

Maneuver reconstructions for initial spindown suggest the MR-XXX thruster produced about 10-12% more impulse than predicted based on ground models. Similar reconstructions for spacecraft turns imply XXXXXXXXX.XX

Acknowledgments

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors wish to acknowledge the following individuals who contributed to this research: Richard Cowley, Jim Erickson, Marlin Klatte, Jim Lewis, Joe Lewis, Hartwell Long, Mike Marcucci, Barry Nakazono, Tim O'Donnell, and Fred Serrichio. The authors would like to gratefully acknowledge the contributions of Victoria Scarffe and Genevie Yang, who helped bring this paper to fruition.

References

[1]Roncoli, R. and Ludwinski, J., "Mission Design Overview for the Mars Exploration Rover Mission," presented at AIAA/AAS Astrodynamics Specialist Conference, August 5-8, 2002, Monterey, California.

[2]Erickson, J.; Adler, M.; Crisp, J.; Mishkin, A.; and Welch, R.: "Mars Exploration Rover Surface Operations," IAC-02-Q.3.103, 53rd International Astronautical Congress, October 10-19, 2002, Houston, Texas.

[3]Bhandari, P.; Birur, G.; and Gram, M.: "Mechanical Pumped Cooling Loop for Spacecraft Thermal Control," Paper No. 96-1488, 26th International Conference on Environmental Systems, July 8-11, 1996, Monterey, California.

[4]Barber, Todd J.; Krug, F. A.; and Renner, K. P.: "Final Galileo Propulsion System In-Flight Characterization," AIAA Paper 97-2946, 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, July 6-9, 1997, Seattle, Washington.

[5]Barber, Todd J. and Cowley, R. T., "Initial Cassini Propulsion System In-Flight Characterization," AIAA Paper 2002-4152, 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, July 7-10, 2002, Indianapolis, Indiana.