Mars Sample Return: Architecture and Mission Design[1,2]

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Abstract—Mars Sample Return (MSR) architecture and mission engineering, led by Boeing for JPL, is presented. The study sought credible data to support planning a 2011 mission to return 500g of scientifically selected samples.

Phase 1 compared diverse architecture options to accomplish the mission. 17 theme-based architectures were conceived, quantified, measured, and scored. Two primary and three secondary architectures were recommended.

Phase 2 developed engineering detail for a simple architecture specified by JPL: dual mission to two landing sites; short-range, radioisotope-powered sampling rovers; Mars orbit rendezvous; and electric return propulsion with Shuttle rendezvous. The design comprises nine system elements. Solutions for sample handling and breaking the back contamination chain are detailed. Total mission duration is five years.

Technology tailoring, rather than technology creation, is required. Mission development cost, including margins and wraps, is $2.8B. The study concluded that many schemes can feasibly accomplish Mars sample return, depending on program objectives adopted.

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1. INTRODUCTION

Boeing Company, Human Space Flight and Exploration business unit, was competitively selected by JPL in early 2001 for a Mars Sample Return (MSR) Technical Approach Study, one of four parallel industry studies of the mission. The contract (JPL-1229282) was small ($1M) and fast-paced (6-month), ending in October 2001.

Due to the unprecedented complexity of the MSR mission, Boeing integrated and led a cross-industry team of domain experts: Mission Architect Dave Smith (SpectrumAstro, formerly of JPL and SpaceDev), Science Architect Dr. Ron Greeley (Arizona State University), Robotics Architect Dr. William "Red" Whittaker (Carnegie-Mellon University), Transportation Architect Gordon R. Woodcock (Gray Research, formerly of Boeing), and autonomous rendezvous specialist Gregg Barton (Draper Labs). Special analyses were provided by Innovative Orbital Design (Weak Stability Boundary trajectories) and Aerospace Corp. (cost estimation benchmarking). Program management, system engineering, planetary protection engineering, most flight vehicle engineering, technology planning, and cost estimation were performed by Boeing. Discussions among the four industry teams were precluded during the study.

The technical objective of the study was to develop a mission concept capable of meeting the simple top-level requirement specification shown in Fig. 1. However, the ultimate purpose of the study was to support long-range planning by the NASA Office of Space Science, through analysis-based derivation of development cost estimates and technology demonstration needs to enable the mission. An immediate goal was to inform mission concept definition of JPL's Smart Lander mission, currently slated for 2007. The study was divided into two three-month segments.

- Return ≥ 500 g total mass of rock, regolith and atmosphere samples
- Select them using a payload of scientific instruments and sub-surface sampling tools
- Provide ≥ 1 km mobility (radial distance from the landing site, in a few months) to assure sample diversity
- Collect a sample from a depth of ≥ 2 m
- Access any landing site within 15° of the equator and at an altitude below +1.5 km (with respect to the mean reference)
- Assure landing accuracy no worse than 50 km (semi-major axis of the 3σ landing ellipse)

Figure 1 – Top-level MSR requirements.

[1]0-7803-7231-X/01/$10.00/© 2002 IEEE
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2. PHASE 1 – BROAD TRADE STUDY

Phase 1 (first three months) was required to generate and compare at least two different ways of accomplishing the mission [1]. We conceived and studied 17 diverse, theme-based architectures (Table 1) to discern the full range of what MSR could do for the Mars Exploration Program. Some are intended as actual mission concepts, whereas others are intended as analytical fictions to deepen overall understanding by exploring the trade space. We performed an abbreviated but broad architecture trade study, using standard Boeing methodology. Upon analysis, some architectures were aborted or combined; ten were carried through a rigorous downselect process.

The science, robotics and transportation implementations for each architecture were quantified using real-time, physics-based spreadsheet performance models, and integrated through two analysis cycles. Derived data, including technology legacy and relative cost, were generated for each. No particular mass margin was required by JPL in this study phase. The architectures were then consistently measured using eight weighted attributes. As shown in Fig. 2, half the total weight was given to explicit contracted requirements, another quarter to implicit program requirements, and the final quarter to characteristics the team determined might drive sustained public support for the mission. Unique, pre-determined utility functions were used to process each metric into usable scores as illustrated in Fig. 3. The particular example illustrated applies an algorithm based on the Mars Exploration Payload Advisory Group (MEPAG) priorities, for scoring science value. All the processed scores were tallied as shown in Fig. 4, enabling the team to recommend two primary and three secondary architectures to the Mars Program System Engineering Team (MPSET) in July 2001. The trade study history shown in Fig. 5 traces how each individual architecture was dispositioned.

We also performed an extensive set of key mission trades, including options for: main propulsion, entry and landing, surface mobility method, range and power, sample acquisition methods, Mars ascent propulsion, Mars-space rendezvous, and Earth retrieval. Our results favored direct entry to the surface, precision rather than pinpoint landing, wheeled mobility except for specific site applications, radio-isotope Stirling conversion for mobile power, large roving distances with long surface collection times, Mars ascent using solid-propellant guided missiles with "smart" head-end steering units, autonomous Mars orbit rendezvous rather than direct return, electric propulsion for high mass performance and gradual return to Earth's vicinity, and use of the Shuttle for final verification and retrieval in Earth orbit.

One interesting result was that, for sampling sites of interest, and given current image-based knowledge and the use of precision landing to avoid dune fields, a radial roving range of ~5km is probably adequate to assure access to rock outcroppings – a key MSR science objective. For reasonable site coverage however, this can easily translate into a total rover design range of 10^2 km.

Our two primary architecture recommendations were "Multiple Sites" and "Anywhere, All the Time". Both emphasize directly-comparative sample science and in-mission planning flexibility, but in very different ways. "Multiple Sites" would return samples from five sites simultaneously, thereby dramatically enhancing the statistical significance and completeness of what is learned about the planet. The sites would be determined after arrival in Mars orbit, to take advantage of up-to-date science, meteorological, remote sensing and other operational information. "Anywhere, All the Time" would land a roving science base. The base would traverse the length of a river channel, correlating outwash samples with their sources along the flow feature. Parasitic robots would extend the rover's sampling capability into less accessible local features via walking and hopping. The roving base would carry the ascent vehicle, to be launched from wherever the traverse ended. Both of these architectures far exceed traditional expectations for how and where to collect 500g of sample for return, and would thereby help assure that the samples were worth the trip. In addition, the intrinsic robustness of their designs yields a comparatively high probability of mission success, and they are inherently interesting enough to attract and retain public support.

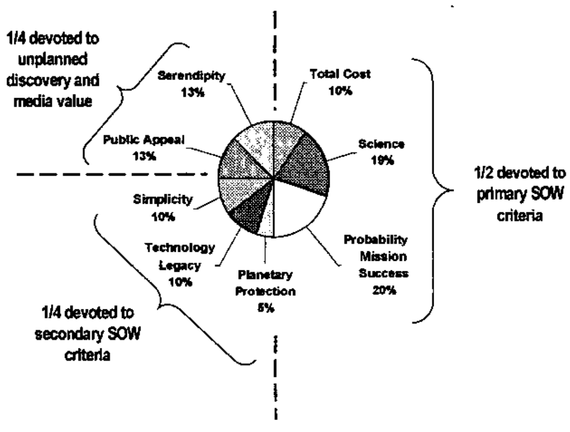
Our three secondary recommendations were "Ice", "Cliffhanger" and "Architecture 0". "Ice" would send landers simultaneously to the summer and winter polar regions to collect water ice, CO_2 ice (at the winter pole), and liquid water (if any is found) in addition to the conventional sample types. It would return the ice to Earth unthawed. This architecture works particularly well for the astrodynamics of the 2013 opportunity. "Cliffhanger" would send two landers to the surface, one to the edge of a mesa and the other to the valley floor below. The upper lander would release two rovers that rappelled down the cliff face within telescopic view of the lower lander, collecting samples by penetrating laterally into the cliff face. One would return to the top and transfer its samples into an ascent vehicle on the upper lander; the other would descend to the valley floor and rove across it, then transfer its samples into an ascent vehicle on the lower lander. Cliffhanger was not the highest-scoring of the middle cluster in Fig. 4, but was recommended because its significant differences from all others would be most likely to reveal novel insights upon analysis. "Architecture 0" was a "science baseline" architecture required by the contract. We derived it as a single-site version of "Multiple Sites".

Table 1 – Descriptions of 17 Alternative MSR Study Architectures

Theme	Purpose	Goals	Benefits
Arch 1 Multiple Sites	Sample a diverse set of sites on a single MSR mission opportunity	Modest goal: sample several (e.g. >4) of Mars' 80 distinct geological units Stretch goal: visit sites distributed widely around the planet	Technical: Enable immediate comparative science Programmatic: Mitigate criticism of any particular site selection. Reduce risk to science if program is terminated after first mission.
Arch 2 Ice	Sample water ice, CO_2 ice and liquid water, in addition to rock, regolith and atmosphere	Return cold samples to Earth in their pristine condition (e.g. unmelted ice). Sample a summer pole (water ice) and a winter pole (CO_2 ice also) on the same mission.	Technical: Literally "follow the water" to return the "fourth, fifth and sixth types" of sample Programmatic: Guarantee high public interest. Accelerate accomplishment of inevitable eventual science objectives. Completely dual-redundant
Arch 3 Bring Back a Lot	Return significantly more sample mass, larger individual samples, and/or greater number of individually packaged samples, than possible in 500g	Modest goal: 5 kg Stretch goal: 50 kg	Technical: Enable richer sample analyses Programmatic: Mitigate negative perception of high cost/benefit of the mission. Reduce risk to science if program is terminated after first mission
Arch 4 Go Deep	Sample putative subsurface ice/water deposits in lower-latitude regions	Drill multiple sampling holes to 30 m depth	"Follow the water" in warmer climatic and protected conditions, to seek evidence of past/extant life
Arch 5 Least Risk	Determine the least-risk method of meeting basic MSR sampling requirements	Lower-bound mission risk, by using risk-minimization as the primary criterion to resolve all principal trades	Understand the realistic risk "floor" for a mission of this complexity. Identify the highest-risk mission elements to be worked.
Arch 6 Least Cost	Determine the least-cost method of meeting basic MSR sampling requirements	Establish a cost benchmark, by using cost-minimization as the primary criterion to resolve all principal trades	Understand the realistic cost "floor" for a mission of this complexity. Identify the highest-cost mission elements to be worked.
Arch 7 High Capability	Invest in a highly capable base at a single site (antithesis of Arch 1)	Explore in depth a single, carefully selected region. Achieve high science synergy by integrating all assets into one surface facility.	Technical: Enable continuous, iterative investigations using all assets. Understand some place on Mars to best ability within means. Programmatic: Establish a base to enable more advanced future missions.
Arch 8 Tech-nology Push	Determine the likely evolution of MSR mission capability (beyond 2011) as technology continues to advance and is introduced into a series of missions	Incorporate into all mission areas, elements and systems the most appropriate, aggressive technology improvements that are likely to occur by 2020	Technical: Understand the realistic capability ceiling for the mission. Programmatic: Identify the highest-leverage technology developments.
Arch 9 Mission Series	Distribute the science objectives across a series of mission opportunities	Use the results (science) and proof (capability) from each mission to drive the next. Structure a reasonable, multi-mission campaign of escalating accomplishment.	Enhance program P_{go} by obtaining science results in modest increments (flatten cost profile). Establish stakeholder commitment to long-term campaign of multiple missions.
Arch 10 Asset Dependent	Reduce cost by emplacing enabling capabilities on the 2007 and 2009 mission opportunities	Define partitionable MSR functions that can be offloaded onto precursor missions	Understand the degree to which potential 2007 and 2009 mission designs can enable MSR. Further integrate the MEP missions.
Arch 11 High Flexibility	Successfully accommodate a range of mission conditions far outside the "design mission"	Be able to choose key parameters after launch (e.g. landing site, science hypotheses, mobility plan, sampling strategy). Alter the operations concept enroute and throughout the surface mission.	Technical: Preserve the ability to adapt the mission design to emergent investigation needs. Take full advantage of ongoing precursor science. Programmatic: Assure all stakeholders that mission relevance will remain current and responsive.

Table 1 – Descriptions of 17 Alternative MSR Study Architectures (Continued)

Theme	Purpose	Goals	Benefits
Arch 12 Go and Come Back Now	Accomplish the MSR mission within one synodic period	Fit the round-trip mission into a single opposition-class mission profile. Complete the planetary phase (from capture to departure) within a ~30-45d window	Technical: Minimize mission system lifetime requirement and mission operations duration risk. Programmatic: Obtain tangible results most quickly (to maintain public interest). Minimize duration-driven operations costs and risks.
Arch 13 Anywhere, All the Time	Return samples from any location or local feature, and retrieve them to orbit whenever desired.	Enable access throughout the range of season, latitude, distance, site, topography and substrate conditions, and duty cycle that science objectives may actually target by 2011.	Technical: Understand the limits of "best access" Programmatic: Assure mission capability to reach whatever sites may ultimately be deemed worthy of the MSR investment.
Arch 14 Extended Science	Leverage the MSR surface assets for *in situ* sample science or non-sample science after departure of the MAV	Optimize division of the science payload into sample-related and non-sample science. Enable rich autonomous and tele-science investigations continuously and indefinitely.	Technical: Enable source-locale science after the returned samples are analyzed. Bridge multiple mission opportunities with continuous surface science. Facilitate long-term & HEDS science. Programmatic: Mitigate perception of "one-shot" mission objective. Use MSR to deliver other science to the surface.
Arch 15 Cliffhanger	Target MSR directly to the most likely locations of recent liquid water	Collect samples from MOC-imaged cliffside sites (which may be brine seeps or episodic ice-melt features).	Technical: Most directly "follow the water". Programmatic: Dramatic opportunity for public engagement.
Arch 16 Store and Fetch	Allocate the sample-collection and sample-return functions to different opportunities	Primary: Cache samples on the surface or in Mars orbit for retrieval by a later mission. Secondary: Collect Ponsolidated return flight.	Technical: Extend the time available for scientific sample selection. Allocate more landed mass to surface operations functions. Programmatic: Risk only half the mission functionality on each mission opportunity. Greater mass allocation is available for potential cross-strapping schemes.
Arch 17 Solar Polar	Perform continuous sample collection operations without nuclear power sources	Use northern hemispheric summer continuous sunlight (2011 opportunity) for long-term polar-dwelling surface operations.	Non-nuclear way to accomplish high duty-cycle polar region sampling mission.



	Good is...	*Valued at...*	*Measured by...*
Total cost	Low development and launch cost	100	Relative cost value compared to reference data from prior cost models
Science	Relevant, rich, diverse science	200	Score using MEPAG algorithm
Probability of mission success	High relative probability of achieving mission theme	200	P(mission event success) integrated over the sequence of mission events. using standardized assumptions
Planetary protection	Low relative inherent risk of back contamination	50	Qualitative assessment by PP expert team, on a simple scale
Technology legacy	Exploits technologies being developed by other programs	100	Number of technologies incorporated from ongoing technology development programs
Simplicity	Program management that is not inherently complicated	100	Number of distinct types of mission elements
Public appeal	Perceived to be unpredictable or contain high drama	125	Simple ranking, team consensus
Serendipity	Inherently introduces capacity for unplanned scientific discovery	125	Total possible km traverse over 2-year surface exploration mission
		1000	

Figure 2 – Weighted metrics used to score architectures.

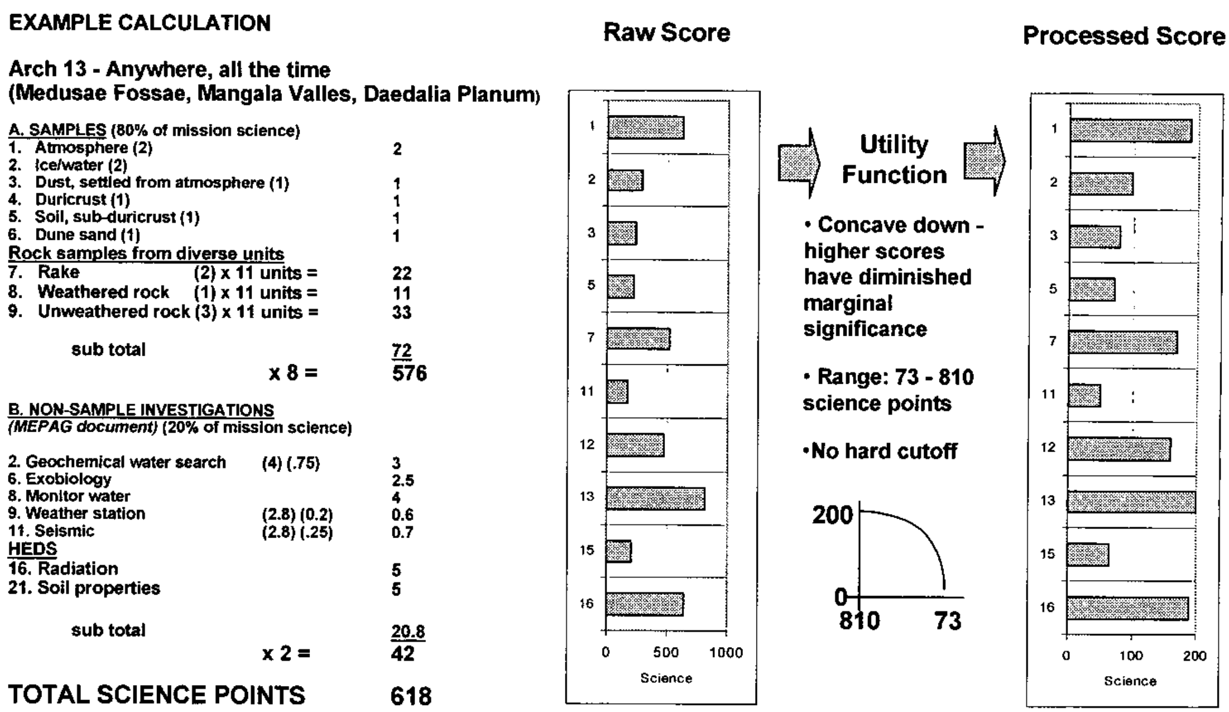


Figure 3 – Example (Science) score development and processing.

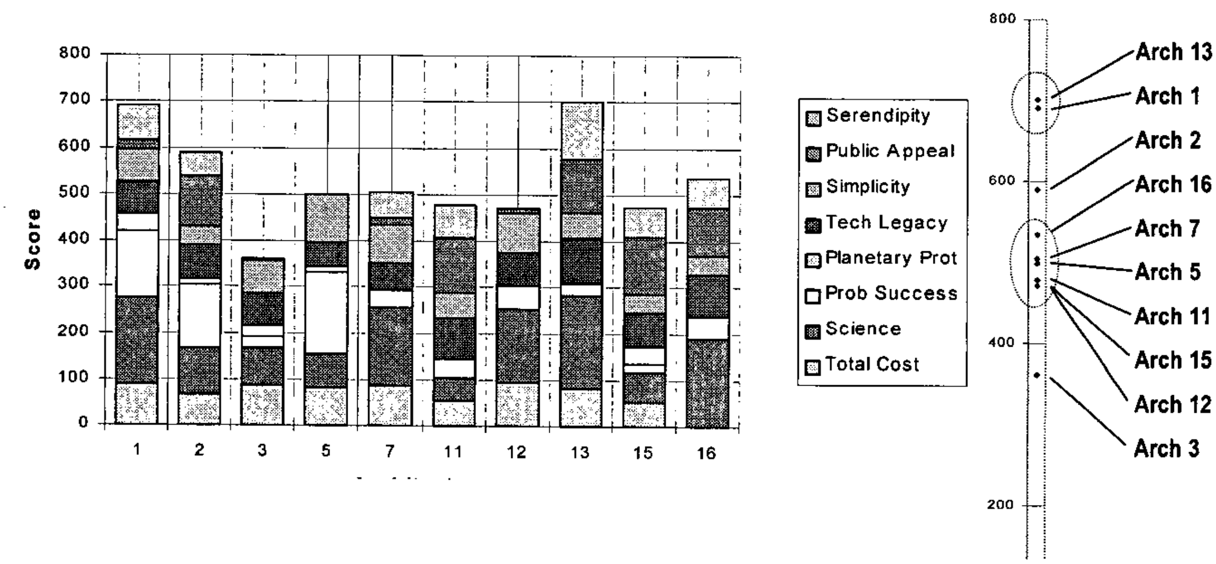


Figure 4 – Final architecture scores.

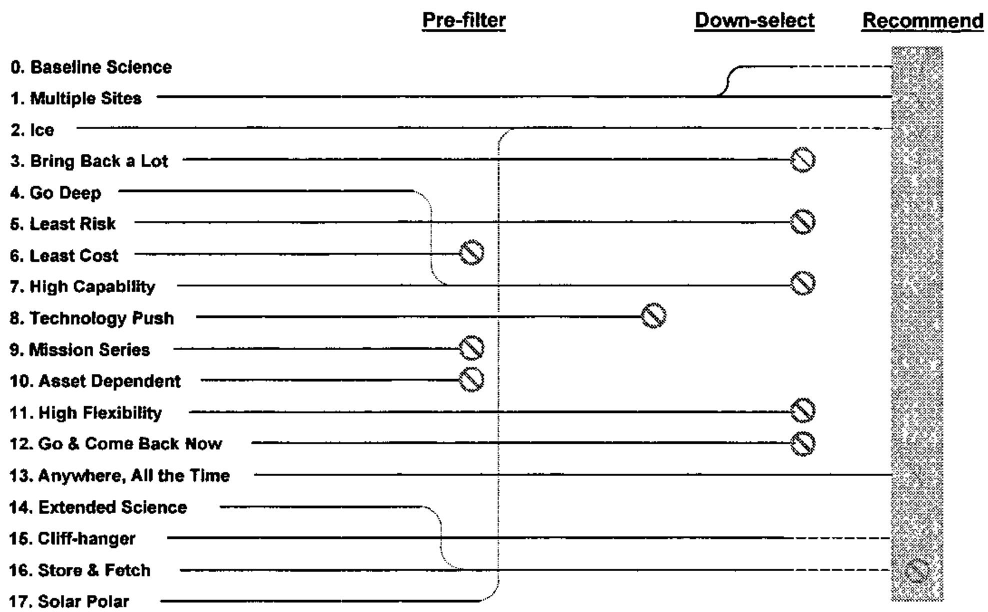


Figure 5 – Disposition history of the 17 architecture.

3. Phase 2 – Directed Mission Design

Phase 2 (final three months) was required to develop a single architecture, specified by JPL, into a typically documented Phase-A mission design [2]. JPL selected an architecture based on "Architecture 0", with the salient requirements listed in Fig. 6. In this phase, the contract required 30% margin on all power systems, 43% margin on all mass estimates, and 30% margin on cost. Ultimately, our design solution embodied key themes from many of the Phase 1 study architectures: multiple sites (Arch 1), least risk (Arch 5), asset dependence (Arch 10), and extended science (Arch 14).

There are nine cost elements in the flight system: Sample System, Rover, Radioisotope Power Source (RPS), Cruise Stage, Entry Vehicle, Lander, Mars Ascent Vehicle (MAV) Booster, MAV Head-End Steering (HES) unit, and Electric Propulsion (EP) Return Stage.

Fig. 7 depicts the five-year mission profile. A Delta IV-H launches 5700kg to Mars on 12 October 2011, including two 1900kg planetary spacecraft and a single 1570 kg, 15kWe EP Stage. Each planetary spacecraft comprises a Cruise Stage and Entry Vehicle. Each Entry Vehicle contains a Lander, which in turn carries a 200kg Rover and a 215kg, 2-stage solid-propellant MAV with HES. The two planetary spacecraft separate from the Delta upper stage immediately after its first trans-Mars injection (TMI) burn, cruise to Mars and release their Entry Vehicles, which perform dual, widely separated direct entries on 23 October 2012. The EP Stage separates from the Delta upper stage immediately after a second TMI burn, cruises to Mars and spirals down at Mars into a 600km circular orbit.

The Landers descend using parachute systems and propulsive braking, to soft landings in Gale Crater (5.5°S, 222.5°W, -3.1km) and Eos Chasma (13.3°S, 40.7°W, -3.8km). Upon touchdown, each Lander immediately collects a small contingency sample, stows it inside the MAV, then deploys its Rover. Powered by a Stirling RPS, each Rover uses a 2m drill and field geology manipulator end-effectors to collect 2kg of individually packaged samples over five months, within a 1km radius of its Lander.

After the nominal surface mission, the best 500g of samples are selected for loading into each MAV. The EP Stage spirals down to a 400km rendezvous altitude, and (after a coincident solar conjunction blackout period) the MAVs are launched and their HESs attain orbit. The Landers and Rovers continue into their extended surface mission. The EP Stage performs two sequential, active rendezvous maneuvers, capturing and stowing the HESs. The EP Stage then departs Mars on 18 May 2013, spiraling up for its long cruise to Earth. It finally spirals down to a 570km orbit for a 28 Sep 2016 Shuttle rendezvous.

Fig. 8 illustrates the elements we designed to execute this mission sequence. "Forward mission" elements are based on heritage solutions to minimize risk. The Cruise Stage and Entry Vehicle are conventional, based directly on Viking and Pathfinder experience (except that they are parasitically powered by the rover's RPS). The Lander is based on the leading concept for JPL's Smart Lander design, a hexa-symmetric, tensegrity-stabilized outrigger configuration with crushable-pallet underbelly. In addition to the Smart Lander's hazard detection and avoidance (HDA) approach, using downward-looking radar and lidar,

Unique to "Arch 0 - Science Baseline"

- Dual launch (may use single launch)
- Ballistic cruise for lander, propulsive capture in elliptical Mars orbit for chute and propulsion soft-landing (may use direct entry)
- SEP ERV transfer, spiral to low Mars circular orbit, spiral from Mars orbit, spiral into Earth LEO for Shuttle pick-up (no Earth aerocapture)
- One rover with RPS and 2m drill and 1km range

Special concern

- Performing MOR with large SEP solar arrays deployed

Trades

- Expansion to two landers
- Impact of drill on lander only

Common to all MSR contractor studies

- OpNav camera on all orbiters and direct-entry landers. Detect unpowered OS
- OS beacon detectable by existing orbital telecomm asset
- OS back-up capability to be detected while unpowered
- Terminal hazard avoidance on lander
- Capability by all landed assets to communicate with existing orbital telecomm asset. Continuous EDL telemetry sent to orbital telecomm asset.
- Meet Science Baseline
  - Total mass of samples returned > 500g
  - Samples include rock, regolith, atmosphere selected using scientific instruments and sub-surface tools
  - Mobility for sample selection and collection payload
  - Mobility not less than 1km radial distance from landing site, in a few months
  - Sample from single hole, depth > 2m
  - Access any landing site within 15 deg of equator, any altitude below +1.5km wrt MGS/MOLA mean reference
  - Landing accuracy no worse than 10km semi-major axis of 3-sigma landing ellipse
- Costs in real year dollars

Figure 6 – Requirements for directed mission design.

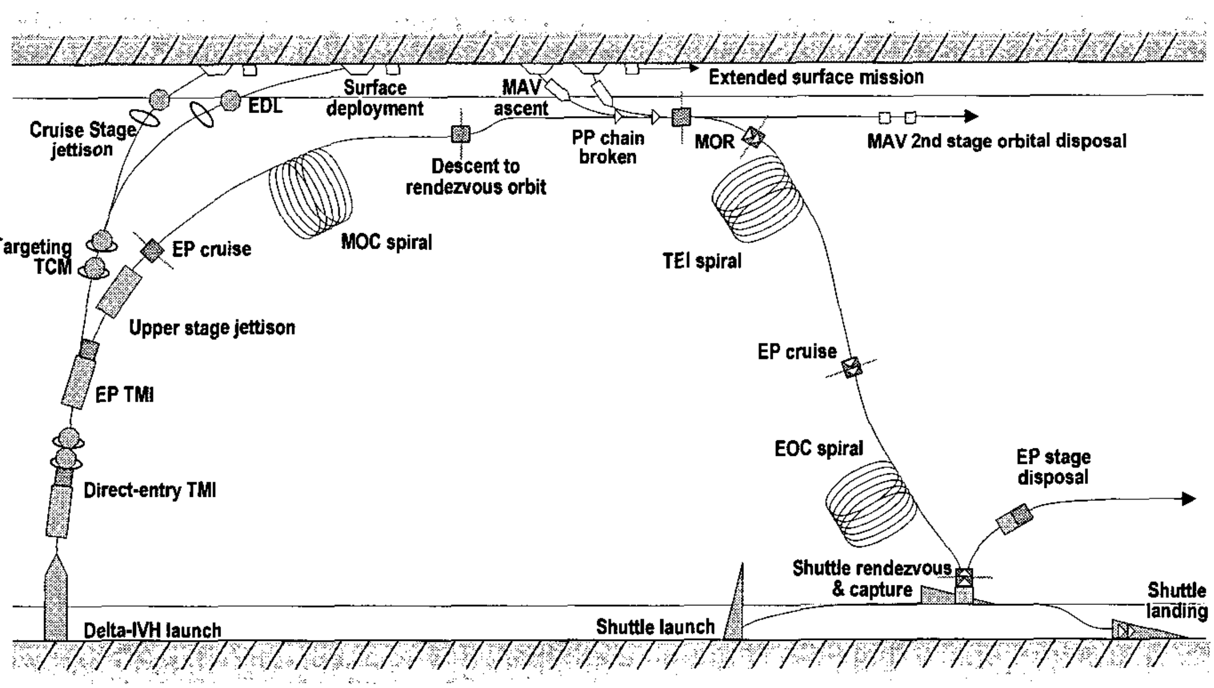


Figure 7 – MSR mission profile.

with 100m lateral maneuvering authority upon terminal descent, we added propellant margin for a post-landing "nudge" maneuver to assure stable basing. Our Lander superstructure is turntable-mounted, to permit separate azimuthal re-orientations for contingency sample collection, rover egress/ingress and MAV launch. The MAV launch tube is mounted laterally for transit but erects for MAV launch. During transit and sample transfer, the Rover straddles the launch tube. Lander power is provided by deployable, fixed solar arrays with battery storage.

The surface mission is designed to optimize thorough scientific selection of the returned samples. The anticipated European '07 telecommunications orbiter provides vital

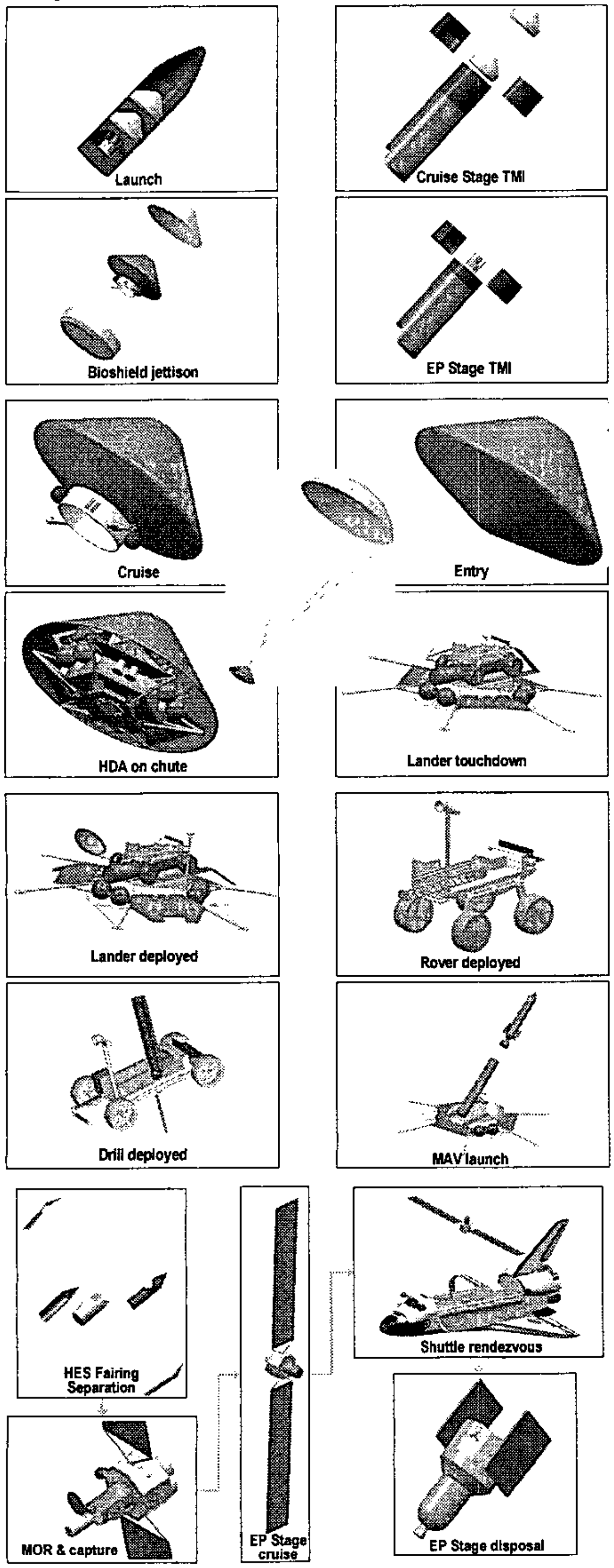


Figure 8 – MSR mission element sequence.

coverage for this mission. Using it, we can achieve 2.5 Gb per sol of downlinked science and image data. Redundant links are provided: rover-Orbiter and rover-Lander-Orbiter at 128 kbps, and contingency rover-Lander-Earth at 2 kbps.

Our primary sampling machine is a 1.2 km/hr, four-wheeled, skid-steering, adjustable-suspension rover. At its fore end is an instrument mast with stereo and panoramic cameras, a body-mounted mini-corer, a 5-DOF manipulator with fixed camera, and carousel-stowed manipulator instruments, including sampling devices, micro-imager, and alpha-particle X-ray, Mössbauer and Raman spectrometers. Amidships is a deployable, segmented coring drill assembly with built-in sample microscope. Aft is the 110 kW$_e$ RPS with dual Stirling converters.

The Sample System is distributed among several flight elements: Lander, Rover, HES and EP Stage. The Rover carries the sample packaging, stowage and sorting functions (Fig. 9). Samples are introduced into 3 cc (mini-core) and 10 cc (regolith) evacuated, hermetic casings. The Rover carries 240 of these casings, held 30 at a time in eight storage disks. The disks are housed in a climate-controlled container, within which they are rotated and indexed to present a single casing receptacle at a time to the entry port. At mission end, 60 selected casings are transferred into two flight disks, which the rover manipulator introduces into the HES for return.

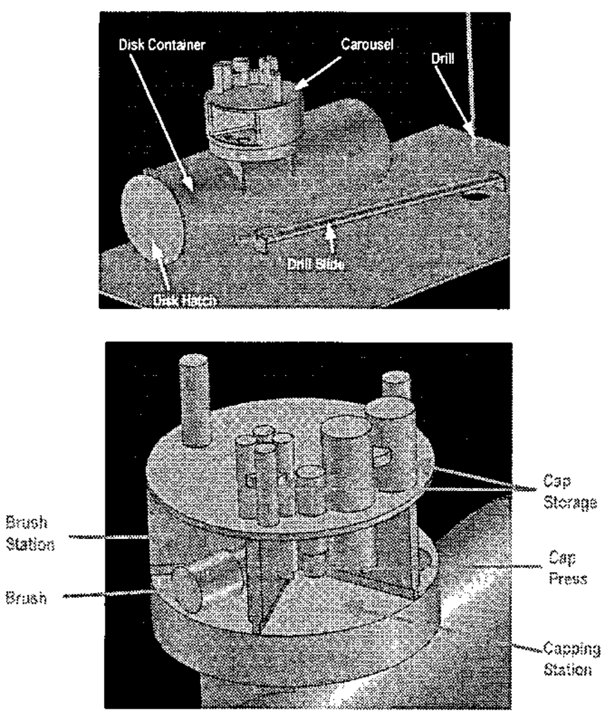


Figure 9 – Rover sample handling system.

Our primary sampling machine is a 1.2 km/hr, four-wheeled, skid-steering, adjustable-suspension rover. At its fore end is an instrument mast with stereo and panoramic cameras, a body-mounted mini-corer, a 5-DOF manipulator with fixed camera, and carousel-stowed manipulator instruments, including sampling devices, micro-imager, and alpha-particle X-ray, Mössbauer and Raman spectrometers. Amidships is a deployable, segmented coring drill assembly with built-in sample microscope. Aft is the 110 kW_e RPS with dual Stirling converters.

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The Sample System employs a "Tutankhamun" containment scheme, in which the samples are sealed into successive layers of containment, all the way back to Earth, rather than ever being removed from one assembly for transfer to another. Two such layers are inside the HES (Fig. 10): a solder-sealed sample container that holds the contingency samples, flight disks and a tritium source; and a solder-sealed sample chamber that holds the sample container and a leak detector (mass spectrometer tuned to the tritium decay daughter Helium-3). The next layer is dual return vessels on the EP Stage, into which the HESs are individually sealed intact upon rendezvous in Mars orbit, and which contain secondary Helium-3 leak detectors. The final layer is dual vacuum vaults in the Shuttle payload bay, into which the entire return vessels are introduced upon Shuttle rendezvous. These assure integrity in the event of re-entry mishap. The vaults are transferred to the sample receiving facility at Johnson Space Center (JSC), where the vacuum vaults and return vessels are opened, the HES is disassembled, and the sample chamber and sample container are cut open for sample removal.

The MAV is a fairly straightforward guided missile, with two high-thrust solid-propellant stages for boost and orbit circularization, respectively. Motor burn times are of order 20 sec, separated by an apogee coast interval. The launch tube provides thermal conditioning (> -20°C) for the solid propellant, pre-launch inertial fix with a boresighted star tracker, proper launch elevation of about 40°, and blast deflection to protect the Lander instruments. The boost stage has pop-out fins for stability in the Mars atmosphere, and the HES provides all control authority during flight, with divert

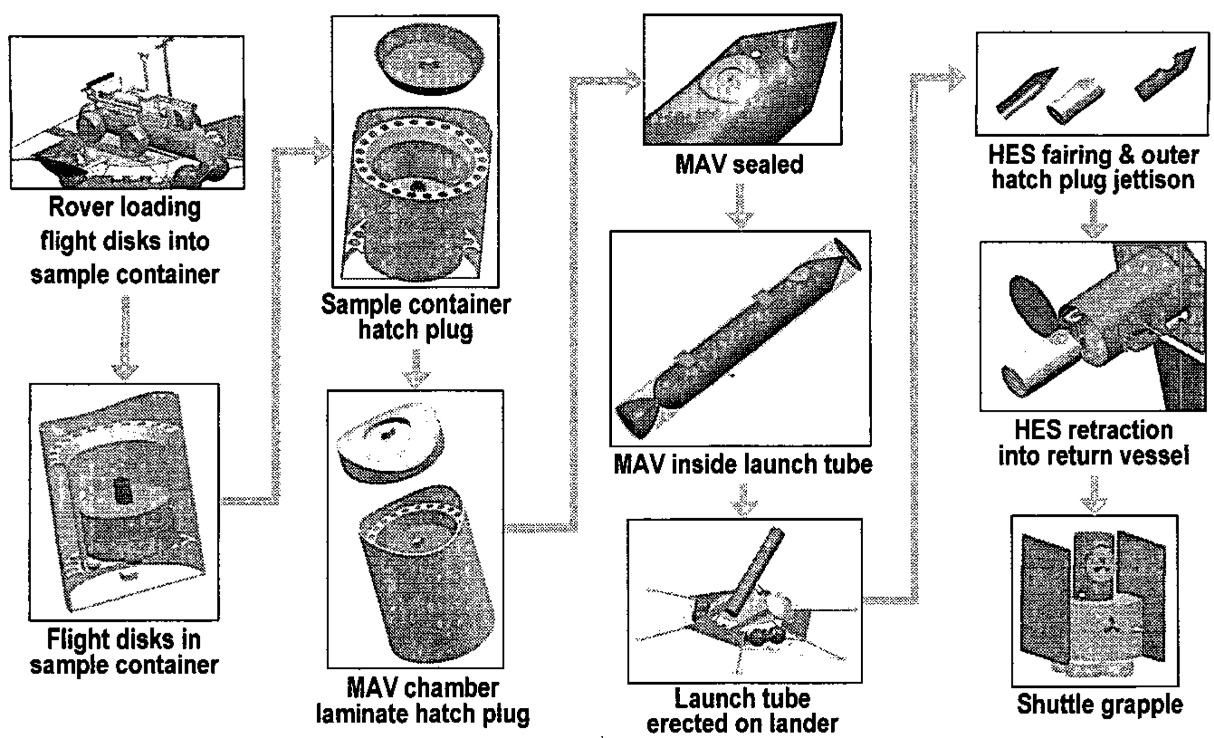

Figure 10 – Nested sample containment approach.

thrusters (four large, eight small) that burn hydroxyl ammonium nitrate (HAN)-water-glycine monopropellant. This non-toxic propellant was chosen to allow safe HES disassembly inside the sample receiving facility at JSC. MAV design sizing is based on 6-DOF ascent simulations. The final function required of the Sample System is "breaking the chain" that otherwise might back-contaminate Earth with potential Mars organisms (the requirement is 10^{-6} probability of a single Mars organism entering Earth's biosphere). The HES, along with the rest of the MAV, is sealed inside the Lander's launch tube until the moment of launch; only the interior of the HES chamber is exposed to Mars. Stray dust is precluded on the final seal surfaces by polymer tape peeled away just prior to hatch installation and soldering. Upon second stage separation, the HES fairing separates, along with the outer layer of the HES chamber hatch assembly, exposing only factory-sterilized surfaces over the entire HES. Finally, a net-zero-thrust duration burn is performed on all divert thrusters, to sterilize their exposed surfaces. The HES is now prepared for rendezvous with the EP Stage. As a final precaution, all surfaces exposed to potential contamination – HES sample chamber interior, HES hatch region exterior, EP Stage return vessel interior – are treated with biocidal coatings, and can be flooded with biocidal gas at key steps in the mission.

The Mars Orbit Rendezvous (MOR) concept is fully autonomous, driven by the signal delay between Earth and Mars, but with a few stable "hold points" designed in so that mission managers can verify correct execution. The approach assures excellent viewing angles during all phases of target approach, accommodates sensor failures and subsequent system reconfiguration, and supports minimal risk of unplanned contact with the target. The rendezvous sensor suite is rich with complementary, dual-redundant sensors designed to provide primary measurements during one phase while serving a backup role in another. The autonomy framework, including laboratory demonstrations of the flight sensor suites, complete system integration checkouts, and Earth-based flight demonstrations, is set to be demonstrated by DoD, DARPA, and other ongoing NASA rendezvous programs (e.g. Orbital Express, XSS-11, DART).

The HESs communicate with the European Relay Orbiter throughout ascent, and directly with the EP Stage during rendezvous. They also carry the Vis-Nav system developed by JPL, to enable autonomous terminal rendezvous and final capture. Capture mechanisms in the EP Stage return vessels extend out for operation, then withdraw the HESs inside the vessels for the return trip.

The EP Stage is based on heritage systems to minimize risk: SpectrumAstro 200-HP bus, two pairs of gimballed N-Star xenon ion engines (uprated to 3900 sec I_{sp} at 3200 W_e), and Boeing solar arrays (BSS702 triple-band-gap-junction cells on a BSS601 structure configuration modified for stiffness during HES rendezvous and for retraction upon Shuttle rendezvous). Four clusters of three 220 mN xenon hot-gas thrusters provide bang-bang attitude control for rendezvous. Upon return to Earth orbit, the EP Stage retracts its solar arrays, is captured by the Shuttle remote manipulator system (RMS), and attached to a disposal stage mounted in the payload bay. Final visual micro-inspection and chemical leak-sniffing inspections are performed before the RMS transfers the return vessels into the vacuum vaults for re-entry. If leakage is detected, the option exists to dispose of the stage and payload. In any case, the EP Stage itself is ultimately boosted to a high disposal orbit before the Shuttle returns to Earth.

4. Development and Integration

With a mission requirement that emulates eventual human missions in miniature, and is executed by nine flight elements of such diverse type, MSR will require a development program of unprecedented complexity. The need for mission assurance will argue for intensive scrutiny, many developmental and flight tests, and an extensive array of developmental hardware units for functional interface verification across many contractors and labs, possibly even international space agencies. We defined an extensive test program consistent with this scenario, including many MAV flight tests, and a Shuttle-based Earth orbital test of the Mars Orbit Rendezvous event. Including all flight, spare, test, engineering development, mockup, brassboard and "iron-bird" units, we accounted for 182 equivalent hardware end-items in the development program.

Our hardware integration assumptions depart from the traditional JPL method: developmental units brought together at JPL, then replaced one by one with flight hardware until the full-up system is integrated and tested, then de-integrated and shipped to the Cape for launch. Experience with International Space Station (ISS) systems validates another approach, in which interface verification occurs digitally throughout development, and physical integration occurs only at the Cape. Integration of all MSR flight elements cannot occur until they are processed at the Cape, because of the nested configuration of hazardous systems (pyrotechnic charges, solid propellants, hydrazine, and radio-isotopes) and because of the elaborate procedures required to meet NASA's stringent planetary protection cleanliness requirements: Level V (sample system – the requirement is 10^{-2} probability of a single Earth organism contaminating a Mars sample), Level IVB (landing site) Level IVA (planetary entry), and Level III (controlled Mars orbit). We planned a combination of facility-based clean procedures, followed by flooding of the enclosed spacecraft with ethylene oxide, to meet the forward contamination requirement for organisms and macromolecules (e.g. 30 spores total for the vehicle). Fig. 11 depicts the processing flow at the Cape.

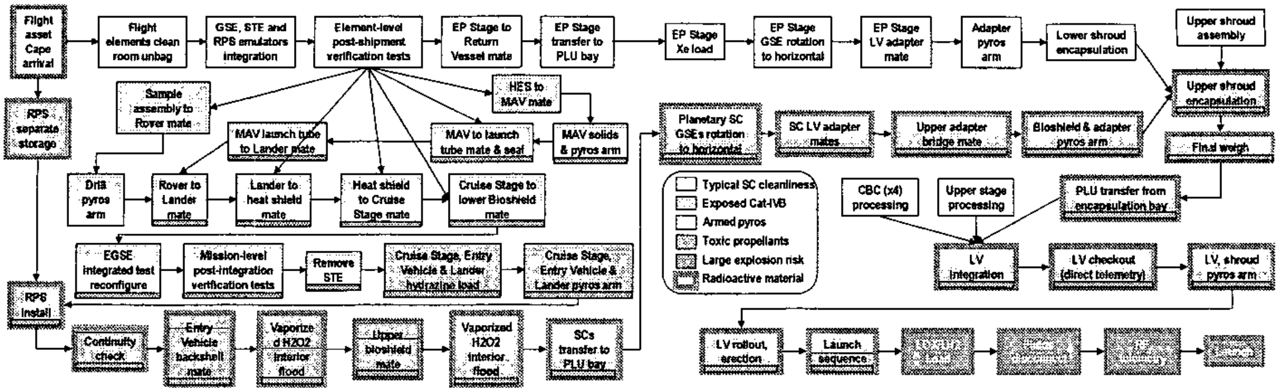

Figure 11 – Launch integration processing flow.

5. Technology Requirements

One of the principal objectives of the study was to identify MSR technologies requiring development to reach Technical Readiness level (TRL) 6 by 2006. We assumed ongoing NASA technology thrusts: the New Millennium Program series (including Deep Space 1, ST6 and ST7) and JPL mission-area endeavors (deep space navigation, instrumentation, communications and spacecraft, and *in situ* science systems). We surveyed each subsystem in our Phase 2 MSR mission design to identify the heritage for key elements, paying special attention to multi-subsystem functional areas like autonomous rendezvous and capture, descent and landing, and planetary protection. For technologies not already on a trajectory to attain TRL 6 by 2006, we specified capability targets, laid out development roadmaps and identified test facilities required.

To the maximum extent, our Cruise Stage, Entry Vehicle and Lander designs build upon past and planned JPL technology developments for Viking, Cassini, Pathfinder, Mars Surveyor, Smart Lander, and Mars Observer. Essentially no new technology development would be required for these elements. In the case of the Rover, MAV, HES, and EP Stage, and for the autonomous rendezvous and capture, descent and landing, and planetary protection functions, not all technologies will reach TRL 6 without concerted effort. For example, appropriate planetary protection technologies are available but not altogether space qualified; in some cases compatibility testing is required to assure that preferred techniques can be used for specific flight subsystems. However, almost all of the required technologies enjoy some development foundation from other, non-Mars, non-NASA and even non-government programs: terrestrial roving robotics, guided missile propulsion and control, electric propulsion, automated space rendezvous, and terrain-responsive flight control. What MSR needs is technology tailoring, not technology creation.

We identified the 15 key MSR technology need areas listed in Fig. 12. For each of these, we specified subsystem performance targets (some high-attention examples are shown in Table 2), time-phased technology development roadmaps to reach those targets on schedule, and capital facilities required to support the roadmaps. Of the areas prioritized by our analysis, some are relatively architecture-independent, such as a Stirling cycle RPS for mobile power, and miniaturization of navigation and communication subsystems for Mars ascent.

- Solar electric thrusters
- Radiation-hardened systems
- Trajectory control (autonomous low-thrust navigation)
- Stirling cycle converter
- Autonomous rendezvous and capture
- Sample Selection and Handling
- Autonomous Planetary Drill
- Micro-Electro-Mechanical Systems Inertial Measurement Unit
- HAN-based monopropellant
- Lightweight UHF transponder
- Visual navigation sensor & Smart Lite Beacon
- Rendezvous and landing Lidar
- Autonomous surface operations
- Precision entry and landing
- Planetary protection testing

Figure 12 – Key MSR technology need areas.

Table 2 – Selected technology development performance targets.

Item	Performance Presumed	Mass (kg)	Power Req (Watts)	Volume CC	Notes
N star thrusters	Max 92.7 mN thrust, lifetime 14,000 hours, 3900sec max Isp	8.3	3200 Max		Requirement for MSR exceeds DS-1 Flight Demonstration
MEMS IMU	1 deg/hr drift, rad-hard	0.28	0.8	26	Shown on MAV, may apply to other subsystems, similar to tactical system application
HAN-Water-Glycine for HES	Isp 230 (200 pulse), 20 ms minimum pulse, high thrust 325N, low thrust 15N	NA	NA	NA	Baselined for recovery safety on HES
VisNav Sensor	100 meters range, S/N .002	1	5	1500	On EP Stage
Smart Lite Beacon (per unit)	3 watts per cm² at 150m	0.1	1	200	Multiple units on HES
Stirling cycle converter	4.2 W/kg 110W continuous heat reject 350W per $100W_e$	2.6	-		Dual converters, heat control by radiators, heat pipes during cruise.
Drill	3 m length, 1 m/hr rate, bit & stem change out capability		55		
Miniaturized UHF Transceiver	10,000 km max, 400 MHz	1	10	100	MAV and SEP units
Rendezvous LIDAR and Landing Unit	1μm scanning mechanical scan	5	32	4000	Same basic unit assumed for both mission phases

6. Cost Estimate

To estimate program development cost, we first developed the work breakdown structure (WBS) to the individual system/subsystem level, resulting in 291 discrete input cells for the cost model. We used a combination of parametric, grass-roots, and cost-estimating-relationship methodologies as appropriate for each WBS line-item. For the parametric method, our engineering cost team used nine input parameters to describe each WBS item. Certain subsystem costs (e.g. the RPS) were provided as pass-throughs by JPL, and NASA "marginal cost" values were used for Shuttle mission costs. All cost values were escalated to then-year values using factors provided by JPL. The 11-year reference program schedule includes the operations phase, and begins at the end of CY05.

Total program development cost (excluding technology development programs and capital facilities, science instruments and science team, and mission operationsp, but including 30% cost margin and all escalation, overhead costs, cost-of-money burdens and prime contractor fees) is estimated at $2.8B for the dual mission. Averting cost by deleting the second landing site is ineffectual, since the non-recurring development and test program comprises the bulk of the cost. Indeed, multiple missions on a series of opportunities would be a highly cost-effective use of the MSR investment. Breakdown of the cost contribution ratios, by top-level WBS element and by spacecraft element, are shown in Fig. 13. Both Shuttle missions – the MOR flight test and the sample retrieval mission – are included (in "Other"), even though they would not likely be

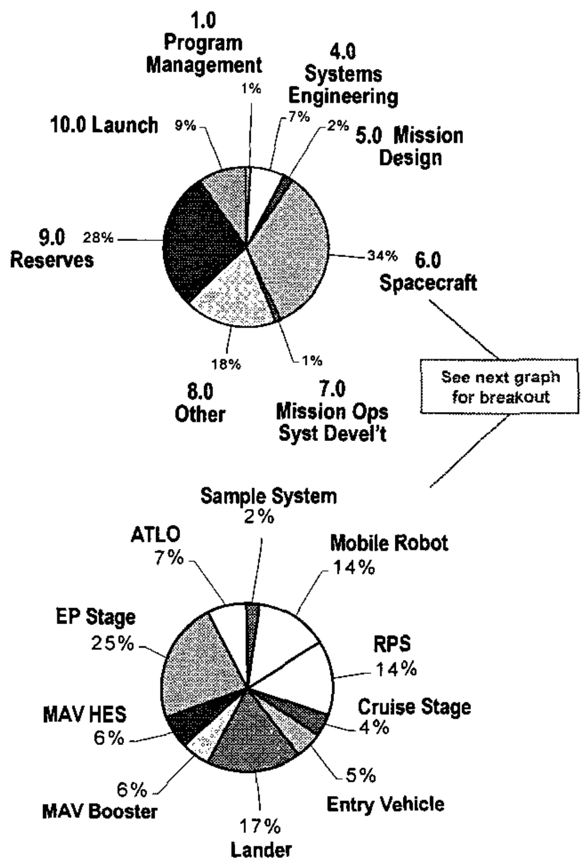

Figure 13 – Cost element ratios for total MSR development program (top) and its spacecraft cost element (bottom).

paid for by Code S. In the second graph, ATLO (Assembly, Test and Launch Operations) is considered by JPL to be a separate spacecraft cost element.

Our estimate is based on highly conservative development program assumptions, as described in the previous section. We tested the estimate's validity in two ways: through regression analysis to confirm that our assumptions of manufacturing complexity are consistent with 30-year trends for planetary missions, and through analyzing sensitivity of the result to reasonable uncertainties in model parameters.

7. SUMMARY FINDINGS

We found that it is feasible to engineer a credible design and plan for returning small amounts of scientifically selected Mars material to Earth. It is also feasible to do so without reliance on dramatic technology breakthroughs, but rather by building on the evolutionary heritage of preceding Mars Exploration Program missions. Finally, it is feasible to meet NASA's strict requirements for controlling forward, cross and back contamination.

Many diverse mission schemes can accomplish basic Mars sample return requirements. Different architectures can meet diverse, yet reasonable and foreseeable program priorities. Aggressive and dramatic missions are technically possible. Knowing this, we can engage a rich stakeholder dialog regarding how MSR missions can and should support ongoing investigation of the geological and meteorological history of Mars, the role of water on the planet, possibility of past or extant life there, and the preparation necessary for eventual human missions – both in terms of planetary protection and engineering development.

Successfully accomplishing MSR will likely require simultaneous development of diverse flight elements, by multiple contractors and laboratories distributed across several spacefaring nations. At the least, NASA will wrap itself around this "crown jewel" of planetary exploration, intent to apply the best capabilities the industry can muster. Managing this programmatic complexity poses a far greater challenge than any mission yet undertaken by JPL, and may benefit more from the lessons learned on ISS than from those learned on Viking and Pathfinder.

Even the simplest MSR mission would be costly by current robotic planetary exploration mission budget standards. This is problematic for near-term planners. Yet the central issue may not be cost *per se*, but rather value – that is, benefit as a function of cost. 500g of Mars for over $2B equates to $1M per carat, roughly 250 times the value of cut diamonds. This may, or may not, be reasonable – ultimately, public and political considerations will determine the nature of expected science that can justify approval and sustenance of even the first MSR mission.

8. FUTURE DIRECTIONS

By the time our nation decides to invest of order $\$10^9$ to return Mars material to Earth, and by the time the mission occurs, stakeholder expectations will have continued to evolve from current thinking. For example, the quest for direct evidence of life may overshadow other, more methodical science objectives. MSR may be the means to verify planetary protection protocols for human exploration. Stereo high-definition TV from Mars may be essential to maintain public support. In the extreme, demand for commercial sale of Mars material could conceivably even drive the requirement for returned quantity.

Until the potential proffered by unconventional architecture options is really understood, "break-points" in the value proposition will remain undiscovered (thus unavailable to stakeholder discussions), and a clear national consensus on MSR mission objectives will remain elusive. Without such consensus, any particular mission design is an academic response to a specific reference set of requirements. Therefore it is premature to "pot" the MSR mission architecture, and care should be taken to recognize that Mars Sample Return may look quite different when realized.

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