(Preprint) AAS 19-583

POTENTIAL CAMPAIGN ARCHITECTURES AND MISSION DESIGN CHALLENGES FOR NEAR-TERM INTERNATIONAL MARS SAMPLE RETURN MISSION CONCEPTS[*]

Robert E. Lock[†], Austin K. Nicholas[‡], Sanjay Vijendran[§], Ryan C. Woolley[**], Alan Didion[††], Frank Laipert[‡‡], Zubin Olikara[§§]

Mars Sample Return (MSR) continues to be a high priority in the planetary science community and a decades-long goal of international planetary exploration programs. Options for architectures and mission concepts are currently under study by NASA and ESA to find potential partnership opportunities to achieve MSR in the 2020s. The major elements of a potential MSR campaign have significant architectural flexibility and mission launch, arrival, and return options. The decision criteria often depend on mission design and functional allocations across many elements. This paper outlines the reference architecture and key trades among the campaign elements.

INTRODUCTION

Mars Sample Return (MSR) continues to be a high priority in the planetary science community and a decades-long goal of international planetary exploration programs. From the earliest Mars missions it was recognized that the cost of sending instruments to study Mars would always limit the investigation of Mars as a system. The scientific community has long held that, in combination with global and in-situ investigations, terrestrial investigations of carefully selected Mars samples would be needed to understand the complex history of Mars.

Significant mission studies were conducted in the late 1970s, late 1980s, and 1990s. International studies were introduced in the late 1990s and have received frequent updates since the mid-2000s. Some of these studies are explained in more detail in the next section – MSR Background.

[†] Development Manager, Mars Program Formulation Office, NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109; robert.e.lock@jpl.caltech.edu.

[‡] Systems Engineer, Project Systems Engineering & Formulation, NASA Jet Propulsion Laboratory, California Institute of Technology

[§] Mars Sample Return Lead, Human and Robotic Exploration Directorate, European Space Agency - European Space Research and Technology Centre (ESTEC), Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands.

[**] Mission Design Engineer, Inner-Planets Mission Analysis, NASA Jet Propulsion Laboratory, California Institute of Technology

[††] Systems Engineer, Project Systems Engineering & Formulation, NASA Jet Propulsion Laboratory, California Institute of Technology

[‡‡] Mission Design Engineer, Flight Path Control, NASA Jet Propulsion Laboratory, California Institute of Technology

[§§] Navigation Engineer, Inner-Planets Mission Analysis, NASA Jet Propulsion Laboratory, California Institute of Technology

Mission architectures in the last two decades have remained similar: launch a lander carrying a rover and an ascent vehicle to acquire scientifically significant samples and to launch them to orbit, and an orbiter to return the samples to Earth. The technical approach based on heritage, experience, and industrial capability has advanced over time leading to variations in proposed implementations. The architectures currently under study have achieved a high level of maturity such that cost and risk can be carefully managed.

Advances in technology, industry capability, and flight experience come from a wide variety of sources. The expansion of spacecraft capabilities in Earth orbit to meet scientific, military, and commercial needs has provided large, relatively inexpensive launch vehicles, large spacecraft designs, high-power electric propulsion, and complex trajectory designs and operations. Planetary missions have expanded the experience of NASA and ESA to explore targets across the solar system. Ever more complex trajectories, system designs, and autonomous operations have been accomplished. Entry, descent and landing systems for Mars and Earth return vehicles have been demonstrated at many scales and with a variety of technologies. The MSR mission options under study collaboratively by NASA and ESA make use of the newer capabilities and are working to ensure the campaign mission architectures are feasible. New approaches to the design of systems, trajectories and operations concepts are optimized to fit constraints of launch vehicles, development schedules and budgets, and mission timelines.

Analysis tools and techniques have been developed to take advantage of the new opportunities and to understand the feasibility of large, complex, and high-power mission concepts. This paper discusses the international MSR architecture currently under study and is submitted as part of a group of papers that each discuss some of the recent work that shapes the architectural opportunities and feasibility analysis leading to the specific architecture options in the current study. The papers submitted with this one are based on the architecture options described in this paper. These papers are:

- Woolley, et al, "Low-Thrust Trajectory Bacon Plots for Mars Mission Design," [1] describes low-thrust analogs to pork chop plots for Mars missions including the MSR campaign architecture studies. These bacon plots underlie the end-to-end mission analysis for all of the architectures in the current MSR studies.
- Laipert, et al, "Hybrid Chemical-Electric Trajectories for a Mars Sample Return Orbiter,"[2] defines methods for developing trajectories for Mars sample return orbiters using both solar electric propulsion and high impulse chemical propulsion systems.
- Haw, et al, "Mars Sample Return - Orbital Rendezvous Detection Methods,"[3] describes key navigation trade studies for detection of the orbiting samples at Mars that have strong influence on the architecture of the Sample Return Orbiter.
- Olikara, et al, "Chemical and Solar Electric Propulsion Orbit Matching for Mars Sample Rendezvous,"[4] describing orbit matching concepts for time efficient rendezvous with orbiting samples at Mars for sample return orbiters using chemical propulsion or electric propulsion.
- Nicholas, et al, "Simultaneous Optimization of Spacecraft and Trajectory Design for Interplanetary Missions Utilizing Solar Electric Propulsion,"[5] in which a tool ("MORT") is described for simultaneously optimizing the spacecraft design alongside the trajectory given mission constraints and objectives. MORT is essential for primary parameter exploration, first order spacecraft sizing and mission timeline assessment for MSR mission architecture development.
- Nicholas, et al, "Mission Analysis for a Potential Mars Sample Return Campaign in the 2020's,"[6] demonstrates a method for modeling the various campaign elements, synthesizing coordinated campaign timelines, and assuring trajectory feasibility in the presence of

many constraints. The campaign architectures under study use this method for key decisions and trade studies.

While the reference architecture under study is described in this paper, there are significant trade studies examining the effects of technology readiness, industry capability, alignment of international development schedules, and others. Several architecture options are under study reflecting potential constraints from these sources. A short discussion of these options is provided.

MSR BACKGROUND

After initial global and in-situ discoveries made by the Viking missions in the late 1970s, the National Academies of Science recommended strategies for the return of samples from Mars as well as continuing orbital and in-situ investigations.[7] Significant studies brought forth strategies for site selection, sampling priorities, planetary protection and for segmenting the mission into technically feasible elements.

In the late 1980s, NASA planetary science strategies called for a Mars Rover Sample Return (MRSR) mission and a pre-project was started to develop it.[8] The mission was a four-flight concept consisting of a communications orbiter, a lander with a rover, a Mars ascent vehicle and a sample return orbiter. Several options for these concepts were studied; by the end of the decade, new national exploration priorities were put in place and the MRSR mission was cancelled.

In the following decade, Mars orbital science and in-situ landed missions from the United States, Europe, and elsewhere continued, advancing technologies and flight experience at Mars in high resolution orbital science, increases in landed mass and precision, new landing techniques, aerobraking, and rover mobility.

A NASA MSR project was formed in partnership with the Centre National d'Études Spatiales (CNES) in 1998, nearly reaching Preliminary Design Review (PDR) stage.[9] That project was canceled after the losses of Mars Climate Orbiter (MCO) and Mars Polar Lander (MPL) in 1999, but laid the foundation for future MSR mission concepts. Subsequent international studies refined an MSR architecture to include: 1) a lander mission with a rover for collecting samples and a rocket called a Mars Ascent Vehicle (MAV) to put a sample container into orbit; 2) an orbiter mission that would return the samples to Earth; and 3) a sample receiving facility (SRF) to contain and preserve the returned samples. In addition, focused industry studies were commissioned to define the MAV design and another set to define the SRF and processes to be performed at the SRF. Feasibility studies concluded that the sample collecting and caching rover and the MAV would likely need to be launched on separate lander missions.

MSR has continually been the subject of debate for competition for funds with in-situ and orbital missions. The National Research Council (NRC) report “An Astrobiology Strategy for the Exploration of Mars” published in 2007,[10] indicated that not only was returning samples the highest priority for astrobiology, but also that with the current missions on the books at that time, there would be enough information to select an appropriate sampling site. Since then, MSR has been regarded among the highest priorities in the National Academy of Science planetary science decadal surveys.[11,12]

Significant accomplishments and developments have increased NASA’s confidence in the technical feasibility of MSR. These come from many NASA and ESA missions and mission studies. Recent NASA Mars missions: Mars Pathfinder, Mars Global Surveyor, Odyssey, Mars Reconnaissance Orbiter, Phoenix, the Mars Exploration Rovers Spirit and Opportunity, and the large Mars Science Lander Curiosity have all contributed technologies, design heritage, and flight experience needed for MSR. ESA’s Mars Express and Trace Gas Orbiter missions have advanced the ESA heritage in a similar way. Other non-Mars missions such as Dawn, Deep Space 1, SMART-1, ESA's BepiColombo, and a variety of GEO-comsats have advanced the solar electric propulsion heritage needed to enable the sample return orbiter mass capability and mission flexibility. NASA's Stardust and Genesis missions demonstrated navigation capabilities for targeting an Earth entry vehicle for landing the samples.

Recent NASA and ESA MSR mission studies and technology development activities along with missions already in development such as JUICE and Mars 2020 have expanded the design capabilities and methods to develop a complex MSR mission. In particular, NASA studies from 2013 through 2017 introduced solar electric propulsion (SEP) to Mars science orbiter and MSR orbiter concepts[13,14,15] culminating in the Next Mars Orbiter (NeMO) concept based on the Next Orbiter Science Analysis Group (NEX-SAG) report of the Mars Exploration Program Analysis Group (MEPAG).[16] The NeMO mission concept is a multifunction Mars orbiter to conduct science observations and return Mars samples, potentially for launch in the mid 2020s. Finally, the general advance of space mission capability of industry in the United States and Europe has also made the MSR campaign more feasible and lower in cost than the missions contemplated in 1980s and 90s.

CURRENT MSR ARCHITECTURE STUDIES

During 2018 and 2019 the MSR campaign and its elements are being conducted as NASA and ESA mission studies, intended to reach the level of technical and programmatic maturity required to pursue an effective partnership, as noted in the 2018 Joint Statement of Intent between NASA and ESA on Mars Sample Return.[17] While not final or agreed to as yet, the reference mission architecture described below is the result of recent work and is the basis for a comprehensive trade space used in the concepts under study. An overview of the MSR Architecture elements and functional relationships is shown in Figure 1.

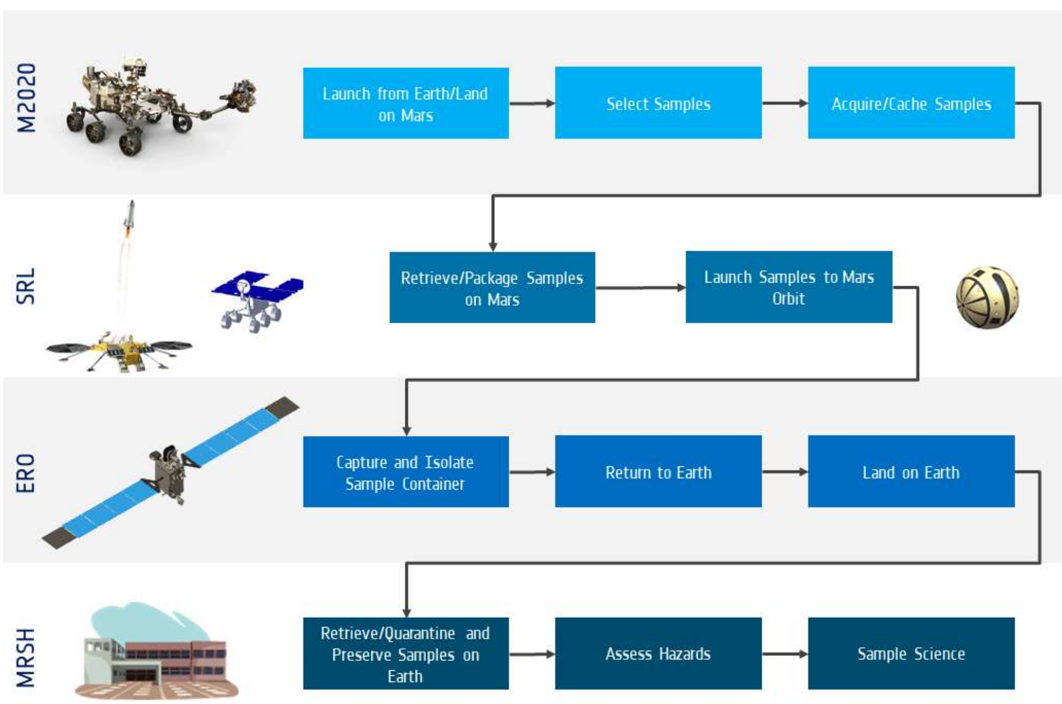


Figure 1. Overview of the notional MSR campaign.

Both NASA and ESA apply a “lean approach” to the implementation of MSR. This approach aims to execute development affordably emphasizing early and focused technology development for cost savings, the strong use of design heritage/existing technologies, no heavy lift launcher, i.e. SLS, no in-situ science instruments, and the use of existing infrastructure where possible (e.g. communications orbiters, M2020 delivery)

Functional Objectives

The functional objectives for a potential MSR campaign include the following:

- Acquire and return to Earth a scientifically selected set of Mars samples for investigation in terrestrial laboratories.
- Select samples based on their geologic diversity, astrobiological relevance, and geo-chronologic significance.
- Establish the field context for each sample using *in situ* observations.
- Ensure the scientific integrity of the returned samples through contamination control (including round-trip Earth contamination and sample-to-sample cross-contamination) and control of environments experienced by the samples after acquisition.
- Ensure compliance with planetary protection requirements associated with the return of Mars samples to Earth’s biosphere.
- Achieve a set of sample-related scientific objectives including: life, geologic environments, geochronology, volatiles, planetary-scale geology, environmental hazards, and In Situ Resource Utilization (ISRU).

MSR Architectural Elements

The notional Mars Sample Return Architecture under study by NASA and ESA is comprised of three separately launched flight elements and one ground element. The elements are:

- The Mars 2020 Rover flight element - responsible for sample selection, acquisition and caching.
- A Sample Retrieval Lander (SRL) flight element - would include a Sample Fetch Rover (SFR) to collect the cached samples, the Orbiting Sample (OS) container, in which the samples would be loaded, a Sample Transfer Arm (STA) to load the samples into the OS and the Mars Ascent Vehicle (MAV) to launch the OS into Mars orbit.
- An Earth Return Orbiter (ERO) flight element (including its payload) – would provide relay communications for SRL and its sub-elements, rendezvous and capture of the OS, and include the Capture/Containment and Return System (CCRS) which would capture and contain the OS and provide a capability to return it to the surface of Earth.
- A Mars Returned Sample Handling (MRSH) facility ground element - would receive, quarantine and curate the samples. It would also be responsible for assessing hazards, and providing the opportunities for the international science community to conduct sample science.

MSR Mission Scenario and Roles

The current study, based on the joint NASA/ESA Statement of Intent, places NASA as lead in the MSR campaign and providing the Mars 2020 sample collecting rover, the SRL and the orbiter’s CCRS payload. ESA role is to provide the ERO mission, a Sample Fetch Rover, and a Sample Transfer Arm. Figure 2 shows the current architectural elements, their general interfaces, and the currently assumed roles.

NASA's Mars 2020 Rover is designed to accomplish the first step in the MSR campaign.[18] Its mission has the goal to perform the initial caching and depositing of carefully selected samples within specially designed hermetically sealed containment tubes. These tubes will be deposited on the surface of Mars for possible collection by subsequent missions, or stored onboard for direct delivery to a return mission. The landing site for the Mars 2020 mission has been the subject of an extensive series of workshops, with the final site selected to be Jezero Crater in December 2018.

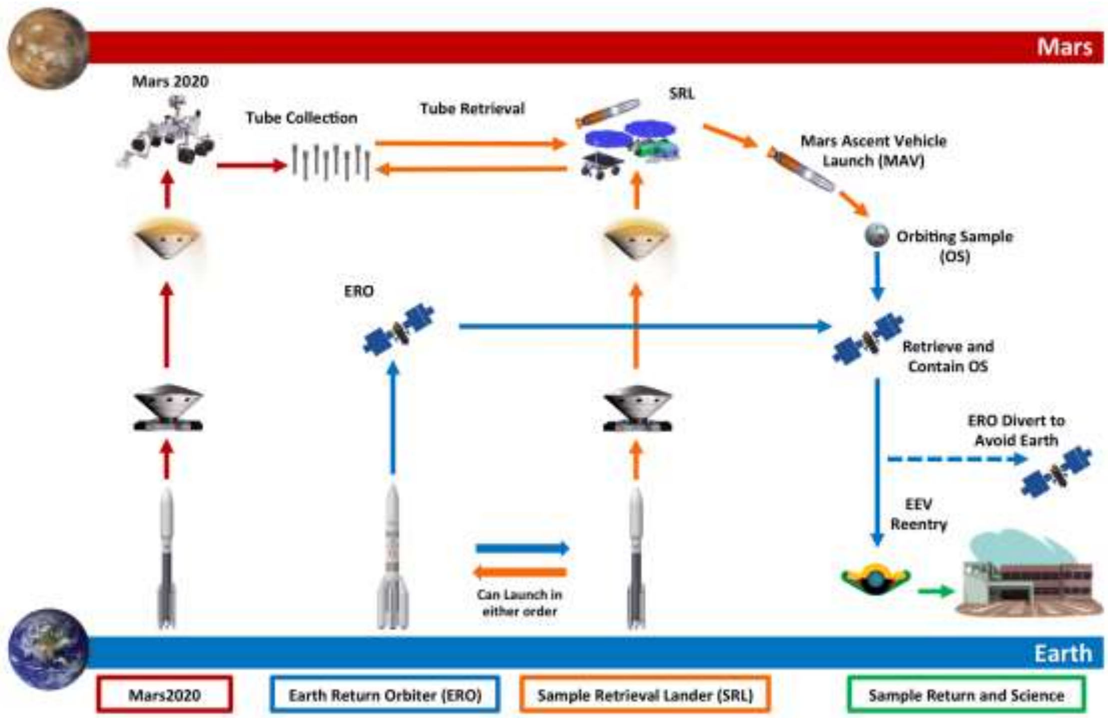


Figure 2. Potential MSR Mission Scenario. Arrow colors indicate roles: Red is NASA Mars 2020, orange is NASA SRL, blue is ESA SRO, and green is NASA and international sample curation and analysis.

NASA's SRL mission would land a platform carrying a MAV and ESA's SFR in the near vicinity of the sample tube depot. The SFR would then egress and retrieve the sample tubes deposited on the surface and return these to the platform. STA would then be responsible for the transfer of the sample tubes from the SFR into an OS canister, which sits atop the MAV on the SRL platform. The MAV would then launch the OS, and be responsible for its release into Low Mars Orbit (LMO), where the subsequent mission would capture it.

ESA's ERO mission would provide the third element. The ERO spacecraft carries the CCRS payload, currently being studied by NASA's Jet Propulsion Laboratory. ERO's mission would be to carry the payload to Mars orbit, monitor the launch of the MAV, and autonomously rendezvous and capture the OS. Once the OS is captured, the CCRS would be responsible for the containment of the Mars samples to ensure compliance with backward planetary protection requirements and its transfer into an Earth Entry Vehicle (EEV). The ERO would then return to Earth with the EEV and release it onto an Earth entry trajectory, before itself performing an Earth avoidance maneuver and ending in heliocentric orbit. While the mission concepts are listed in functional order, the development and launch order could be different based on programmatic priorities, launch vehicle capability, and orbiter and lander propulsion concepts.

Following touchdown of the EEV on Earth, the recovered samples would be safely transferred to a dedicated Mars Returned Sample Handling (MRSH) facility(ies). This would allow for the safe storage and quarantine of the landed samples, ensure their safety and integrity, and provide the infrastructure necessary for bio-hazard and scientific analyses and later distribution.

Figure 3 shows a notional "fast" MSR timeline which could return samples as soon as 3 years after SRL and ERO launch. This timeline formed the basis of the concepts under study.[19] For MSR (especially the reference 3-year return), timeline is a critical resource.

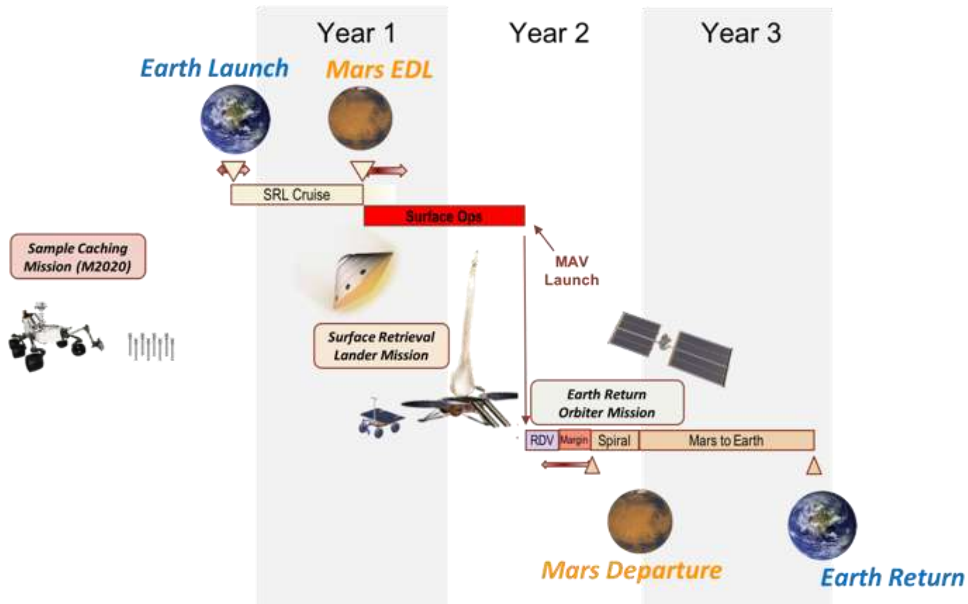


Figure 3. Notional "Fast" MSR Timeline.

The feasibility of the MSR campaign depends on both SRL and ERO, and their in-flight interaction. To address this, the approach so far is that NASA develops parametric models of both SRL and ERO flight systems and their trajectory choices, capturing relevant trades. Existing formulation tools are used wherever possible, with significant interaction with ESA to ensure models represent their current understanding of system design methods, constraints and margins. Having all the models in one place allows for rapid exploration of large architecture spaces and searches for a global campaign optimum in the early development phase. NASA optimizes at architecture level to ensure feasibility across all flight elements.

The timeline shown in Figure 4 is the result of mission analysis and system architecture assessments for the reference mission architecture that meet programmatic constraints. Nearly every trade-off in orbiter and surface mission design parameters results in a different timeline. As international programmatic, technical and implementation constraints are assessed, significant changes in timeline could result. Several architectural trades under consideration including ERO power/propulsion, SRL EDL enhancements, and SFR autonomy would benefit from more mission timeline and phasing with favorable Martian seasons than the reference architecture. Several potential 5-year mission timelines are being considered in reaction to these trades.

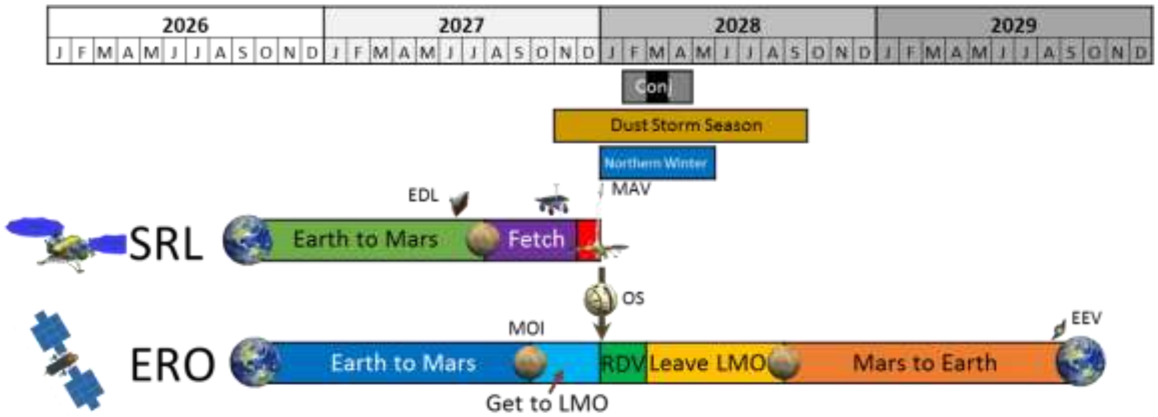


Figure 4. MSR reference campaign timeline.

Backward Planetary Protection

Backward planetary protection is a critical design driver for a potential MSR campaign. All aspects of the campaign and element architectures under study are intended to reflect requirements derived from NASA and ESA planetary protection policies and requirements. The objectives of Backward Planetary Protection (BPP) are to prevent the return to Earth of unsterilized or uncontained Mars material. This requires a strategy for the use of analysis, design, and test of the elements and systems that would be implemented and validated/certified to deliver Mars surface sample tubes to Earth, while containing and/or sterilizing any other Mars material that might reach the biosphere of Earth. The methodologies used to achieve this objective are referred to as "Break-the-Chain" (BTC).

Key Architecture Trades

Several MSR campaign elements are in active study and their systems concepts are undergoing high level configuration trade studies. The Mars 2020 mission is in integration and test and its hardware is not subject to MSR design trades. Mars 2020 operations strategies are included in campaign-level MSR trades. The design of the MRSH element is not in active study presently although technology work is currently being progressed by ESA . The science community is studying roles and requirements for the curation and study of returned samples that will lead to future element level design studies. The SRL and ERO elements each have significant architecture trades in play. A summary list of high level trades for each element is listed as follows:

SRL

- Lander configurations: options include Skycrane Delivered Lander (SDL) and Propulsive Platform Lander (PPL).
- EDL: Various enhancements under consideration for further increasing landed mass and improving landing accuracy.
- Cruise stage: heritage Mars2020-like ballistic delivery vs propulsive options (CP or EP)
- MAV: reference is a hybrid propulsion single-stage-to-orbit while a two-stage solid rocket propulsion option is under consideration as backup technology.
- OS: trades include size options based on number of samples selected for return and whether the shape would be spherical or oblong.
- SFR: trades include number and type of wheels, stow and egress configuration, technologies for rapid driving and sample retrieval.

ERO

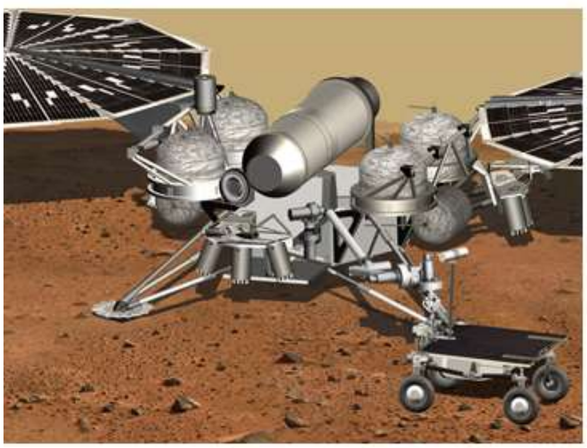
- ERO is considering propulsion options including chemical propulsion, electric propulsion, and hybrid (mix of CP and EP). Various staging options are also under consideration. These trades are strongly affected by the CCRS mass, campaign timeline and the timing of the SRL mission.
- CCRS is conducting architecture studies and considering alternatives for capture and transfer mechanisms, number of containers, robust container sealing techniques, EEV thermal protection technologies, and EEV entry trajectories for safe landing

Aspects of the trades above respond to campaign level needs and optimizing strategies. Other aspects reflect the technical and programmatic constraints of each element.

SAMPLE RETRIEVAL LANDER CONCEPTS UNDER STUDY

Lander Concepts

NASA has been actively studying two lander concepts, a Propulsive Platform Lander (PPL) and a Skycrane Delivered Lander (SDL). The SRL must land on Mars, deploy the Sample Fetch Rover (SFR), and maintain the lander and the MAV within safe operating conditions, including temperatures, while the rover retrieves the M2020 sample tubes. Once the SFR returns with the tubes, the following operations would be conducted: transfer tubes to the Orbiting Sample (OS) in the MAV Payload Assembly (MPA), using the Sample Transfer Arm (STA); assemble the MPA to the MAV; prepare the MAV for launch (heat to operational temperatures and erect); and execute the MAV launch. The two lander concepts at the time of terminal descent are shown in Figure 5. Most of the Entry, Descent and Landing (EDL) technology is common to both options and is based on Mars Science Laboratory. This includes the aeroshell and the parachute system.



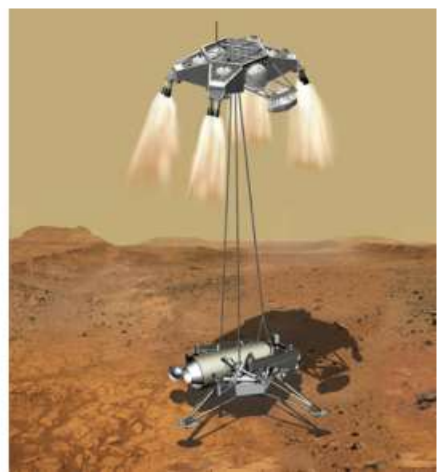


Figure 5. Design Concepts for a Propulsive Platform Lander (left) and a Skycrane Delivered Lander (right).

The key study elements are the same regardless of the option. Accommodation of both a MAV (400 kg allocation) and fetch rover (120 kg allocation) within the lander and inside an aeroshell with margins on both mass and volume is currently being studied. Presently, the SRL (including SFR) is being studied as a purely solar option, incorporating no nuclear material in any elements (per programmatic direction from NASA, the option of radioisotope power systems is not being considered for these MSR mission concepts.) Both solar power and thermal design are being carefully studied for the worst-case environments. The MAV propulsion technology, performance (including mass), and reliability is currently being evaluated for multiple propulsion systems. Several challenges with the OS, including tube accommodation and insertion into MAV, are being studied. Finally, planetary protection design and implementation strategies are being considered.

Both concepts currently meet functional constraints and have specific advantages/disadvantages. The SDL concept provides a softer landing with less plume/ground interactions due to the Skycrane technology. The PPL concept provides larger configuration and packaging flexibility/margin (in both volume and mass) but presents the complication of potentially significant plume/ground interactions due to the landing thrusters firing closer to the ground (the thrusters utilize a shower head nozzle but the ground pressure and effects are still being studied) The concepts are in the early study phase and require much deeper study and design including areas such as SFR accommodation, MAV accommodation (including launch) and tube transfer.

Orbiting Sample (OS) Container Concept and Sample Transfer Arm

The OS must hold the desired number of sample tubes as cached by Mars 2020. The final number of tubes and the shape of the OS (e.g. spherical or cylindrical) to be returned is still being traded, but currently ranges from 20 to 36. The maximum assumed mass and diameter are 12 kg and 280 mm respectively. Tubes would be inserted into the OS by the Sample Transfer Arm on the lander, transferring from a tube storage system on the SFR directly into the OS. After the samples have been inserted (See Figure 6), the OS then must be assembled and finally launched to orbit by MAV. The tubes need to be secured and maintained through environmental conditions through Mars launch, Earth return and Earth landing. Constraints placed on the management of the sample tubes by science include maintaining the temperature to less than +30 ºC and magnetic field below ½ mT (at the sample). Additionally, the OS must accommodate rendezvous and tracking by visual wavelength cameras on the orbiter and have sufficient albedo to be detected in Mars orbit.

Figure 6. Spherical OS concept in assembled configuration (left) and open with sample tubes installed (right).

Mars Ascent Vehicle Concept

The MAV is responsible for launching the OS from the surface of Mars to a ~350 km altitude, 25-degree inclination, circular orbit. Dispersions are currently desired to be maintained below ±1 degree of inclination and ±32 km in semimajor axis. Accommodation drivers for the MAV are the mass (400 kg) and geometry (3 m long by 0.57 m diameter) in order to fit within the lander. A MAV launch from a PPL concept is shown in Figure 7.

The hybrid MAV concept is a single-stage-to-orbit hybrid propulsion system using a wax-based fuel and Mixed Oxides of Nitrogen (MON) oxidizer capable of being stored in the variable and low temperature conditions on Mars.

Figure 7. Notional Propulsive Platform Lander with MAV launch.

Numerous propulsion options have been evaluated in the past for the MAV. Most recently these included: single stage monopropellant, liquids and hybrids as well as two stage solids. The hybrid option was selected as the reference and for technology development to mature the novel propellant combination that resulted in both the lowest Gross Lift-Off Mass (GLOM) of the study as well as low-temperature storage capability.

Sample Fetch Rover Concept

The SFR's job would be to acquire sample tubes from the Martian surface. In order to achieve this objective within the fast mission profile, the SFR mission duration would last a maximum of 150 sols, with an average traverse distance required of approximately 250 m/sol. This distance is being traded against the SRL landing divert capability.

The fetch rover conceptual design has a not-to-exceed mass allocation of 120 kg and a stowed volume of approximately 1 m^3. A JPL design concept used for lander sizing and campaign analysis is shown in Figure 8. This design leverages 2.5 m^2 of solar arrays to power the rover. Navigation is achieved with onboard image processing to support autonomous driving and tube manipulation activities. A UHF relay between the fetch rover and Mars orbiters would be used for communication. ESA is currently performing competitive Phase A studies of the SFR, with European industrial contractors, and are therefore not able to provide any additional information as the studies are still on-going.

Figure 8. NASA Concept for Fetch Rover.

The possibility of using Mars 2020 to return tubes to SRL was studied and the option was found to be feasible, although risk assessment continues as Mars 2020 would run beyond its design life during the SRL mission. The SRL would need to carry minimal additional hardware to transfer tubes from Mars 2020 to the OS. The current reference architecture maintains the capability to return samples delivered by both the fetch rover and Mars 2020 as the most robust solution. Future study will refine this strategy.

THE EARTH RETURN ORBITER MISSION CONCEPT UNDER STUDY

The ERO mission could be the first spacecraft to make the round-trip between Earth and Mars.[20] The spacecraft would consequently also likely be the largest that has ever been sent to Mars, as it needs to carry the propellant needed for both the outbound trip and the return journey to Earth. At Mars, the ERO would also be the first spacecraft to perform autonomous orbital rendezvous around another planet. Due to the distance from Earth, the rendezvous with the OS container around Mars requires a higher level of on-board autonomy than has been flown for previous missions. The ERO would also need to undertake an aggressive staging strategy in Mars orbit to shed unwanted hardware (once the OS has been captured) and reduce system mass and thus, the required time and propellant mass for the return trip.

Mission Concept Overview

An overview of the major events in the notional ERO mission timeline is shown Figure 9 with event descriptions below.

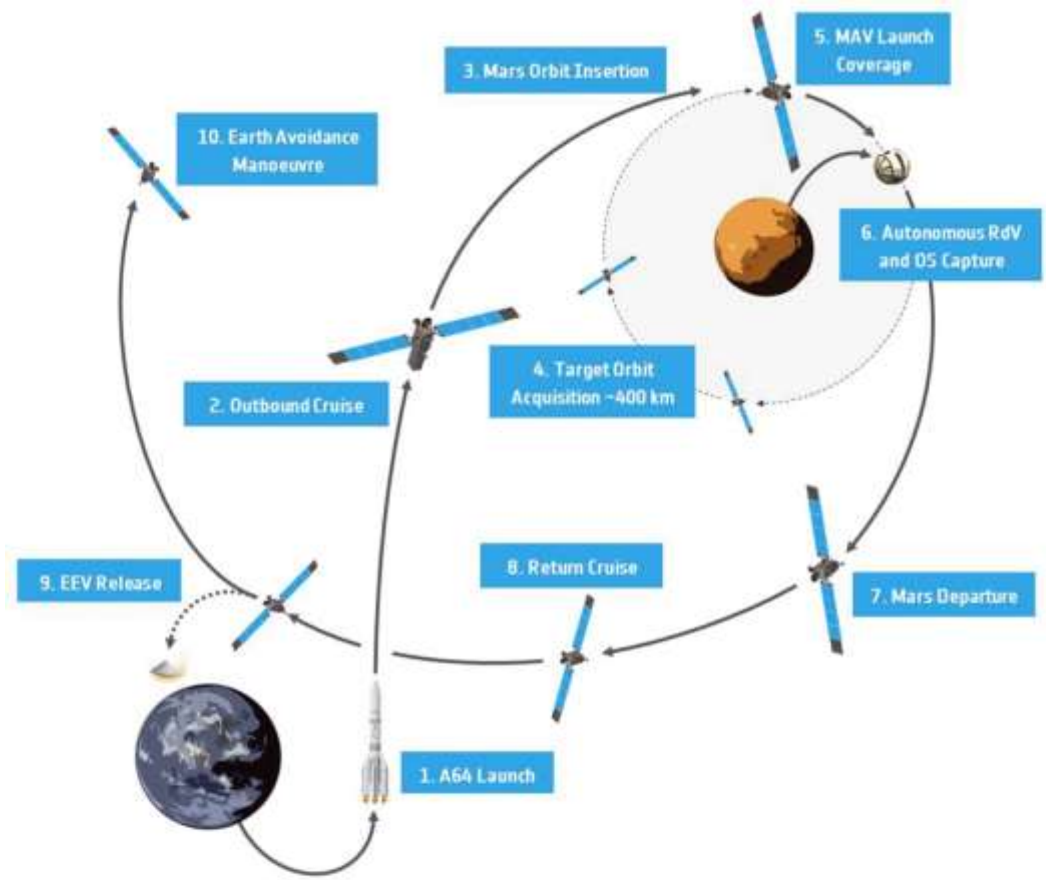


Figure 9. Key events of the conceptual ERO mission timeline.

1. The ERO would be launched by the Ariane 6.4 from Kourou. The spacecraft would be inserted by the launcher into a direct Earth escape orbit with positive C_3 energy.

2. The spacecraft makes the outbound journey to Mars, with a notional time of flight of between 320 and 450 days. Using Electric Propulsion (EP), the spacecraft would perform a continuous low-thrust burn for a significant portion of the flight time outbound leg.

3. The ERO performs Mars Orbit Insertion after arrival at the Mars SOI. This is performed using a Chemical Propulsion (CP) stage to insert the spacecraft into a highly elliptical orbit.

4. The spacecraft maneuvers from the highly elliptical orbit down into the circular target rendezvous orbit approximately 400 km above the surface of Mars. The spacecraft relies on low-thrust EP inward spirals to reach the target orbit. During this time and after achieving the target orbit, the spacecraft provides telecommunications coverage to surface assets.[21]

5. The ERO would be positioned to provide tracking and monitoring of the launch of the Mars Ascent Vehicle (MAV). The MAV lifts off from the surface of Mars and releases the OS into a circular orbit at approximately 400 km altitude.

6. The ERO performs an initial acquisition and orbit matching with the OS based on optical images and tracking and telemetry data from the MAV launch. The spacecraft maneuvers to reduce the separation to the OS, relying on data from its on-board sensor suite. At approximately 100 m separation, the spacecraft is positioned to make the autonomous terminal approach and capture of the OS. Once captured, the CCRS payload performs break-the-chain and containment

operations on the OS before transferring it to the Earth Entry Vehicle (EEV). The Capture and Orientation Module (COM), the Containment Module (CM) of the CCRS, and the rendezvous sensors are jettisoned in Mars orbit once the containment and transfer operations are complete. The ERO also releases its propulsion module ('Drop Stage') in Mars Orbit to reduce the return system mass.

7. The spacecraft begins electrically spiraling out to Mars escape.

8. The ERO makes the in-bound journey from Mars to Earth, with a notional time of flight between of 220 and 450 days. The spacecraft would perform continuous low-thrust burns for a significant portion of the transfer.

9. Upon arrival at Earth, the ERO targets and releases the EEV on a trajectory targeting the landing site, 1-4 days before Earth arrival at a V_∞ of less than 4.5 km/s.

10. The ERO performs an Earth Avoidance maneuver following the release of the EEV. This is to ensure that the spacecraft does not enter the Earth's atmosphere due to the potential risk that it may be contaminated with residual unsterilized Martian dust particles. Additional maneuvers after the Earth flyby may be used to reduce the long-term Earth collision probability.

ESA is currently performing competitive Phase A studies of ERO, with European industrial contractors, and are therefore not able to provide any information on the ERO spacecraft concepts being considered as the studies are still on-going.

Key Design Challenges

Launch Mass - One of the key challenges of ERO is the launch mass of the system due to the high delta-v nature of the round-trip mission. Given the mass allocation for the CCRS payload, which is currently 500 kg (total launch mass), launch on the Ariane 6.4 of a chemical propulsion mission is considered very challenging once all margins have been taken into account. As such, the ERO uses a hybrid mix of EP and CP in order to improve launch margins and mission flexibility. The CP concepts studied have typically around 2,000 kg of dry mass and a launch mass of around 5,000 kg. Hybrid concepts have typically around 3,000 kg of dry mass and a launch mass of around 6,000 kg. Due to the use of the high-efficiency electric propulsion, higher launch masses are permissible with EP as a lower C_3 can be targeted by the launcher.

Autonomous Rendezvous in Mars orbit - The autonomous rendezvous with the OS is identified as a challenging and critical element of the mission design. Following the launch of the MAV, the orbiter is required to detect and locate the passive 28 cm diameter OS in Mars orbit using an on-board sensor suit.[22] Once the OS is detected, the ERO will need to match the OS's orbit. Orbit matching of the ERO with the OS orbit requires a fine balance between ΔV, and therefore propellant mass, and the time needed to complete the activity. Both chemical and electrical propulsion techniques are available so careful optimization will be needed to balance mass and mission timeline constraints. The need for on-board autonomy during the rendezvous phase is driven by the round-trip light time delay between Earth and Mars on the order of 20 minutes, and the ground-based processing delays on the order of minutes to hours. The rendezvous itself requires maneuvers to be performed every few minutes, or faster. This statistical maneuver cadence is far shorter than the light speed delay to Mars, implying that ground-based processes cannot be relied on to assist the rendezvous.

Planetary Protection - Unlike previous Mars orbiters, both forward and backward Planetary Protection measures need to be taken into account for ERO. The ERO mission would be classified under Planetary Protection measures as COSPAR Category V, restricted Earth return. In addition to minimizing potential contamination of Mars by Earth materials, preventative measures are required to 'break the chain' of contact between Mars and the Earth. Strict adherence to Planetary Protection principles is necessary for all phases of the ERO mission development in order to prevent the potential contamination of Earth's biosphere by unsterilized Mars material.

CONCLUSIONS

This paper serves to provide a status report of on-going study activities toward a potential MSR campaign, including progress toward NASA's SRL mission concept and toward ESA's ERO mission concept in collaboration with European industry partners. A high-level notional reference architecture for an international MSR campaign has been agreed between NASA and ESA and this has allowed both NASA and ESA to undertake investigations and preparatory activities for contributing elements to this potential campaign. The campaign architecture trade space is well understood, with reference options defined where appropriate and options are being evaluated to achieve robust campaign architecture closure. The major technical elements are at an appropriately detailed level of definition for this phase of a pre-project effort. Technology development is proceeding per plan. The international and NASA cross-agency team is proceeding toward closure of a robust MSR campaign architecture in late 2019.

ACKNOWLEDGMENTS

The information presented about potential Mars sample return architectures is provided for planning and discussion purposes only. Neither NASA nor ESA have made any official decisions to implement Mars sample return. This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. Government sponsorship acknowledged.

REFERENCES

[1] R.C. Woolley, F. Laipert, A.K. Nicholas, and Z.P. Olikara, "Low-Thrust Trajectory Bacon Plots for Mars Mission Design," AAS Astrodynamics Specialist Conference. Maui, HI, Jan. 2019.

[2] F. Laipert, A.K. Nicholas, Z.P. Olikara, R.C. Woolley, and R.E. Lock, "Hybrid Chemical-Electric Trajectories for a Mars Sample Return Orbiter," AAS Astrodynamics Specialist Conference. Maui, HI, Jan. 2019.

[3] R. J. Haw, E.D. Gustafson, "Mars Sample Return Orbital Rendezvous Detection Methods," AAS Astrodynamics Specialist Conference. Maui, HI, Jan. 2019.

[4] Z.P. Olikara and A.K. Nicholas, "Chemical and SEP Orbit Matching for Mars Sample Rendezvous," AAS Astrodynamics Specialist Conference. Maui, HI, Jan. 2019.

[5] A.K. Nicholas, R.C. Woolley, A. Didion, F. Laipert, Z.P. Olikara, R. Webb, and R.E. Lock, "Simultaneous Optimization of Spacecraft and Trajectory Design for Interplanetary Mission Utilizing Solar Electric Propulsion," AAS Astrodynamics Specialist Conference. Maui, HI, Jan. 2019.

[6] A.K. Nicholas, A. Didion, F. Laipert, Z. Olikara, R.C. Woolley, R.E. Lock, "Mission Analysis for a Potential Mars Sample Return Campaign in the 2020's," AAS Astrodynamics Specialist Conference. Maui, HI, Jan. 2019.

[7] National Research Council. 1978. *Strategy for Exploration of the Inner Planets: 1977-1987*. Washington, DC: The National Academies Press. https://doi.org/10.17226/12379.

[8] Sally K. Ride, "Leadership and America's Future in Space: A Report to the Administrator," National Aeronautics and Space Administration, NASA, 1987.

[9] Mattingly, R., and May, L., "Mars Sample Return as a Campaign," 2011 IEEE Aerospace Conference , Big Sky, MT, 2011.

[10] National Research Council, An Astrobiology Strategy for the Exploration of Mars, Washington, DC: The National Academies Press, 2007.

[11] National Research Council. 2003. *New Frontiers in the Solar System: An Integrated Exploration Strategy*. Washington, DC: The National Academies Press. https://doi.org/10.17226/10432.

[12] National Research Council. 2011. *Vision and Voyages for Planetary Science in the Decade 2013-2022*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13117.

[13] Lock, R. E., Bailey, Z. J., and Kowalkowski, T. D., "Mars Sample Return Orbiter Concepts Using Solar Electric Propulsion for the Post−Mars2020 Decade," 2014 IEEE Aerospace Conference , Big Sky, MT, 2014.

[14] Bailey, Z. J., Sturm, E. J., Kowalkowski, T. D., Lock, R. E., and Woolley, R. C., "Round-Trip Solar Electric Propulsion Missions for Mars Sample Return," AAS 14-365, 24th AAS/AIAA Space Flight Mechanics Meeting , Santa Fe, NM, 2014.

[15] T. D. Kowalkowski, Z. J. Bailey, R. E. Lock, E. J. Sturm, R. C. Woolley, "Robotic Mars Exploration Trajectories Using Hall Thrusters," AAS 14-364, 24th AAS/AIAA Space Flight Mechanics Meeting, Santa Fe, NM, Jan 2014.

[16] Next Orbiter Science Analysis Group (NEX-SAG) report of the Mars Exploration Program Analysis Group https://mepag.jpl.nasa.gov/reports/NEX-SAG_draft_v29_FINAL.pdf]

[17] T. Zurbuchen (NASA), D. Parker (ESA) signatories, "Joint Statement of Intent between the National Aeronautics and Space Administration and the European Space Agency on Mars Sample Return," 2018 Berlin Airshow, 26 April 2018. https://mepag.jpl.nasa.gov/announcements/2018-04-26%20NASA-ESA%20SOI%20(Signed).pdf

[18] A. Karp, F. Beyer, B. Muirhead, "Mars Sample Return Lander Mission Concept," 69th International Astronautical Congress, Bremen, Germany, 2018.

[19] T. Zurbuchen, "Mars Exploration Program," Review of Progress Toward Implementing the Decadal Survey Vision and Voyages for Planetary Sciences, August 28-30, 2017, Woods Hole, Massachusetts

[20] A. G. McSweeney, S. Vijendran, J. Huesing, R. E. Lock, A. K. Nicholas, "The Earth Return Orbiter Mission as part of an international Mars Sample Return Campaign." International Astronomical Congress, October 2018.

[21] C. D. Edwards, Jr., A. H. Farrington, R. E. Gladden, C. H. Lee, R. E. Lock, B. K. Muirhead, A. K. Nicholas, R. C. Woolley, "Proximity Link Telecommunication and Tracking Scenarios for a Potential Mars Sample Return Campaign," 2019 IEEE Aerospace Conference. Big Sky MT, 2019

[22] A. M. Didion, A. K. Nicholas, J. E. Riedel, R. J. Haw, and R. C. Woolley, "Methods for Passive Optical Detection and Relative Navigation for Rendezvous with a Non-cooperative Object at Mars", AAS 18-288, 2018 AAS/AIAA Astrodynamics Specialist Conference, Snowbird, UT, Aug. 2018.