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The Planetary Protection Strategy of Mars Sample Return's Earth Return Orbiter Mission

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Abstract

The Mars Sample Return campaign aims to use three flight missions and one ground element to safely bring rock cores, regolith and atmospheric samples from the surface of Mars to Earth to answer key questions about the geologic and climate history of Mars, including the potential for ancient life. Since its landing in Jezero Crater in 2021, the first mission, NASA's Mars 2020, has collected a number of samples on the crater floor and on the delta using the Perseverance rover. Subsequent missions would recover the sealed sample tubes, launch them into Mars orbit, and transport them back to Earth. The ground element would be a high-containment facility that would isolate and protect the samples during initial sample characterization, which would include sample safety assessments and time-sensitive scientific investigations. These elements are currently in the planning and design stages of development, and represent an international effort of NASA, the European Space Agency (ESA), and many industry partners. The work presented here provides an overview of the Planetary Protection strategy of the third flight mission, the ESA-led Earth Return Orbiter (ERO), which hosts the NASA-provided Capture, Containment, and Return System (CCRS). ERO-CCRS would detect and capture the container with up to 30 sealed tubes previously put in Martian orbit, contain them in redundant containers to ensure that no potentially hazardous Mars particles are released, and return them to Earth through an entry vehicle. Both NASA and ESA policies comply with the United Nations' Outer Space Treaty by planning to protect Earth's biosphere from any potential adverse effects from material returned from solar system bodies beyond the Earth-Moon system. In the conduct of Mars Sample Return, the two agencies have mutually agreed to apply approaches consistent with their own planetary protection standards to the campaign elements they each provides.

Keywords: Mars Sample Return, Earth Return Orbiter, Planetary Protection, Break the Chain.

1. Introduction

One of the major scientific objectives of the Mars Sample Return (MSR) campaign is to search for signs of ancient life on the Red Planet by collecting compelling samples of rock, regolith (broken rock and dust) and atmosphere for a possible return to Earth [1, 2, 3, 4, 5]. Years of data from past missions to Mars have confirmed that some areas offered habitable conditions that were capable of supporting life in the past. Much of this warmer, wetter period is believed to have occurred during the Noachian to early Hesperian period about four to three and a half billion years ago [6], within the same geologic timeframe as early life began on Earth, established by the early fossil record [7]. This commonality and the fact that the oldest rocks on Earth have been significantly altered by active plate tectonics and weathering effects that did not occur on Mars raise the prospect that discoveries on Mars will yield important insights about prebiotic chemistry and clues about the origin and evolution of life on Earth.

MSR would fulfill many years of external guidance to NASA, including the top recommendation of the U.S. science, astrobiology and exploration communities in their most recent national strategy entitled Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032 [8]. Beyond the search for life, the MSR campaign could also help scientists understand the detailed geological history of Mars, the evolution of its climate, and the potential for hazards in the Martian environment that could affect future human explorers.

Figure 1 shows the four elements of the planned MSR campaign. The first one, Mars 2020 [9], launched on July 30, 2020 and landed in the Jezero Crater on February 18, 2021. As of August 2023, the Perseverance rover has collected and sealed 1 atmospheric sample, 17 rock cores, 2

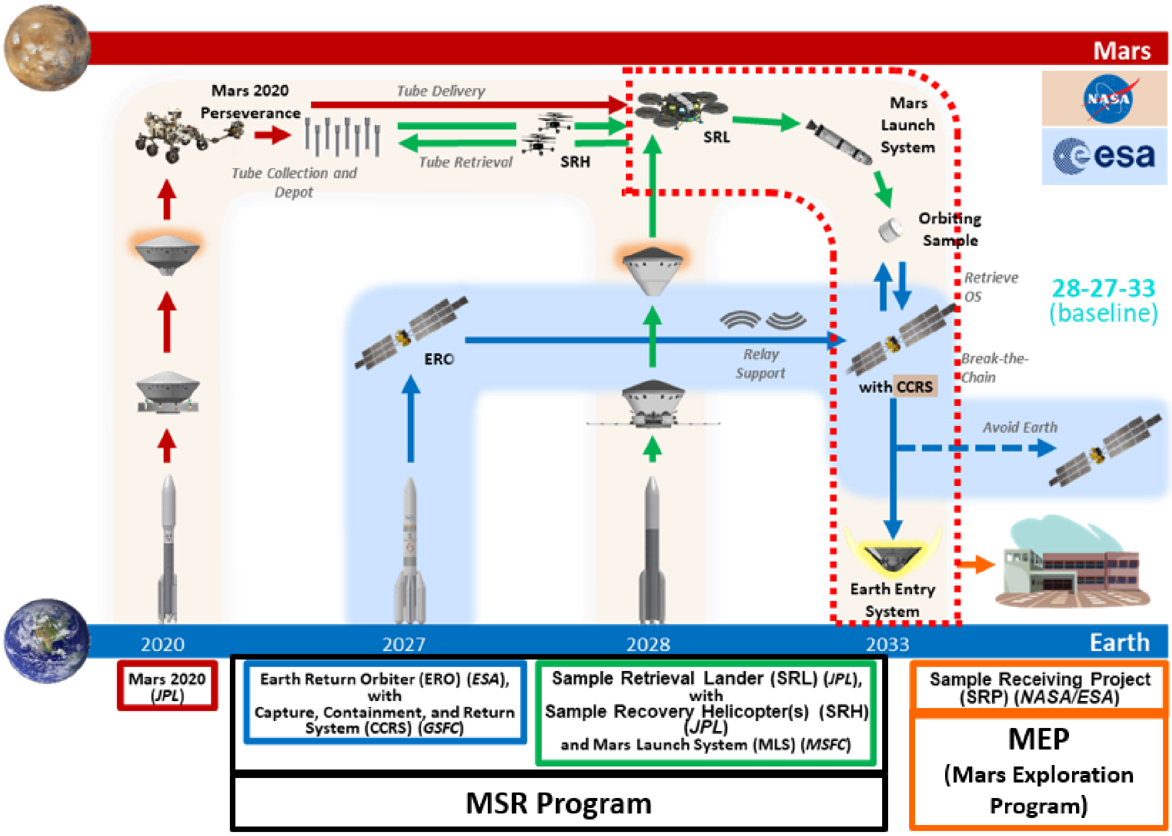

Fig. 1: Elements of the planned MSR campaign.

regolith samples and 3 witness tubes [10, 11, 12]. Ten of these sealed tubes were left at the Three Forks depot in Jezero Crater for possible return to Earth as a contingency cache.

The second element is the Sample Retrieval Lander (SRL), which would launch no earlier than 2028 to carry the Mars Launch System (MLS), the Sample Recovery Helicopters (SRHs) and the Sample Transfer System (STS). While Perseverance would be the primary means to deliver the samples to SRL, the SRHs, based on Mars 2020's Ingenuity [13], would play a back-up role in case Perseverance would become unable to perform this task. The NASA-operated STS, with a set of cameras for visual processing and operations [14] and an ESA-provided Sample Transfer Arm (STA) [15], would be capable of transferring the sealed sample tubes from Perseverance to the Orbiting Sample (OS) container aboard the MLS, which would perform the first launch from another planet and place the OS in Mars orbit.

The third element, the Earth Return Orbiter (ERO), would launch no earlier than 2027 to provide communication relay support for SRL and, using the Capture, Containment and Return System (CCRS), capture the OS, sterilize its exterior, encapsulate it in a secondary containment vessel, and return it safely to Earth through an Earth Entry System (EES). These two elements, the SRL and ERO, which form the MSR Program, are currently in the planning and design stages of development and represent an international effort comprising NASA, the European Space Agency (ESA) and many industrial partners.

The fourth element of the campaign is the Sample Receiving Project (SRP), which is part of NASA's Mars Exploration Program and aims to design and build a high-containment facility that would host and analyze the returned samples under the most protective measures, comparable to measures employed for handling biological toxins and known infectious agents in biological research laboratories, while also protecting the samples from contamination with Earth-origin materials that could compromise science investigations. The samples would be kept under these stringent containment conditions and not released to other laboratories until it is determined that they are safe through extensive analyses or rendered biologically inactive through sterilization. Similar to the lunar samples from the Apollo missions to the Moon, the samples to be returned from Mars would be studied in great detail for many decades by future generations of scientists, using instruments and techniques that have yet to be invented.

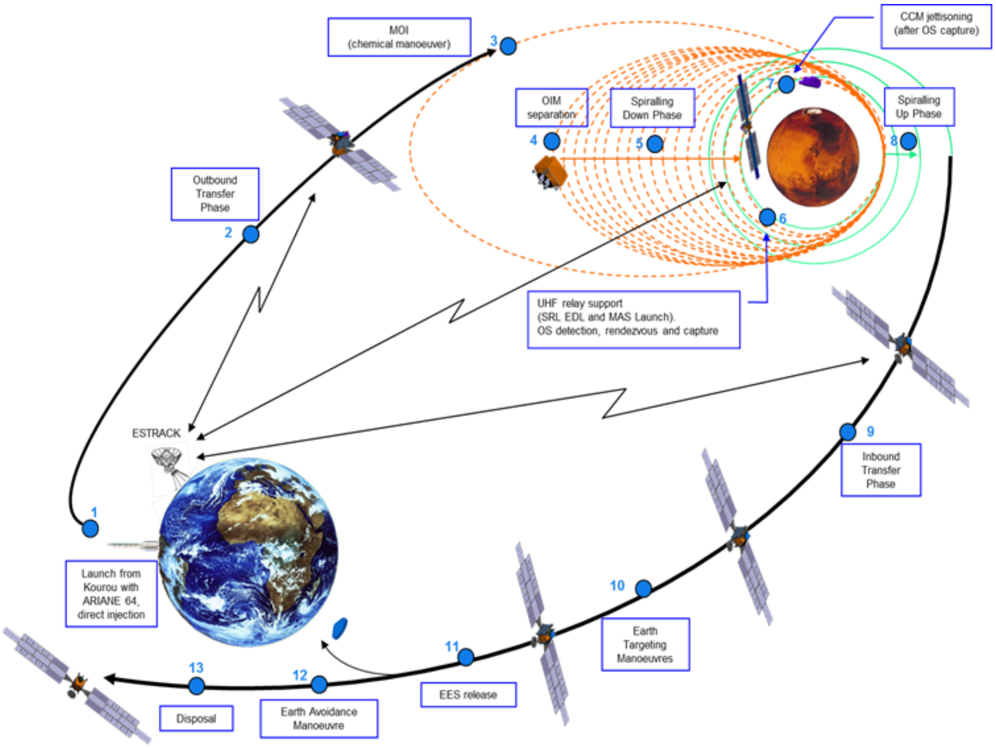

Fig. 2: Overview of the baseline ERO mission with the main phases highlighted.

The focus of the work reported here is the planetary protection (PP) strategy of the ERO-CCRS mission, which would address the potential contamination of Mars with Earth-origin material and the protection of Earth's biosphere from any potential adverse effects from Mars material. The manuscript is organized as follows: Section 2. provides the reader with the motivation for and background behind planetary protection efforts. Section 3. gives an overview of the ERO-CCRS mission both in terms of spacecraft and payload design and mission architecture. Section 4. describes the planetary protection strategy in detail and the path to compliance with the requirements. Finally, Section 5. summarizes the main findings and provides future perspectives.

2. Motivation and background

Mars is a challenging environment for active biology or biomolecules due to the following factors: 1) the ultraviolet (UV) and galactic cosmic radiation environment damages many of the biomolecules and organic compounds associated with life [16, 17, 18, 19], 2) temperature and water activity on Mars rarely (if ever) reaches levels required for active metabolism [20, 21], 3) absent active metabolism, biomolecule degradation cannot be actively repaired [22]. As a matter of fact, the samples being collected by the Perseverance rover are from the first few centimeters of a planetary surface that is very dry and exposed to intense UV and ionizing radiation, which would sterilize all cellular biology as we know it directly exposed at the surface. This is one of the reasons why MSR's science strategy is focused on finding traces of now extinct ancient life from long ago, when the Martian environment was wetter and warmer, and not modern extant life, which would be challenged to survive in these harsh conditions of the present-day Martian surface environment. It is also important to emphasize that data from in-situ measurements on Mars and the analysis of Martian meteorites in laboratories on Earth are consistent with an absence of extant Martian biology in the Martian near surface.

In general, the potential for Mars samples to represent a hazard to Earth's biosphere is extremely low. Host-pathogen relationships are evolutionary in nature and Mars-Earth exchange is infrequent, so even assuming life is present on Mars, a potential pathogen is unlikely to have assembled the specific pathogenic capabilities required to utilize Earth species (including humans) as a host. Potentially invasive species from Mars would also encounter a largely inhospitable environment on Earth where much higher temperatures and water activity levels are common. Finally, Mars material arrives naturally on Earth as meteorites, some on relatively fast trajectories that do not experience sterilizing dosages of ionizing radiation [23], posing a high likelihood that life on Mars would be delivered

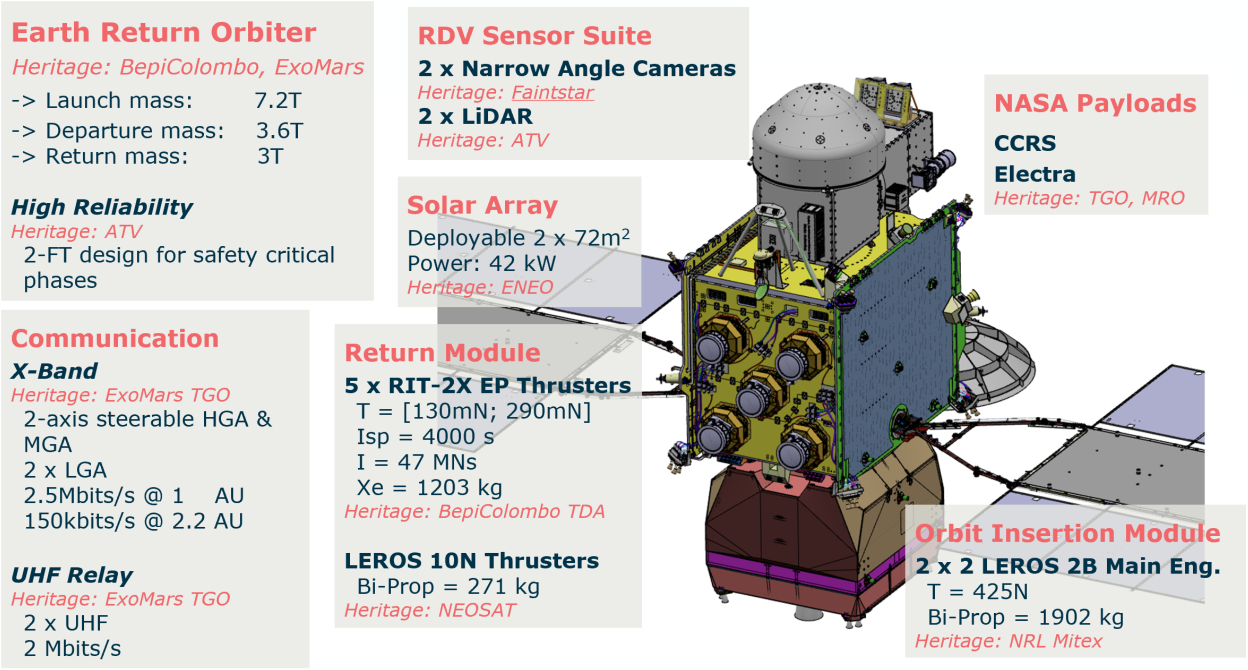

Fig. 3: Overview of the ERO spacecraft with its main characteristics highlighted (credit: Airbus Defence and Space).

to Earth's biosphere without catastrophic effect. Despite the low hazard potential and the high likelihood of ongoing natural transfer, the potential for harm to Earth's biosphere from a sample return is not zero. In recognition of this logic, MSR has adopted a "Safety First" approach and would safely contain all potentially hazardous Mars material returned to Earth.

This approach is in line with current policies [24, 25, 26, 27], which all affirm the need for protecting solar system bodies from harmful contamination by terrestrial materials (forward planetary protection – FPP) while protecting the Earth-Moon system from possible harmful extraterrestrial contamination that may be returned from other solar system bodies (backward planetary protection – BPP).

For restricted sample return missions (i.e., those in which sample containment is required due to the potential for encountering extant life), the translation of these policies into engineered systems consists of establishing and implementing a strategy and design concepts to *break the chain* of contact with the target body, isolate and robustly contain the restricted samples. CCRS plays the key role in breaking the chain of contact during MSR by sterilizing the external surfaces of the OS that were exposed to wind-borne Martian dust during surface operations, enforcing a clean zone to protect the EES, and containing the OS and its payload of sealed sample tubes in a redundant containment layer. ERO further contributes to this by delivering the EES on a high-precision trajectory to facilitate a predictable landing state and then avoiding Earth.

3. Mission and spacecraft overview

An overview of ERO's mission phases and main events is shown in Figure 2, while a summary of the key reference mission parameters can be found in Ref. [15].

Following its planned launch in October 2027 from Kourou, French Guyana, ERO would make a two-year low-thrust transfer to Mars, using Solar Electric Propulsion (SEP). Upon arrival at Mars, ERO would use its Orbit Insertion Module (OIM) to perform a chemical Mars Orbit Insertion (MOI) into a highly elliptical orbit around Mars. After a successful maneuver, ERO would lower its orbit slightly and then jettison its OIM. Using SEP, it would spiral down for one year into a circular orbit to provide relay telecommunication support to the MSR surface elements, including the relay support for the entry, descent and landing of the Sample Retrieval Lander. At the end of the one-year surface mission, ERO would reposition itself in a different orbit to provide tracking and monitoring of the launch of the Mars Launch System (MLS) and the release of the OS. ERO would then optically detect [1] the MLS and OS.

Once the OS orbit is determined, the spacecraft would rendezvous with and capture the OS. The jettisonable elements of the CCRS payload would be released into Mars orbit after the OS has been transferred into the EES by CCRS. The return module and the retained parts of CCRS not jettisoned in Mars orbit would then begin the Mars

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[1] To supplement the rendezvous capability, detection by ERO of a radio frequency beacon on the MLS is planned.

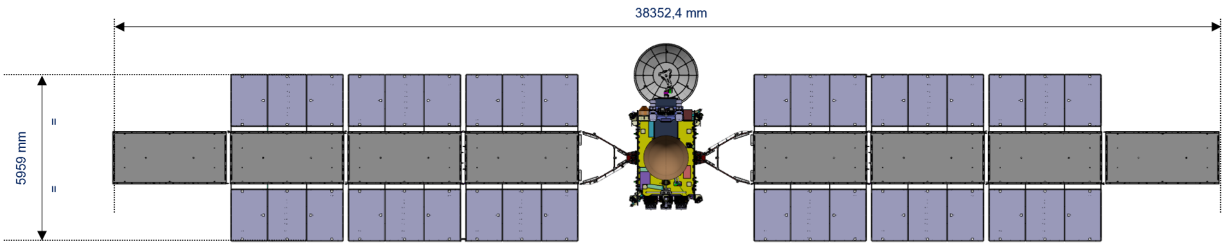

Fig. 4: ERO in its deployed configuration (credit: Airbus Defence and Space).

departure by using SEP to spiral out of its rendezvous orbit and make the inbound journey towards Earth, which would be nearly two years in duration. During this time, ERO would remain on a trajectory that avoids Earth until about one week before closest approach, when ERO would maneuver onto an Earth-intercept trajectory. Then, approximately 3 days before Earth arrival, ERO and CCRS would release the EES and perform an Earth Avoidance Maneuver (EAM). The EES would passively enter Earth's atmosphere, descend on a highly predictable trajectory, and safely land on well-characterized soils within a secure site. The current preferred landing site is the Utah Test and Training Range (UTTR); NASA is in the process of completing environmental impact reviews for this site. ERO would perform the final step in the MSR Program some time after the EAM by performing a long-term Disposal Maneuver (DM) (step 13 in Figure 2). The combination of the EAM and DM would put ERO on a Heliocentric orbit for at least 100 years that would prevent any potential delivery of residual Mars material on the spacecraft and its CCRS payload to Earth's biospheres, consistent with ESA and NASA policies.

3.1 Spacecraft

The ERO platform is a modular flight system that includes a Return Module (RM), an Orbit Insertion Module (OIM) and a Rendezvous Sensor Suite (RSS). Furthermore, the ERO platform also carries CCRS, which is a payload developed by NASA and described in detail in the following section. Figure 3 outlines, while Ref. [15] details, the ERO composite spacecraft.

Return Module The RM serves as the main accommodation platform. It quarters key features such as:

- A High Gain Antenna (HGA) and a Medium Gain Antenna (MGA) to ensure telemetry and telecommand operations for nominal operations. The fields of view of both antennas complement each other to ensure a global coverage;
- Two arrays of solar panels (39-m span, 144-m^2, providing up to 42 kW at 1 AU beginning-of-life) to provide the spacecraft with power, which can be seen in its deployed configuration in Figure 4;
- A plasma propulsion panel accommodating five electric propulsion thrusters with their pointing mechanisms, with each thruster capable of delivering up to 255 mN of thrust;
- Chemical propulsion thrusters, used for attitude control, rendezvous and capture operations;
- Two fully redundant On-Board Computers (OBC). The first to perform nominal control and monitoring of all the spacecraft operations. The second to monitor critical function anomalies and spacecraft fault-tolerance state with the capability to autonomously control the spacecraft.
- Dedicated Fault Detection, Isolation and Recovery (FDIR) for safety critical phases.
- An accommodation space for the CCRS and RSS.

Orbit Insertion Module The OIM is integrated with the RM and provides the thrust required for Mars Orbit Insertion phase. Once the required insertion maneuvers have been performed the OIM would be jettisoned into a stable Mars orbit. To achieve these goals, the RM has the following key characteristics:

- Two bi-propellant main engines ($\sim$400 N, with two redundant engines) to perform the aforementioned maneuver and assure redundancy during that critical phase of the mission,
- A secondary set of chemical propulsion thrusters for attitude control throughout the cruise to Mars and during the main engines boost.

Rendezvous Sensor Suite The RSS contains the Guidance, Navigation and Control (GNC) sensors for the OS detection and rendezvous. The RSS is currently foreseen to be composed of two Light Detection and Ranging system (LiDARs) and two narrow angle cameras (NACs). The first would be directly mounted on the Capture Enclosure (CE) of CCRS (see Fig. 5) and the latter would be mounted on the RM. Their fields of view are unobstructed and allow the OS to be tracked from release up to capture. The objective behind this accommodation is to be as close

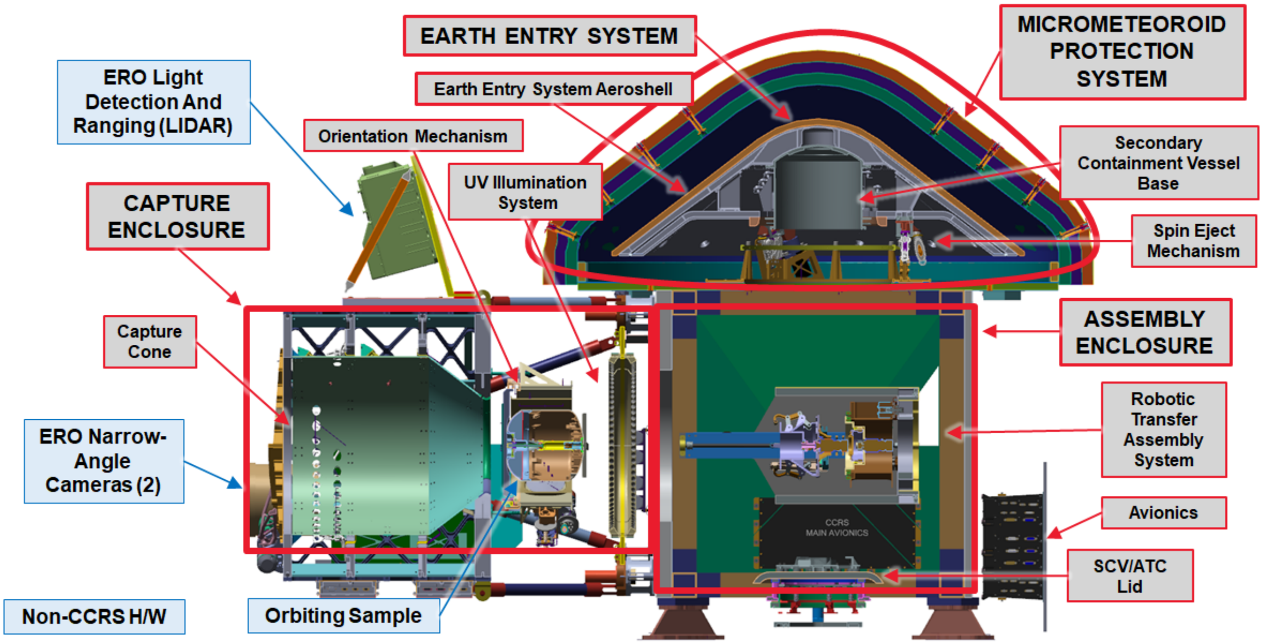

Fig. 5: Overview of the CCRS payload with its main elements highlighted.

as possible to the capture axis and to be partially jettisoned from ERO prior to Mars departure along with the CCRS CE in order to reduce flight system mass and the thrust required to leave Mars.

3.2 *Payload*

Figure 5 provides an overview of the CCRS payload with its main elements and subcomponents: 1) the Capture Enclosure (CE), 2) the Assembly Enclosure (AE), 3) the Earth Entry System (EES), and 4) the Micrometeoroid Protection System (MMPS).

The CE, directly exposed to Mars material, would be the place for capturing the OS while providing control of Mars particles, as well as a sterilization capability that serves to break the chain of contact between Mars and Earth. The sterilization approach was changed from heat to ultraviolet radiation and the OS now also acts as the Primary Containment Vessel (PCV). More details on this previous architecture can be found in Ref. [28].

After capture, the entire OS external surface would be exposed to UV radiation to sterilize any potentially hazardous Mars particles, that is, any Mars material or particle $\geq$ 50 nm in diameter. The AE would receive the sterilized OS and robotically assemble it into the Secondary Containment Vessel (SCV) inside the EES Aeroshell. The combined OS and SCV would form the Contained OS (COS).

During the spiral-up phase, where electric propulsion is used to raise ERO's orbit, the CE would be ejected in Mars or heliocentric orbit; options for final disposition of the CE are actively being evaluated with regards to both FPP (e.g., a stable orbit of required lifetime, or bioburden with or without burn-up/break-up analyses) and BPP (Mars particle control).

The combined EES Aeroshell and COS would form the EES and reside inside the MMPS, a protective debris shield, during transit back to Earth; the MMPS would support BPP compliance by providing micrometeoroid protection measures to ensure integrity of the entry system.

Upon successful delivery by ERO to the desired release position, velocity and attitude, the EES would be released from CCRS through a spin eject mechanism on an Earth return path with high reliability and precision.

The EES would then deliver the Mars samples to the selected landing site on Earth, providing containment of the COS throughout approach, entry, descent and landing. BPP compliance within this phase would be addressed through trajectory selection, redundant containment layers, thermal protection for entry, and impact resistance.

The AE and MMPS would remain attached to ERO, which would be guided, under ESA's direction, to a stable heliocentric orbit which, in the nominal mission plan, would not intersect Earth for at least 100 years.

All these operations have been subdivided into specific phases, which are described in more detail in Ref. [29].

4. Compliance to planetary protection requirements

NASA, as well as ESA's member states, are signatories of the United Nations' Outer Space Treaty [24], which in its Article IX states that "States Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose." As a result, NASA and ESA have put in place policies to protect Earth's biosphere from potential adverse effects of material returned from solar system bodies. These policies are consistent with guidance published by the Committee on Space Research (COSPAR) [25]. ESA policies are captured in the European Cooperation for Space Standardization (ECSS) requirements [27] while NASA policies are captured in its Procedural Requirements "Planetary Protection Provisions for Robotic Extraterrestrial Missions" [26].

Both FPP and BPP requirements are specific to the type of mission and the explored planetary body. Therefore, a mission is assigned one of four FPP categories (Categories I-IV) and one of two BPP categories (Category V restricted or unrestricted) according to the type of encounter it will have (e.g., flyby, orbiter or lander) and the nature of its destination (e.g., a planet, moon, comet or asteroid). If the target body has the potential to provide clues about life or prebiotic chemical evolution, a spacecraft going there must meet a higher level of cleanliness and some operating restrictions will be imposed [26].

Based on this, for FPP purposes, both CCRS, as a NASA-provided hardware element launched with ERO, which is an ESA-provided Mars orbiter, and ERO itself are proposed as a Category (Cat.) III payload and spacecraft, respectively. This category applies to FPP for flyby or orbital missions which, by the contamination they might cause, could compromise future investigations on a celestial body of significant interest relative to the process of chemical evolution and the origin of life.

For BPP purposes, both CCRS and ERO are managed under BPP policies for Category V, Restricted Earth Return (Cat. V(r)) missions, which is applied to prevent backward contamination from payloads and spacecraft directly involved in returning samples from a body with the potential to harbor life. Sample returns from Mars are automatically classified as Cat. V(r), the most stringent PP category in NASA and ESA policies, and are not assessed according to the categorization schema published by NASA or COSPAR [25]. While the Apollo 11, 12, and 14 missions were conducted in a manner that sought to protect Earth from any potential biological contamination of Lunar origin, MSR would be the first interplanetary mission to address backward contamination.

Note that CCRS will comply with NASA FPP requirements at delivery to ESA for integration and perform to NASA BPP standards as an element of the MSR Program during flight. The ERO spacecraft will comply with ESA's PP policies for Cat. III FPP and Cat. V(r) BPP mission through impact avoidance [27].

4.1 ERO planetary protection strategy

4.1.1 ERO FPP approach

To achieve FPP compliance for ERO (and the CCRS payload), the ESA strategy is to plan ERO Mars orbits to be stable for longer than the required impact avoidance period or be limited in duration such that the probability of spacecraft failure during execution remains below impact probability requirements (i.e., $< 1\%$ impact probability for the first 20 years after launch, $< 5\%$ impact probability for the 30 years thereafter) as required by ECSS [27] and consistent with COSPAR's planetary protection guidelines [25]. The orbits of any jettisoned elements from the ERO spacecraft are also planned to be in line with these guidelines. During periods when the spacecraft resides in orbits that are subject to natural degradation in less than the required duration, the probability of critical hardware failures and micrometeoroid impacts are also considered and the trajectory design is adapted accordingly to ensure compliance with Cat. III impact probabilities.

While Cat. III FPP compliance is planned to be achieved through a Mars impact avoidance strategy that imposes no bioburden limits on the spacecraft, ERO requirements include the need for compatibility with bioburden assessments as a contingency to ensure that a bioburden-based compliance path is possible if mission success considerations result in Mars orbital parameters that exceed allowable Cat. III impact probabilities.

4.1.2 ERO BPP approach

The ERO spacecraft and mission are being designed to comply with two driving requirements. The first driving requirement for ERO is probabilistic: the probability of releasing an unsterilized Martian particle [2] into Earth's biosphere shall be less than one in a million for the first 100 years after departure from Mars. The second driving requirement requires that all safety critical functions[3] of ERO be compliant with the ECSS safety standard Ref. [30] (i.e., fault tolerance).

The starting assumption the project has taken is that ERO carries unsterilized particles for the following reasons. Firstly, ERO carries CCRS, which contains the OS, back to Earth. Secondly, ERO also takes the assumption

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[2] Particle size of diameters ≥ 50 nm are being considered.

[3] Safety Critical functions are functions that can lead to the risk of releasing unsterilized material from Mars and flight hardware exposed to unsterilized material from Mars into the terrestrial environment.

that the exterior surface of the spacecraft does host unsterilized Martian particles [4].

The main objective of the ERO mission is to release the EES toward a designated landing site on Earth and as such must be on an Earth impact trajectory at some point to achieve this objective. To comply with PP requirements, ERO has designed an Earth Avoidance Manoeuvre (EAM) to divert from a collision course after successful release of the EES. The EAM is also the main tool of ERO to divert from an Earth collision course in the case of a major failure on the spacecraft or payload. Furthermore, the ERO mission, specifically the return trajectory, has been carefully designed as to be on an Earth miss trajectory for the longest time possible. The result of this mission design optimization is that, for a total mission duration of six years, ERO will be on an Earth-intersecting trajectory only for a few days.

Based on a systems engineering functional analysis, all the functions required to perform the EAM, the release of the EES and the Disposal Manoeuvre (DM) are classed as safety critical following the ECSS standard on safety [30]. As such, failure tolerance is a fundamental design constraint for ERO. These functions have been designed such that, on the launchpad, no single system failure or single operator error and no combination of two independent system failures or operator errors could cause the spacecraft to lose the ability to perform either the EAM or the EES release. Furthermore, the failure tolerance state of the spacecraft and all its inhibits are being continuously monitored by ground as well as the on-board computers with dedicated FDIR levels to allow autonomous execution of the EAM during safety critical phases. The software implemented on safety critical units or software that performs safety critical functions is being developed to the highest possible safety and software standards [30], namely as category A with associated Independent Software Verification and Validation (ISVV). Dedicated telecommand authentication functions have been designed into the Data-Handling sub-system to ensure only authorized commands can be received. These design and safety specifications have been flow down to design and specifications documents at the unit level.

Following the detailed spacecraft design based on a two-fault tolerance architecture, a Probabilistic Risk Analysis (PRA) has been performed to verify the probabilistic target the high-level planetary protection requirements impose on the ERO spacecraft and mission. The PRA will continue to be iterated during the mission and will provide inputs to decision gates. Decision gates are points in time during the mission before major events at which the spacecraft and payload health will be verified and a go/no-go decision will be made. All the safety critical functions must be in a healthy conditions with appropriate failure tolerance levels.

The Mission Operations Centre (MOC) of ERO will be located at ESA's European Space Operations Centre (ESOC) in Darmstadt, Germany and is being developed in parallel with the spacecraft. ERO operations will be performed as per the standard approach for deep space missions operated at ESOC (including Rosetta, BepiColombo, JUICE), applying well-proven operations preparation and execution principles, including thorough validation and verification of all nominal and contingency operations. Special measures put in place for the final days of ERO's Earth return going beyond the usual setup include the following:

- 24/7 double ground station coverage, using both ESTRACK and DSN station networks;
- Implementation of a backup MOC at a location physically different from ESOC, capable of performing all nominal and contingency operations;
- A joint navigation scheme, with ESA's and NASA's navigation teams collaborating for performing orbit determination and manoeuvre planning.

The ERO spacecraft and mission design, including its PP approach, are reviewed regularly by project external experts at key milestones throughout its development phases. In addition, independent oversight bodies are also in place to further review, advise and ensure compliance to PP requirements and appropriate adherence to guidelines.

4.2 CCRS planetary protection strategy

4.2.1 CCRS FPP approach

Consistent with the ERO FPP strategy outlined in Sec. 4.1.1, CCRS would be compliant to ERO-CCRS interface requirements mandating compatibility with bioburden assessments. Similarly, the final disposition of CCRS hardware not returned to Earth is expected to rely on trajectories, in either Mars or heliocentric orbit, that satisfy both Cat. III requirements for FPP and Cat. V(r) requirements for BPP. CCRS would comply with Cat. III FPP through trajectories established and maintained by ERO.

Per NASA planetary protection requirements [31], all CCRS hardware would be assembled, integrated and tested in an ISO-8 or better cleanroom or tested for bioburden directly. This requirement is based on accepted surface biological levels found in ordinary ISO-8 cleanrooms and allows a bounding estimate for the biological load in the absence of assays. For machining and fabrication taking place outside of clean environments, the contamina-

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[4] This is a conservative assumption taken out of precaution due to the large number of unknowns. ERO assumes that all particles on its surface are potentially hazardous. However, there are current uncertainties on how many particles would actually find their way on the spacecraft. Furthermore, only a certain percent of these particles have the potential to be hazardous (i.e., not all particles from Mars are hazardous). Lastly, ERO spends several years in a high-radiation environment, which could prove to be an additional risk reduction factor.

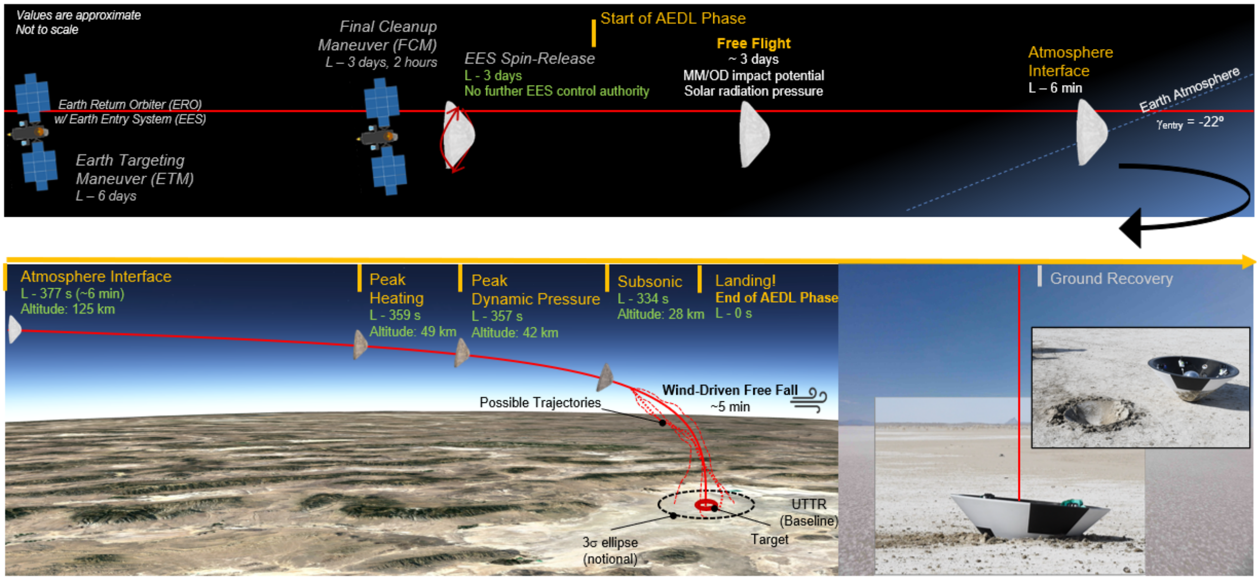

Fig. 6: Current overview of the EES delivery phase, which starts when ERO performs its Earth Targeting Maneuver and spins/releases the EES toward Earth. These operations are followed by the Approach, Entry, Descent and Landing (AEDL) phase, which ends when the EES reaches zero kinetic energy on the ground, thus completing the ERO-CCRS mission and the MSR Program.

tion control implementation plan would provide details on the transition between fabrication and assembly for each subsystem. The UV system would be protected from degradation during exposure to ISO-8 cleanrooms during ERO integration and launch processing. This is because although cleaner areas may be provided for specific activities on request, the nominal processing would occur in ISO-8 areas.

CCRS is also required to provide an inventory that includes all organic materials present on the payload in amounts greater than 1 kg. The goal of this inventory is to aid in determining future scientific impacts if the mission inadvertently contacts Mars. The inventory would consist of the listing of materials with approximate quantities.

Finally, CCRS would archive 50 g of organic materials that are present on the payload in amounts greater than 25 kg. Archived materials would be collected from those processed for flight (e.g., machined, cured, treated, etc.). Archival through the end of mission would be managed by the MSR sample curation facility.

4.2.2 CCRS BPP approach

The several elements of CCRS would comply with BPP requirements in different ways. The CE would be ejected in space in either a Mars or heliocentric orbit. While disposal in Mars orbit would be an FPP concern (see FPP compliance Sec. 4.1.1 above), disposal in heliocentric orbit would be compliant to both Cat. III FPP requirements and Cat. V(r) BPP requirements for Earth avoidance. Note, the CE jettison is not a BPP requirement because the CCRS AE has some probability of transporting potentially hazardous Mars particles liberated from the OS prior to its sterilization and ERO operates under the assumption that it carries one or more potentially hazardous Mars particles.

Cat. V(r) BPP requirements to break the chain of contact would be met through sterilization of the OS exterior and engineered particle containment capabilities of the OS and SCV. Ultraviolet radiation is currently being baselined to sterilize Mars particles through a UV illumination system which exposes the outer surface of the OS to a sterilizing UV dose at a flux at least 3 times that of the Sun for the same wavelength band. The OS would be pulled through the UV illumination system by the Robotic Transfer and Assembly System (RTAS) with the SCV lid attached to it, as it moves from the CE to the AE. All particle paths would be directly controlled by minimizing gaps that could lead to undesired lines of sight either by design (e.g., gaps size, number of particle bounces, etc.) or through mitigation strategies such as, for example, multilayer insulation barriers.

After the end of the sterilization process, the OS would be integrated within the SCV aboard the EES, with RTAS inserting the OS into the SCV base and torquing the OS and SCV lid to seal the SCV. From this point through landing, PP measures taken to ensure control of potentially hazardous Mars material would include anomaly detection, micrometeoroid protection and precision delivery to a trajectory that allows a safe entry, descent and landing. Events such as initiation of Earth return, the Earth targeting maneuver and the release of the EES, may be subject to approvals from federal and international authorities. Should the aggregate flight system status or performance not meet desired levels, the EES would remain with the ERO in a heliocentric orbit and the samples would not be returned.

BPP requirements drive the design of the EES in several ways. First, simplicity and high reliability are achieved by designing the EES as a passive entry vehicle with no powered systems and no parachute. This approach eliminates potential failure points while maintaining adequate safety margins. The cone-shaped EES capsule would be approximately 1.2 m to 1.4 m in diameter and would land with a terminal velocity of roughly 145 km/h. Simulations and ground-based testing have shown that this speed, combined with the soil properties known to exist in the landing area, would produce landing loads that can be managed through structural design to contain all Mars material and protect the samples. The landing is expected to create a depression in the ground with a diameter about the same as the EES, with soil being ejected from the crater to a distance of approximately 15 m (Fig. 6). Second, end-to-end aerodynamic stability would be achieved through a 52.5-degree sphere cone geometry, which balances aerodynamic stability against aerothermal peak heating, and a 3D-woven Mid-Density Carbon Phenolic (3MDCP) forebody thermal protection system (TPS). 3MDCP is derived from the insulation layer of the Heatshield for Extreme Entry Environment Technology (HEEET) material system, using the same approach of infusing a woven carbon-phenolic preform with phenolic resin [32]. Landing footprint management requires releasing the EES as close to Earth as practical, a steep entry flight path angle and landing in a low risk region of the landing site, away from hazards. The current mission plan would include sufficient time on an Earth-intercept trajectory for one primary and one back-up EES release opportunity. Micrometeoroid impact robustness also drives the release timing. The robustness is derived based on the critical damage criterion of the various components of the EES to avoid gas flow-ingestion to its structure during entry. This criterion is derived from the material properties of the TPS forebody and aftbody materials.

The EES landing is currently proposed to take place within the Utah Training and Testing Range (UTTR), the largest contiguous block of restricted airspace in the continental United States. Several landing sites in the continental US were considered and UTTR was selected because of its remote location featuring restricted access and special use airspace with a large landing area free from roads, structures, and hazardous terrain. The large, flat lakebed surface with minimal slope and consistent soil properties is essential for establishing design requirements for the EES and establishing that those requirements are sufficient to ensure BPP. Finally, UTTR possesses the infrastructure to track the EES during its entry, descent and landing that would enable recovery personnel to quickly locate, recover and secure the vehicle for transportation to the sample receiving facility.

Finally, because there is a non-zero probability that Mars particles might remain on the internal or external surfaces of the AE, MMPS and spin eject mechanism (all on ERO), BPP compliance would be achieved, as described in Sec. 4.1.2, by placing ERO on an Earth-intersecting trajectory for, at most, 6 days prior to EES release and maneuver away from Earth 1.5-3 days prior to reaching the Earth entry interface. This timeline may be adjusted to optimize delivery parameters for BPP and mission success. According to NASA and ESA requirements, the CCRS hardware and ERO must be disposed in an orbit that avoids Earth for at least 100 years; Earth avoidance is addressed by NASA only through the ERO-CCRS interface requirements compliant to ERO BPP requirements.

5. Conclusion

The Mars Sample Return Program is being planned and designed to execute the first restricted Earth return mission since the early Apollo lunar landings, in order to bring back compelling samples that would fundamentally increase our understanding of the origin and evolution of the Red Planet, including the prebiotic chemistry that may have led to the origin of life on Earth and, potentially, on Mars. Despite the extremely low likelihood that the samples being collected by Perseverance contain biological hazards that could potentially contaminate Earth's biosphere, a "Safety First" approach is being taken. This approach would consist of a series of on-orbit operations, such as sterilization, redundant containment and particle control, that allow the CCRS payload to break the chain of contact between Mars and Earth onboard ERO. As ERO approaches Earth, the EES would be released on a high-precision trajectory that, in conjunction with a well-characterized, secure landing environment, would deliver the samples safely to Earth while ensuring containment of all potentially hazardous Mars material. Finally, after the EES is released on an Earth entry trajectory, ERO would execute an Earth avoidance maneuver and place itself, and the attached CCRS payload, in a heliocentric orbit that avoids Earth for over 100 years.

Notes and acknowledgments

This document is being made available for information purposes only.

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