NASA Capture, Containment, and Return System: Bringing Mars Samples to Earth

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The Capture, Containment, and Return System (CCRS) project is a key element of the last step in a campaign being planned by NASA and European Space Agency (ESA) to bring Mars samples back to Earth. CCRS and its host spacecraft, ESA's Earth Return Orbiter (ERO), would close a decades-long, multi-mission and multi-national effort to bring Mars surface samples to Earth for decades of scientific studies. CCRS would launch no earlier than 2027 on ERO, which would also provide communications relay services for the Mars Sample Return (MSR) surface missions, NASA's Perseverance rover, and the Sample Retrieval Lander (SRL) (to be launched no earlier than 2028). The primary mission for CCRS begins when the first-ever orbital planetary capture operation occurs, with CCRS catching and securing the Orbiting Sample (OS) in low Mars Orbit. From this point, the system would perform additional "firsts": it would autonomously contain the OS, expose its outside surface to ultraviolet (UV) radiation as required to sterilize any potentially hazardous Mars particles, and assemble the Earth entry capsule, named the Earth Entry System (EES), in orbit around Mars using a gantry mechanism. At approximately 2.8 lunar distances from Earth, or three days from entry into Earth's atmosphere, CCRS would open its micrometeoroid shield and release the EES on a ballistic trajectory toward Earth. The EES is designed to be a fully passive system that would enter the atmosphere and land without a parachute, notionally at the Utah Test and Training Range (UTTR).

Key Words: Mars mission, Sample return, Mission design

1. Introduction

The Mars Sample Return (MSR) Campaign is one of the most ambitious and complex planetary exploration efforts ever attempted. With the participation of the U.S. National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and a large number of industry partners, MSR aims to bring Martian rock and atmospheric samples to Earth to answer key questions about the potential for ancient life on Mars. NASA's Capture, Containment, and Return System (CCRS), hosted on ESA's Earth Return Orbiter (ERO), would bring the samples to Earth.

After capturing the Orbiting Sample (OS) container with the Martian samples in Mars orbit, ERO would journey back to Earth, with CCRS and its assembled EES spacecraft. Three days prior to arrival, CCRS would release the EES on an Earth-entry trajectory from a distance beyond the orbit of the Moon. The passive EES spacecraft would then enter Earth's atmosphere, flying on a fully passive ballistic trajectory, landing safely on Earth, notionally at the Utah Test and Training Range (UTTR), USA.

This paper describes the current design of the CCRS payload, its purpose, and the operation plans of its various subsystems (note: any design information included herein should be viewed as notional, since much of the design at the time of this writing has not yet been formally evaluated by a project-level design review). It begins with a brief introduction to the MSR Campaign before focusing on the ERO mission and CCRS. The architecture of the payload and ground elements of CCRS are described, along with explanations of the operational phases of the ERO mission and their correlation to CCRS operational phases.

The authors will show how the CCRS payload and its subsystems are designed to meet the ERO mission requirements, and how the CCRS mission operation plans have been devised to ensure that the Martian samples would be returned to Earth safely and efficiently.

2. Mars Sample Return Campaign Overview

The CCRS payload is managed by and would be operated by NASA's Goddard Space Flight Center (GSFC). CCRS is part of the Mars Sample Return (MSR) Campaign, a joint endeavor between NASA and ESA. Within NASA, MSR is an "Agency Flagship Program," classified as a Category 1, Class A mission, under the Science Mission Directorate (SMD).

The objective of the NASA-ESA MSR Campaign is to bring back Martian geologic and atmospheric samples. This goal of finding, collecting, storing, and delivering samples to Earth would be accomplished through three flight elements: the NASA-led Mars 2020 Perseverance rover mission; the NASA-led Sample Retrieval Lander (SRL) mission with Orbiting Sample (OS) container, Sample Recovery Helicopter(s) (SRH), and Mars Launch System (MLS); and the ESA-led ERO mission, of which CCRS is a payload.

The MSR Program, shown below in Figure 1, consists of the following two flight missions:

- The ERO mission with CCRS as a payload (planned to Launch no earlier than 2027 & arrive back at Earth in the early to mid 2030s)
- The SRL mission to collect and launch samples into Low Mars Orbit (planned to launch no earlier than 2028)

The MSR Program is part of the larger MSR Campaign, which includes the addition of:

- NASA’s Mars 2020 / Perseverance Rover (Launched in 2020, currently conducting sample caching operations on Mars)
- The Sample Receiving Project (SRP) to provide a high-containment facility for initial characterization of the samples, including a safety assessment

The ERO and SRL projects are overseen by the MSR program, whereas Mars 2020 and the SRP are managed by NASA’s Mars Exploration Program (MEP). In this paper, the terms “Campaign” and Program” are used in accordance with the definitions illustrated in Figure 1.

Figure 2 is a high-level illustration of the MSR Campaign timeline for the 28-27-33 baseline scenario [2028 = SRL launch, 2027 = ERO launch, and 2033 = Earth return]. This baseline timeline is the nominal plan. In case of a contingency, samples could be returned to Earth in 2035.

The MSR Campaign began with the Mars 2020 mission, which launched on July 30, 2020, and successfully landed the Perseverance rover at Jezero Crater on Mars on February 18, 2021. Perseverance is scientifically selecting and acquiring samples and caching them in one or more depot locations on the Mars surface, while retaining a sample set onboard for direct delivery to the SRL. Over 16 samples have been acquired to date, with 10 sample tubes cached in the first depot.

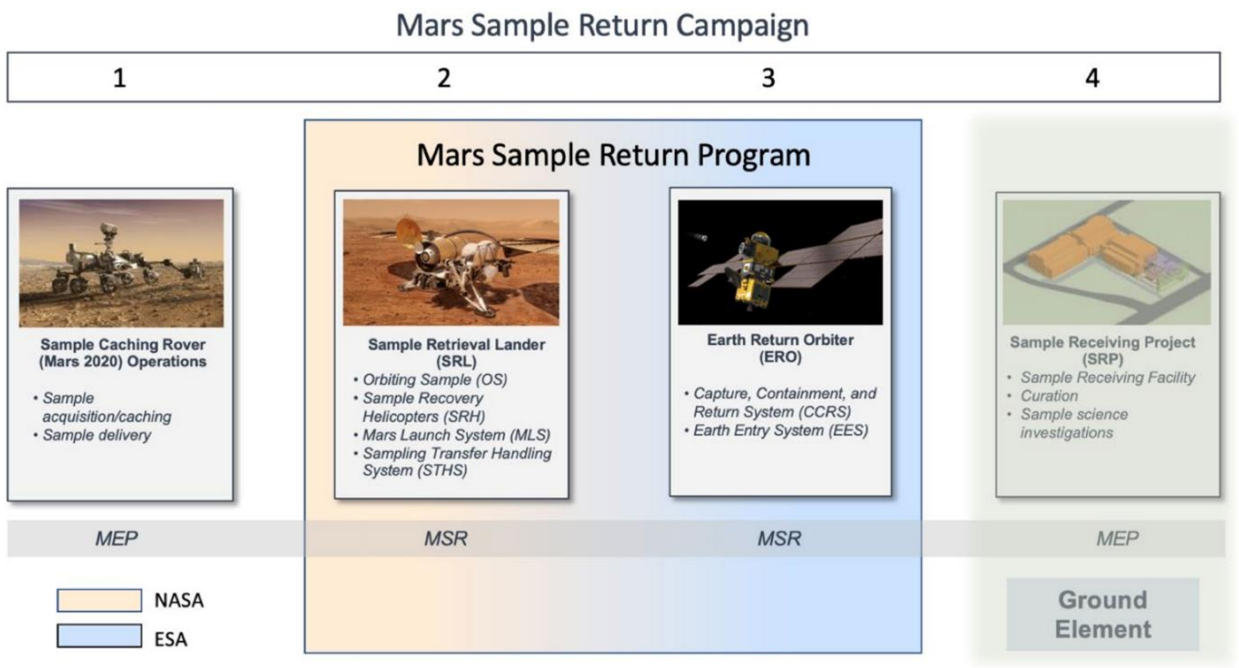

Fig. 1. Planned MSR Campaign and Program elements.

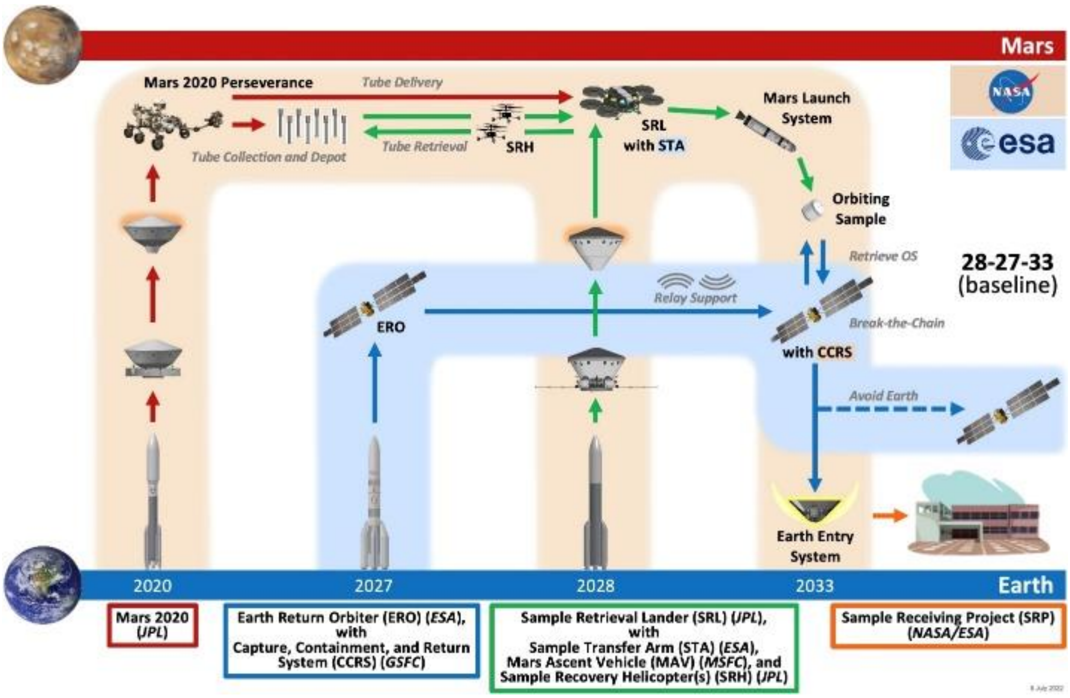

Fig. 2. MSR Campaign planning architecture and timeline.

If launched in 2027, the ERO-CCRS mission would reach Mars orbit in 2029. After Mars Orbit Insertion (MOI) and jettison of its chemical propulsion stage, ERO would use electric propulsion to spiral down to Low Mars Orbit, where it would provide SRL Entry, Descent, and Landing (EDL) communication and relay support of the surface mission.

If launched in 2028, SRL would perform Mars EDL in July 2030 and would prepare to receive the samples to be transported to Earth. Due to its predicted longevity, the Perseverance rover would be the primary means of transporting and delivering the sample tubes it has retained onboard to SRL (baseline). Two NASA SRHs, deployed from SRL, would provide a secondary method for retrieving other samples that Perseverance cached on the Martian surface. If for some reason it is deemed not feasible for Perseverance to deliver its stored sample tubes to SRL, SRH would fly to the depot location(s), retrieve the cached sample tubes, and deliver them to SRL.

The Sample Transfer Arm (STA), developed by ESA and operated by NASA, would transfer the samples from Perseverance or those dropped off by the SRH to the OS container, which is integrated into the two-stage, solid-propellant MLS. After closeout of the OS and the MLS Payload Assembly (MPA), SRL would prepare the MLS for launch, scheduled to occur by 2031. MLS would deposit the OS into Low Mars Orbit.

3. ERO-CCRS Project Overview

Since CCRS is the payload for the ERO mission, CCRS activities would take place throughout the ERO mission timeline. Table 1 lists the major ERO objectives and specifies the responsible entity for each.

Table 1. ERO Mission Objectives.

	Objective	Responsible
1.	Return the OS from Mars inside the EES	ERO and CCRS
2.	Detect & rendezvous with the OS in Mars orbit	ERO and CCRS
3.	Provide surface communication relay at Mars	ERO Only
4.	Support CCRS during the transfer to Mars and at Mars	ERO Only
5.	Return the OS from Mars inside the EES	ERO and CCRS

The ERO mission is divided into 12 phases, each with its own space environment considerations (thermal, dynamic loads, ground communications) due to its trajectory. Figure 3 shows the overall ERO mission, broken up into three categories (Cruise to Mars, Mars Environment, Return to Earth), with the corresponding spacecraft configuration for each.

While the CCRS operational timeline obviously overlaps the ERO timeline, it is broken down into a separate set of project phases, from pre-launch activities through end of mission, that represent changes in operational concepts, system configurations, and/or changes in operational environments. The CCRS project phases, listed in chronological order, are:

1. Launch, Commissioning, & Outbound Transfer (LCOT)
2. Capture & Configuration (C&C)
3. EES On-Orbit Assembly (EESOOA)
4. Protection, Jettison, & Release (PJR)
5. Approach, Entry, Descent, Landing (AEDL)

Figure 4 illustrates the CCRS project phases and their alignment to the ERO mission phases.

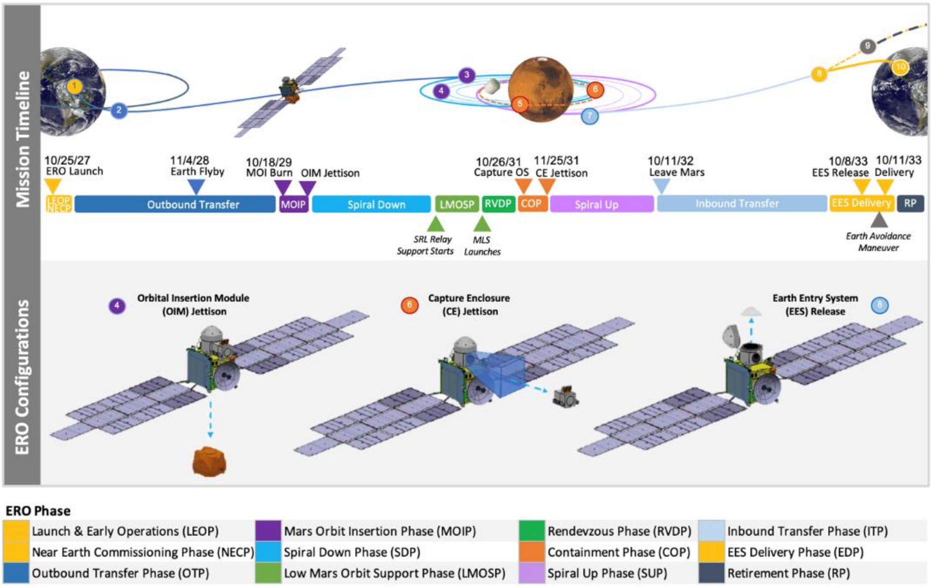

Fig. 3. Planned ERO phases and major mission events timeline.

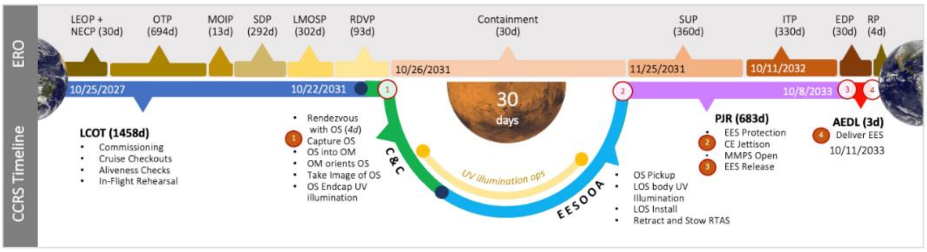

Fig. 4. Planned CCRS and ERO phases and key events.

4. CCRS System Architecture

The CCRS system would include all modules, space- and ground-based, that are the developmental and operational responsibility of the CCRS project. The CCRS system would consist of two elements:

- The CCRS Payload Element, hosted on the ERO spacecraft to perform all in-space operations
- The CCRS Ground Element, consisting of the ground system and all CCRS mission control functions

The system objectives for CCRS are derived from MSR Program needs and are directly tied to established CCRS mission phases (as well as the ground element).

1. Perform overall robotic operation at Mars orbit in a cleanly and timely manner [all CCRS Phases]
2. Capture & Configure the OS [C&C Phase]
3. Perform On-Orbit Assembly of EES [EESOOA Phase]
4. Partial Jettison of CCRS to reduce mass for return & reduce potential contamination [PJR Phase]
5. Protect EES from meteorite impacts and release the EES [PJR Phase]
6. Perform EES Approach, Entry, Descent and Landing on Earth [AEDL Phase]
7. Provide Ground and Operations Support [all CCRS Phases]

The following sections will describe the CCRS Payload and Ground Elements, the baseline activities that would take place during each of the CCRS Project operational phases, and the systems and components used to perform those activities.

5. CCRS Payload Element

The CCRS payload is designed in three modules to achieve its project objectives: the Capture Enclosure (CE), which would capture the OS from Mars orbit and orient it for assembly configuration; the Assembly Enclosure (AE), which would insert and seal the OS in a redundant containment vessel with the return vehicle aeroshell and assemble the Earth Entry System (EES); and the Micrometeoroid Enclosure, which would protect the Contained OS (C-OS) from MicroMeteroid and Orbital Debris (MMOD) damage during transit from Mars to Earth and deliver the protected samples to the landing area.

Figure 5 below shows the three payload element modules and the major subsystems of each. Note that the CE would be jettisoned after the completion of the EESOOA Phase. Summaries of CCRS components and their functions are found in Table 2, Table 3, and Table 4.

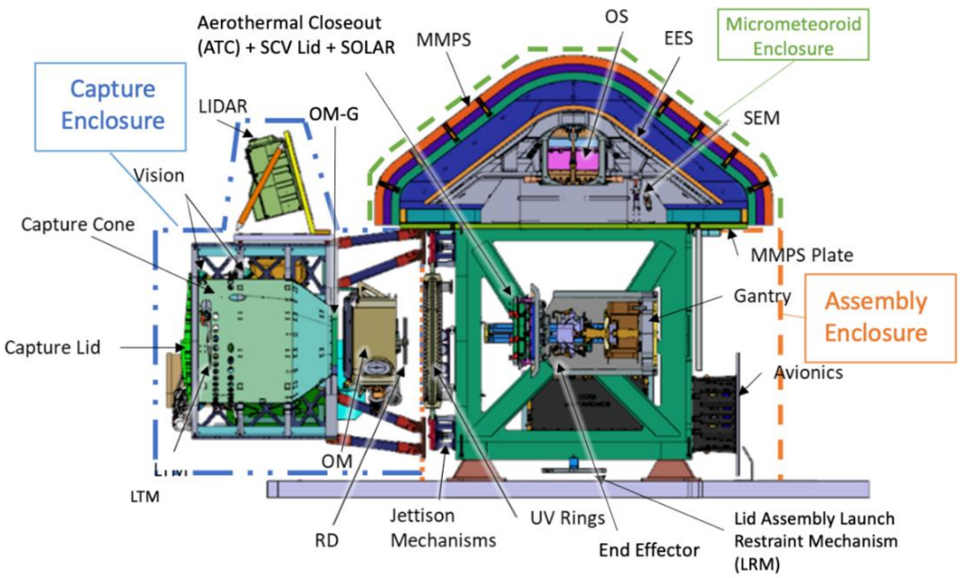

Fig. 5. CCRS major payload systems.

Table 2. Baseline CE components and functions.

Capture Enclosure Components		
Subsystem	**Mechanism**	**Function**
Capture & Containment System (CCS)	Capture Lid Mechanism (CLM)	Serves as a cover to the capture cone
	Linear Transfer Mechanism (LTM)	Cages the OS once it enters the capture cone, and the funnels down the cone into the OM
	Capture Cone	Designed to handle incoming OS impact loads without damaging OS & supports funneling operations
	Orientation Module (OM)	Orients the OS into the proper orientation with the help of the OMG, Paddles and RD.
	OM – Guard (OMG)	Protects the OM during OS capture and serves as a registration surface for SCV lid installation
	OM – Paddles	Orient the OS
	Restraining Door (RD)	Keeps the OS within the OM volume during orientation also seats the OS onto the OMG in preparation for SCV lid installation
	Capture Sensor Suite (CSS)	Two beam-break layers to detect the incoming OS to trigger the LTM to deploy and "capture the OS"
Vision System (VS)	Cameras (x2)	Cameras placed on the outside of the capture cone with strategic holes placed in the capture cone to allow camera visibility of the OS while constrained in the OM
	Illumination Modules (x2)	Infrared LED lights to assist in the image capture of the OS

Table 3. AE components and functions.

Assembly Enclosure Components		
Subsystem	**Mechanism**	**Function**
RTAS	Gantry	2 degree-of-freedom robotic manipulation platform that positions the End Effector for EES assembly operations
	Robotic System Control Electronics (RSCE)	Controls the Gantry and End Effector mechanisms and sensors, reports telemetry
Pickup Installation & Encapsulation (PIE)	End Effector (EE)	2 degree-of-freedom set of mechanisms to perform EES assembly operations. Docks with, latches to, removes, installs, and torques the combined SCV Lid/ OS to the EES
	Lid Restraint Mechanism (LRM)	Set of release devices to hold the SCV Lid (including ATC) during launch. These devices are released once the End Effector has grasped the SCV Lid during EES Assembly operations.
	SCV-OS Latch-Align-Restrain (SOLAR) system	Passive latch mechanism located on the underside of the SCV Lid. Acts as a robotic "tool" manipulated by the RTAS Gantry and PIE End Effector to latch onto a mating interface on the OS during OS Pickup operations for EES Assembly.
	SCV Lid	Contains rotary latch mechanism that, when torqued into a latched position after install into the EES Aeroshell by the End Effector, forms the Containment Assurance seal for Back Planetary Protection.
	SCV Body	Secondary containment vessel body, located within the EES Aeroshell for launch. This is the structure that the SCV Lid and OS are latched into during EES Assembly
EES Aeroshell	Aero-Thermal Closeout (ATC)	Attached to the SCV Lid in the launch configuration and is installed together with the SCV Lid during EES Assembly. Acts as a Hot Gas Barrier during EDL
UV System	UV Rings	2 rings, 1 ring with 84 LEDs for OS Base sterilization, 2 ring with 42 LEDs for OS Body & OS Lid sterilization.
	UV Electronics	Controls the UV Rings

Table 4. Micrometeoroid enclosure components and functions.

Micrometeoroid Enclosure Components		
Subsystem	**Mechanism**	**Function**
Structures & Deployables	Spin Eject Mechanism (SEM)	Provides a deployable structural load path between the Assembly Enclosure and the EES, and is responsible for providing actuation energy, including linear and rotational velocities, to deploy EES.
	Micrometeoroid Protection System (MMPS)	Provides protection of the EES TPS from critical damage during transit to and from Mars. MMPS Lid opens and the EES is ejected.
Earth Entry System (EES)	Earth Entry System (EES)	The fully assembled entry capsule, including the contained OS, which lands on Earth
	EES Aeroshell	The primary structure that carries aerodynamic loads throughout atmospheric entry and descent.
	EES Thermal Protection System (TPS)	The thermal protection layer on top of the EES Aeroshell that protects the EES from the extreme temperatures generated during hypersonic flight through the atmosphere

Table 5 details the subsystems that would be employed in each of the CCRS Enclosures and identifies the mechanisms in each subsystem and the operational phases in which they are used. The CCRS project phases and their operations are detailed in Section 6.

Table 5: CCRS payload mechanisms, subsystems, and phases

CCRS Phase							
LCOT	C&C	EESOOA	PJR	AEDL	**Mechanism/Unit**	**Subsystem**	**Location**
■	■				Capture Sensor Electronics (CSE)	Capture & Containment System (CCS)	Capture Enclosure (CE)
■	■				Capture Lid Mechanism (CLM)		
■	■	■			Orientation Module (OM) Paddles		
■	■				OM Guard (OMG)		
■	■				Restraining Door (RD)		
■	■				Linear Transfer Mechanism (LTM)		
■	■				Illumination Module (x2)	Vision System	
■	■				Camera (x2)		
■	■	■			UV LED Ring (x2)	UV System	Assembly Enclosure (AE)
■		■			Gantry	Robotic Transfer Assembly System (RTAS)	
■					Gantry Launch Locks		
■		■			Robotic System Control Electronics (RSCE)		
■		■			End Effector	Pickup Installation & Encapsulation (PIE)	
		■			SCV-OS Latch-Align-Restrain (SOLAR)		
■		■	■	■	Secondary Containment Vessel (SCV) and Lid		
■					Lid Restraint Mechanism (LRM)		
■	■	■	■		Payload Flight Software (PFW)	Flight Software (FSW)	
■		■			RTS Control Software (RSW)		
■	■	■	■		Main Avionics	Avionics	
■	■				Jettison Avionics		
			■		Cable Cutters	Structures & Deployable	
			■		Micro-Meteoroid Protection System (MMPS) Lid		Micrometeoroid Enclosure (ME)
			■		Jettison Mechanism		
			■		Spin Eject Mechanism (SEM)		
			■	■	EES Aeroshell	Earth Entry System (EES)	
			■	■	EES Thermal Protection System (TPS)		
	■	■	■	■	Orbiting Sample (OS)	SRL Mission	All Locations

6. CCRS ground element

The Ground Element would be responsible for planning payload operations, generating command files to be uplinked to the CCRS Payload, and processing and analysis of ERO and CCRS downlinked telemetry data. Ground Element responsibilities would be shared between three facilities: the ERO Mission Operations Center (MOC) at the European Space Operations Center (ESOC) in Darmstadt, Germany, the CCRS Payload Operations Center (POC) located at GSFC in Greenbelt, Maryland, and the MSR Program at NASA's Jet Propulsion Laboratory in Pasadena, California.

All CCRS commands would originate from the CCRS POC. The POC would plan and generate CCRS stored commands for uplink to the spacecraft, which would be sent to the ERO MOC as Payload Operations Requests (PORs). The MOC would verify and store the PORs when received and transmit them to the Payload upon request from the POC.

All communications with the CCRS flight system would flow through the ERO MOC. The ESOC would use a combination of ESA's European Space Tracking Network (ESTRACK) and NASA's Deep Space Network (DSN) for radio communication between the ERO MOC and the ERO flight system. ESA would coordinate DSN activities through JPL. The ERO flight system would then deliver uplinked packets to the CCRS flight system and provide downlinks of CCRS telemetry.

The CCRS POC would also provide connectivity with MSR Mission Support Area (MSA) at JPL for the purposes of situational awareness and collaboration. This connection would not be part of the CCRS uplink or downlink paths. The POC would also provide connectivity with the CCRS I&T environment and the CCRS Payload Systems Test Bed (PSTB), both located at GSFC.

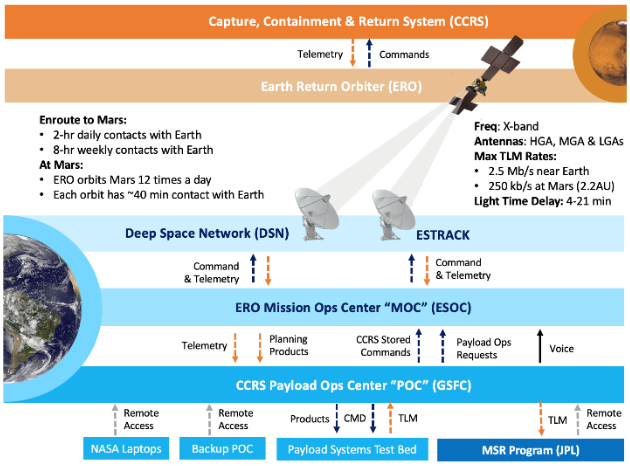

Fig. 6. CCRS ground system architecture.

In addition, CCRS would maintain a secondary operations facility at ESOC. This facility serves a backup POC (bPOC) and can perform all functions of the POC, if necessary, during critical operations. It would also support situational awareness for CCRS-ERO liaison personnel located at ESOC during nominal operations. This facility would be staffed only during critical CCRS operations.

The CCRS Ground Element architecture is shown in Figure 6. High-level summaries of the of the functions of each of the Ground Facilities are in Table 6, Table 7, and Table 8.

Table 6. Baseline CCRS POC functions.

CCRS POC Functions	
Functions	**Details**
Command Generation and Planning	The CCRS POC would plan and generate CCRS stored commands which are sent to the ERO MOC for uplink to the spacecraft. The POC would also generate Payload Operations Requests (PORs) which are sent to the MOC to specify MOC-generated immediate or time-tagged commands.
Data Processing	The CCRS POC would receive, store, and analyze CCRS telemetry and a subset of ERO telemetry. Analysis capabilities would include alphanumeric telemetry pages, time series data plotting and analysis, 3d visualization, and display of camera data. Data processing capabilities would support timely decision making for Ground-In-The-Loop (GITL) operations.
Simulations	The CCRS POC would include software simulators that have lower fidelity but higher availability than the PSTB.
Support Functions	The CCRS POC would provide all supporting capabilities necessary for operations, including communication, collaboration, monitoring, version control, archiving, security, and infrastructure.

Table 7. Baseline ERO MOC functions.

ERO MOC Functions	
Functions	**Details**
Commanding	The ERO MOC would plan, generate and uplink immediate and time-tagged commands, including CCRS commands as requested by the POC. The MOC would also uplink commands for immediate execution, including generating CCRS commands as requested by the POC through planning products. Additionally, the MOC would uplink CCRS stored command products delivered by the POC. All CCRS stored command products that are processed by CCRS Flight Software (FSW) would be generated and tested at GSFC at the CCRS POC and not the ERO MOC.
Telemetry	The ERO MOC would downlink telemetry from ERO and CCRS, immediately forwarding all CCRS telemetry and a subset of ERO telemetry to the POC. This includes playback CCRS telemetry stored on the ERO onboard data recorder. The MOC would also downlink stored telemetry and would transfer the stored telemetry as files to the CCRS POC.
Simulations	The ERO MOC would provide a software simulator that models ERO. The CCRS software simulator would be integrated with this model to allow simulation of joint operations.

Table 8. MSR Support area functions.

MSR MSA Functions	
Functions	**Details**
General Collaboration	Personnel in the MSR MSA would coordinate with the POC and the MOC for planning of program critical activities and anomaly resolution
Navigation	The MSR Program would conduct radiometric navigation during joint navigation mission phases and provide navigation solutions to the CCRS EDL team to predict EES landing location.
Data Distribution	MSR would collect and distribute data relevant to the Sample Dossier, a historical record of sample handling.

7. CCRS Phases

As shown in Figure 4, the CCRS project plan is divided into operational phases similar to the EOR Mission phases but defined according to the CCRS project activities rather than ERO Mission events. Each of the project phases are described in more detail in the following sections.

7.1 Launch, Commissioning, & Outbound Transfer Phase

The LCOT phase would be the longest of the CCRS phases, spanning eight ERO phases, starting with the arrival to the Launch Site in French Guiana and ending about four years later with ERO's arrival at the Homing Interface Point (HIP), which is the location at which ERO would begin Rendezvous operations. For the majority of this phase, CCRS would be in the OFF configuration, only powering ON periodically to perform specific check-out activities. The objective of this phase would be to confirm functionality of the CCRS system without incurring any additional risk to the mission. No LCOT operations are time critical or would be prioritized over ERO spacecraft activities.

Prior to the LCOT phase (i.e., prior to ERO launch), the configuration of the CCRS payload would be as shown in Figure 7.

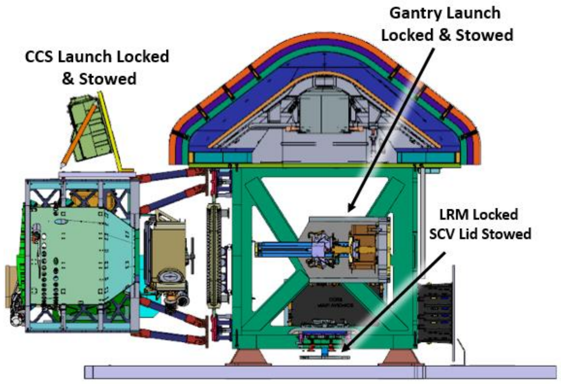

Figure 7. CCRS configuration at start of LCOT phase.

Table 9. LCOT subphases.

CCRS Phase	Launch, Commissioning & Outbound Transfer (1458 d)					
CCRS Subphase	Pre-Launch	Launch	Commissioning	Cruise Alive	Cruise Checkout	In-Flight Rehearsal
Timeframe	TBD to L - 3 hr	L-3 hr to L+7 days	L+7 days to L+30 days	Every 4 months	Once a year	Once during ERO Relay Operations
Key Functions	· Aliveness tests of CCRS components on launch Pad · Confirm ready to launch	· Survive Launch · No CCRS Commanding	· **Release Launch Locks*** · ROM on reversible actuators · Full functional checkout of system	· Temperature & sensor polling	· Small Actuator Moves	· ROM on reversible actuators · Flight Calibrations
Commanding Method	N/A	N/A	GITL Commanding	Autonomous (out of contact)	Autonomous (out of contact)	GITL Commanding
Entry Criteria	ERO arrives at the Launch Site	S/C is configured to Internal Power	ERO is complete with mission critical activities.	ERO not busy	ERO not busy	ERO not busy
Exit Criteria	S/C is configured to Internal Power	ERO is complete with mission critical activities	Ground confirms system functionality post launch	Ground confirms CCRS Health & Safety	Ground confirms Mechanism functionality	Ground confirms system functionality and powers CCRS OFF until arrival at HIP

As shown in Table 9, the LCOT phase would be broken into six subphases: Pre-Launch, Launch, Commissioning, Cruise Aliveness, Cruise Checkout, and In-flight Rehearsal. Brief summaries of each LCOT subphase are:

Pre-Launch: Would begin with arrival of ERO/CCRS at the ESA launch site. Includes system Aliveness checks on the launchpad and powering CCRS survival heaters ON before powering CCRS OFF for Launch.

Launch: CCRS would remain OFF through ERO mission critical events (apx L+7 days). CCRS survival heater telemetry would be available in telemetry after Launch Vehicle separation.

Commissioning: Commissioning is the term for the initial set of system checkout operations that would be performed to ensure that CCRS is ready to perform its mission objectives. After ERO completes its mission critical activities, CCRS commissioning would occur between L+7 days and L+30 days. Major activities include:

- Initial CCRS hardware Power-ON
- Heater calibrations
- Operational range-of-motion checks on actuators
- Check out electronics, Vision system, UV illumination system, and temperature sensors

Cruise Aliveness: Aliveness checks would be performed approximately every 4 months throughout the ERO Outbound Transfer, Mars Orbit Insertion, Spiral-Down, and Low Mars Orbit Support Phases to verify that CCRS is still healthy. During the aliveness checks, CCRS would be powered ON and temperature and sensor data would be polled before powering it OFF again.

Cruise Checkout: Cruise Checkouts would be used to run a limited functional checkout of CCRS during transit to Mars. During these checkouts, CCRS would perform small moves on all reversible actuators and perform a camera checkout, and the ground team would perform data trending on engineering and optical performance data. This also would provide an opportunity for grease remix and maintenance on actuators.

For a 2027 launch, three Cruise Checkout operations are planned:

- Close to Earth Flyby (1 year in space)
- After ERO jettison of the Orbit Insertion Module (OIM) (large dynamic load event)
- In Low Mars Orbit (operational thermal environment)

In-Flight Rehearsal: The last LCOT operation would be a full functional checkout of reversible activities, in the mission's operational environment (Low Mars Orbit).

An additional activity occurring during this subphase would be the SCV Lid Pickup. This sequence of operation includes the following operations:

1. Rotate & Extend Gantry to Cage Lids on LRM
2. Release the LRM
3. Retract, Rotate & Extend Gantry to block AE and CE Opening

The rationale for performing this operation during LCOT and prior to OS Capture is to use the SCV Lid to block the opening between the AE and CE to assist in shielding particles from entering the AE during capture of the OS. Since the nature of the SCV operations requires the use of the Robotic Transfer Assembly System (RTAS) Gantry, the Pickup Installation & Encapsulation (PIE) End Effector, Robotic System Control Electronics (RSCE), and the heaters, this activity would double as a full checkout of the RTAS/PIE System which is the objective for this subphase.

At the completion of the LCOT Phase, the configuration of the CCRS payload would be as shown in Figure 8.

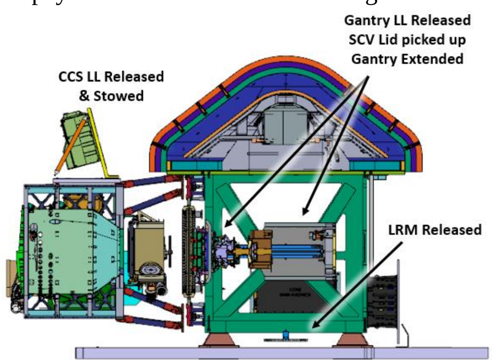

Figure 8. CCRS configuration at end of LCOT phase.

7.2 Capture and configuration phase

The Capture & Configuration (C&C) phase would be the second CCRS phase, starting when ERO is at the HIP. The phase would end when ground control confirms that the OS Base endcap has completed its UV sterilization and is ready for OS pickup by the RTAS/PIE.

As shown in Table 10, the C&C Phase would be composed of six subphases: Pre-Capture, Capture, Funneling, Inspection, Orientation, and Endcap Illumination. Brief summaries of each C&C subphase are included in the next several sections.

Table 10: C&C funneling subphase.

CCRS Phase	Capture & Configuration					
CCRS Subphase	Pre-Capture	Capture	Funneling	Orientation	Inspection	Endcap Illumination
Duration	about 2.5 days* + 8 hrs ground reviews	40 min + 4 hrs ground review	186 min	8 hrs	3.5 min + 4 hrs ground review	UV step #1 = ~30hours + ground review
Key Functions	1. Open capture lid - LTM capture operation checkout - Capture Sensor Calibration	1. OS triggers beam break sensors, actuation of LTM swing arm & lid **2. LTM arm fully deployed*** & locked (OS Captured) **3. Capture Lid Closed***	1. LTM funnels OS thru the capture cone; stops at OM bulkhed	1. OM grasps OS and manipulated into correct orientation 2. Stow LTM 3. Open OM-G	1. VS & Illumination Modules ON to take image of OS end-cap 2. OS constrained in OM (w/RD pre-loading OS against OMG)	1. Open RD 2. Power on UV System 3. UV Illumination Step #1 (Ring-1) of Endcap

Pre-Capture: The first step in the C&C Phase would begin once ERO arrives at HIP and is where CCRS would prepare the CCS for rendezvous and capture of the OS. CCRS would be powered ON, along with the Capture Sensors and Operational heaters, and the Capture Sensors are calibrated. After a 4-hour CLM warming period, the ground would confirm CCRS' readiness to open the capture lid and would uplink an "Open Capture Lid" command.

Capture: During the Pre-Capture period, ERO would slowly approach the OS for roughly 2.5 days, until ground control confirms GO for capture. The Capture subphase would begin with this confirmation, when the OS would be about 100m from the CCS capture cone. Once the OS enters the Capture Cone, it would trigger the optical sensor beams of the CSS, which would trigger the LTM arm to autonomously swing to the deployed position and the Capture Lid to close, trapping the OS within the Capture Cone. Figure 9 depicts the Capture subphase activities.

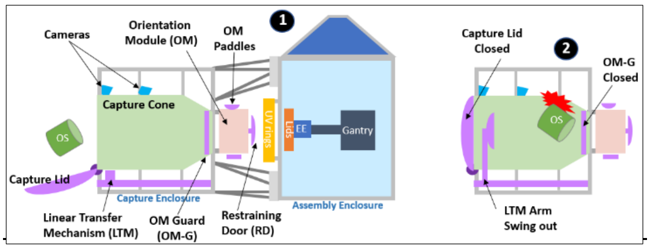

Figure 9: C&C capture subphase.

Funneling: This subphase would begin by opening the OMG, followed by the LTM slowly translating to the end of the capture cone, leaving the OS captured within the OM. Once the LTM reaches the end of its travel, the OMG would rotate to the closed position. Figure 10 illustrates the activity of the Funneling subphase.

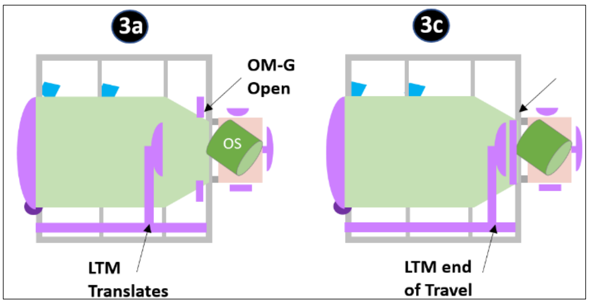

Figure 10. C&C funneling subphase.

Orientation: The Orientation subphase would start with the ground command to the OM to grasp the OS and place it into the correct orientation. The LTM would then be stowed, followed by the OMG being commanded to open in preparation for the Inspection Subphase. Figure 11 shows the Orientation subphase operations.

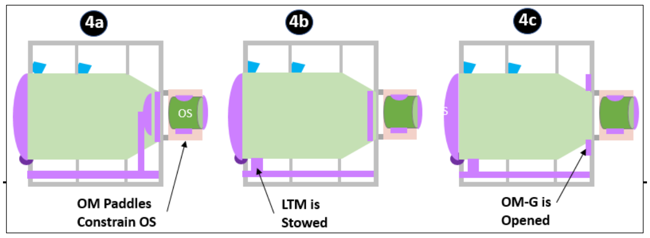

Figure 11: C&C orientation subphase.

Inspection. After the completion of the Orientation subphase, the Inspection subphase would allow the POC operations team to confirm that the OS is oriented correctly, by recording an image of the OS in the OM and downlinking it at the next ground contact. Upon ground review of image(s), if the OS Lid is not pointed towards the CCRS Capture Cone, the ground would initiate a re-orientation operation, which would flip the OS 180 degrees before proceeding to UV Sterilization Phase. Once the OS is correctly oriented, the OMG and the RD would be closed to in order to precisely align the OS to the Orientation Mechanism in preparation for Endcap Illumination in the next subphase. The beginning and ending OS configuration are shown in Figure 12.

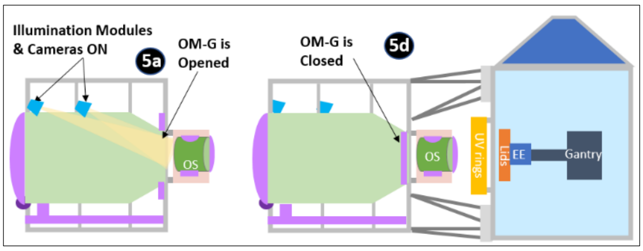

Figure 12. C&C inspection subphase.

OS Base Sterilization: The OS base sterilization subphase would be the first half of the overall UV Illumination System operation, which is planned to expose the OS in order to sterilize any potentially hazardous Mars particles. The UV Illumination System would consist of two separate rings on a single structure located between the AE and CE structure. Operation of the UV system would be split between the C&C

and EESOOA phases:

- Ring-1 would include 84 LEDs in positions specific for OS Base exposure (C&C phase)
- Ring-2 would include 42 LEDs in positions specific for OS Body & OS Lid exposure (EESOOA phase)

The OS base sterilization subphase of the C&C Phase would begin with the OS constrained by the OM paddles. UV Illumination System Ring 1 would then be powered up to perform the first sterilization step: sterilizing the RD. The RD would then be cleared so that the first UV sterilization subphase, OS base sterilization, can begin. Once that subphase is complete, Ring 1 would be powered off for the duration of the ERO mission. The OS base sterilization subphase is depicted in Figure 13.

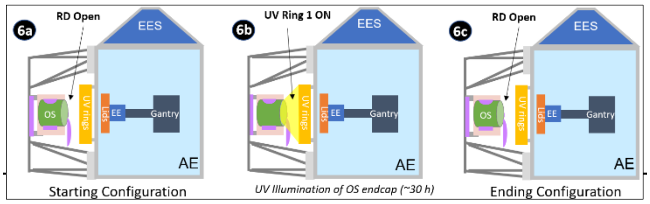

Figure 13. C&C OS base sterilization subphase.

7.3 EES on-orbit assembly phase

The third phase of the CCRS mission is the EESOOA phase, where the UV sterilization of the captured OS would be completed and the EES autonomously assembled by RTAS within the AE. This phase would start at the completion of UV sterilization of the OS Base endcap and end when the ground confirms successful assembly of the Earth Entry System (EES) into its landing configuration. The EESOOA phase would be formed of three subphases, as shown in Table 11: OS Pickup, UV Sterilization, and LOS (Lids + OS) Install. Each of these subphases is explained in the following sections.

Table 11. EESOOA subphases.

CCRS Phase	EES On-Orbit Assembly		
CCRS Subphase	OS Pickup	UV Illumination	LOS Install
Duration	2.5 hours + 3 GITL	Non-thrusting time: ~178 hours Thrusting Allowed: TBD duration for 12 GITL	2.5 hours + 3 GITL
Key Functions	1. Initialize RTS/PIE 2. Extend RTS Gantry towards OS in OM **3. Latch SOLAR to OS * (irreversible)** 4. Retract OM Paddles 5. Retract RTS Gantry with LOS	1. UV Illumination Step #2 - 13 2. Power off UV System	1. Position LOS For Installation 2. Angularly & Axially Align LOS to EESA **3. Assemble EESA into Landing Config*** 4. Retract and Stow RTAS

<u>OS Pickup</u>: When the EESOOA phase begins, UV Illumination System Ring 1 would have completed the UV exposure of the OS Base and is powered down. This first EESOOA subphase is performed in three steps:

1. Power ON the RSCE with the End Effector Operation Heater to allow for system warm-up
2. Extend the RTAS Gantry toward the OS in the OM and latch SOLAR to it
3. Retract the OM paddles from the Lid Assembly + OS (LOS) in preparation for UV sterilization

Figure 14 shows the OS Pickup subphase operations.

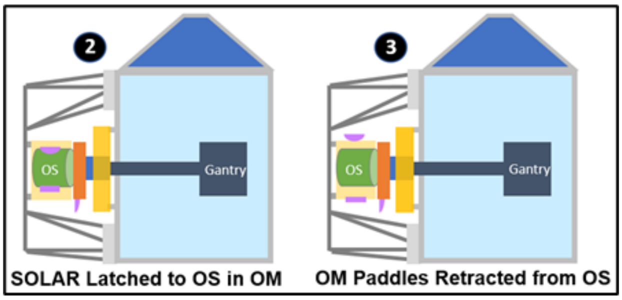

Figure 14. EESOOA OS pickup subphase.

<u>UV Sterilization</u>: The UV sterilization subphase, shown in Figure 15, would be focused on completing the UV exposure of the OS before it is installed into the EES Aeroshell. The RTAS Gantry would retract the OS through UV Ring 2 in 12 steps (approx. 20mm each) for exposure. Once all 12 exposure steps have been completed in this subphase, the ground would command Ring 2 of the UV Illumination System off for the remainder of the mission, and the Gantry would be fully retracted into the AE.

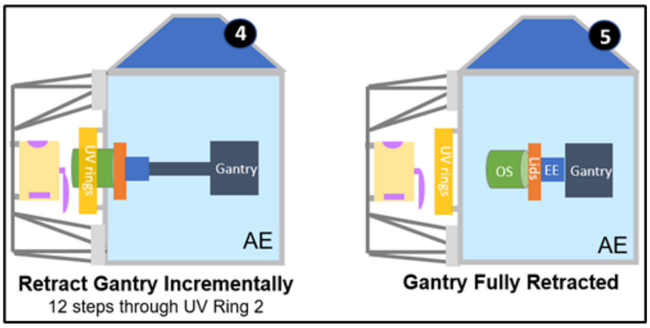

Figure 15. EESOOA UV sterilization subphase.

<u>LOS Install</u>: This is the subphase where the autonomous construction of the EES would be accomplished in 4 major steps, as listed below. Step 1 and Step 4 are illustrated in Figure 16 and Figure 17, respectively.

1. <u>Position LOS for Installation</u> (rotate)
   a) Initialize RTAS/PIE: Power ON RSCE & End Effector Op Heater for warmup
   b) Rotate gantry to align LOS with EES
   c) Free Space approach to EES Aeroshell (EESA)
   d) Insert LOS into SCV in EESA
   (Ground confirms successful execution)

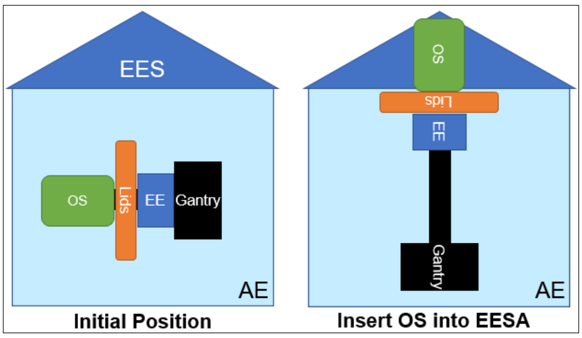

Figure 16. EESOOA LOS install subphase step 1.

2. Angularly & Axially Align LOS to EESA
    a) Relax Grasp to cage LOS, Docking posts push LOS flat against EESA
    (Ground confirms successful execution)

3. Assemble EESA into Landing Configuration
    a) Gripper Fully Opens
    b) Torquer rotates interface to LOS to engage SCV rotary latch mechanism
    (Ground confirms successful installation of LOS into EES aeroshell via telemetry)

4. Retreat & Stow RTAS
    a) Unwind Torquer out of contact with LOS
    b) Retract End Effector to free space
    c) Return End Effector to starting orientation
    d) Rotate to stowed position; Power OFF EE Ops Heater & RSCE
    (Ground confirms successful retraction from aeroshell via telemetry)

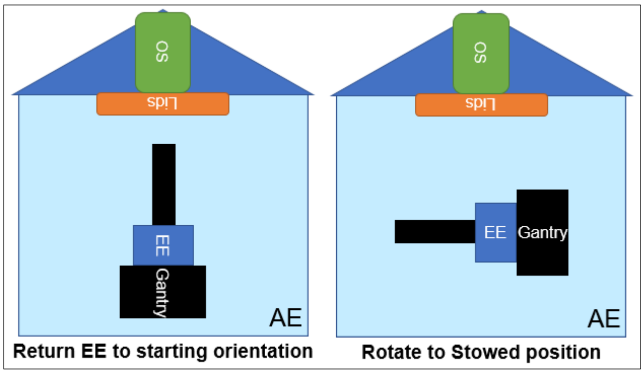

Figure 17. EESOOA LOS install subphase step 4.

7.4 Protection, Jettison, & Release Phase

The PJR Phase would begin after the completion of the EESOOA Phase in Mars orbit, continue through the Jettison operations and the return flight to Earth, and end when the EES would be released for landing. The majority of the time in this phase would be spent in the Mars-to-Earth transit. One of the primary concerns for this phase is providing protection against Micro-meteoroid Orbital Debris (MMOD) for the newly assembled EES. However, this phase would include two major release events, the CE Jettison and the EES Release. As shown in Table 12 below, the PJR Phase is broken into three subphases: Jettison, Transit, and EES Release.

Table 12. PJR phase subphases.

CCRS Phase	Protection, Jettison & Release		
CCRS Subphase	Jettison	Transit	EES Release
Key Functions	**1. Cut Cables** connection between both (CE and AE) and (RSS and ERO) **2. Separate CE from AE** 3. Kick CE off AE/ERO	1. Provide protection against MMOD 2. CCRS Aliveness Checks during SUP & ITP	**1. Open MMPS Lid** **2. Provide ejection capability to release EES from ERO/CCRS**

Jettison: Once the OS has been successfully contained within the EES, CCRS would jettison the CE to reduce return mass, leaving only the AE and EES attached to ERO for the return trip to Earth. The Jettison activity would require particularly tight coordination with ERO, as it would require a specific ERO altitude (365-650 km) to guarantee that the CE remains in orbit around Mars and would not enter the Martian biosphere for decades. Dynamic disturbances on ERO resulting from the Jettison forces would also require the spacecraft to perform an attitude reacquisition afterwards.

The separation activity would start by powering down the CE and physically separating the cable connection between the CE and AE using a Cable Cutter system composed of cutter mechanisms attached to the AE, a cable retraction system mounted to the CE, and associated sensors. The severed cables would be immediately pulled and twisted away from both the cutters and the side walls of the AE, leaving the AE and CE physically connected only by the bipod structures and the Hold-Down Release Mechanisms (HDRMs). After confirming successful cable disconnection, the ground would command the HDRMs to fire, ejecting the AE away from the CCRS/ERO structure. The Jettison subphase is illustrated in Figure 18.

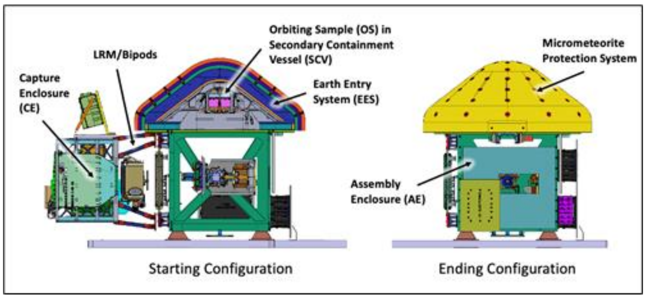

Figure 18. PJR jettison starting and ending CCRS configurations.

Transit: After Jettison, ERO would use electric propulsion thrusting to spiral-up as shown above in Figure 3 until the start of the flight back toward Earth. The ground would also perform periodic aliveness checks during the Transit subphase to verify the health of ERO and CCRS.

EES Release: The final PJR subphase would begin roughly eight days before ERO would reach the Earth Entry Interface Point (EIP), which is defined at an altitude of 125 km above the Earth's surface. The end of the PJR Phase would be defined as the point at which the EES has been released on its trajectory toward UTTR, which may vary depending on mission activities. Nominal EES Release is planned for three days prior to EIP (E-3 days), but in case of any off-nominal circumstance that may cause the MSR program to decide to abort the nominal release; a backup release opportunity is planned for 36 hours later, at E-1.5 days.

Release activities would be initiated using time-tagged commands, which would be uplinked in advance and stored on board CCRS to avoid the possibility of release problems due to ground communication errors. In advance of the planned release time, the MOC would uplink a "Green Button" command to indicate that it is safe to release as scheduled. Should the POC or the MOC determine that the Release should be aborted at any point, MOC would uplink an Immediate "Red Button" command, which would terminate the release sequence and reestablish release inhibits.

The EES would be released through the operation of the SEM, which would impart a controlled spin on the EES as it is ejected toward Earth, allowing the EES to make an accurate ballistic entry into and through Earth's atmosphere

Prior to release, the MMPS Lid must be opened to allow an unobstructed separation path for the EES. Figure 19 illustrates the configuration of CCRS at the start and the completion of the subphase.

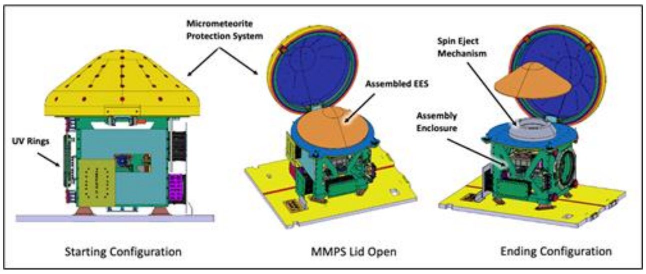

Figure 19. PJR EES release starting and ending CCRS configurations.

7.5. Approach, entry, descent, & landing phase

The AEDL phase would the final phase of the CCRS mission. As its name indicates, it is the phase where the EES would approach, enter, and descend through Earth's atmosphere, finally landing on Earth as planned. The AEDL Phase would include the 36-hour to three-day free-flight through space and end with an approximate six-minute atmospheric flight, culminating in the safe landing of the EES at the UTTR landing site. With the EES landed at the UTTR landing site, the CCRS mission would be complete.

Two very important points affecting the planning of the AEDL Phase are 1.) the EES forebody TPS would no longer be protected by from MMOD by the MMPS after the opening of the MMPS Lid, and 2.) the EES would have no active systems, meaning that there would be no onboard guidance system or landing systems (such as a parachute), and no telemetry system. This means that once CCRS releases the EES, there are no additional opportunities to abort the landing or alter the entry trajectory.

During this phase, the ground team would coordinate closely with the Program Mission Design & Navigation (MDNav) team to reconstruct the precise release trajectory (timing, angles, dynamics response) and update the predicted landing location.

Since the AEDL phase has no active control or monitoring systems, the AEDL phase has no subphases. Figure 20 shows the timeline of events of the AEDL Phase, beginning with the EES Release at the end of the PJR Phase.

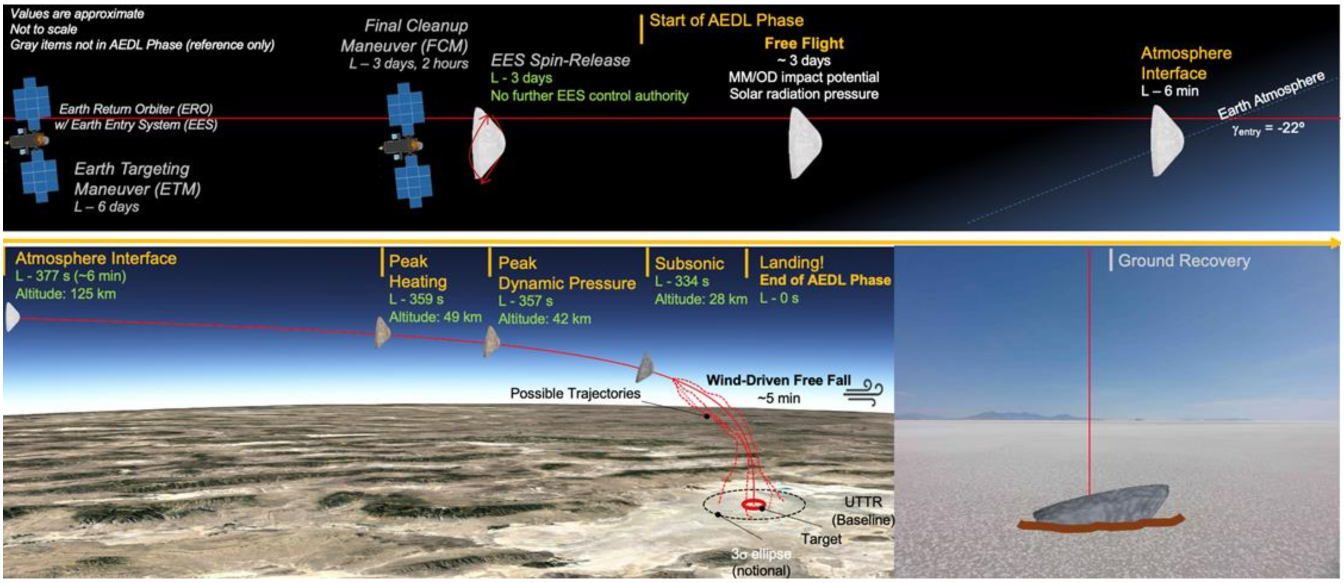

Figure 20: Baseline AEDL phase timeline of events.

8. Environmental considerations

CCRS applies a strict set of Planetary Protection (PP) measures based on national and international policies governing the protection of solar system bodies from potential harmful contamination by terrestrial materials, known as Forward Planetary Protection (FPP) while protecting Earth's biosphere from possible harmful extraterrestrial contamination that may be returned from other solar system bodies, known as Backward Planetary Protection (BPP)

For FPP purposes, CCRS, as a NASA-provided hardware element launched with ERO, is payload on a Category (Cat.) III spacecraft. This category applies to spacecraft on orbital or fly-by missions, that might compromise future investigations on a celestial body of significant interest relative to the process of chemical evolution and the origins of life.

For BPP purposes, CCRS is a payload participating in a sample return from Mars and is managed under BPP practices consistent with Cat. V(r), a Restricted Earth Return.

The CCRS Project plans to employ FPP measures consistent with avoiding contact with Mars to standard Cat. III probabilities through trajectory biasing and orbit selection (both performed by ERO). Thus, BPP is the primary challenge for CCRS. The CCRS Project and MSR Program plans to meet these BPP requirements through on-board UV sterilization and containment activities during the C&C and EESOOA phases, micrometeoroid protection efforts throughout the entire project lifecycle, and robust, redundant containment of any potentially hazardous Mars material during the PJR and AEDL Phases.

9. Conclusions

The Mars Sample Return Campaign is an exciting and ambitious collaborative effort by NASA and ESA to bring samples to Earth from another planet for the first time. CCRS, the payload on the ERO spacecraft, is a complex system whose architecture and operational plans are designed to fully meet the needs and requirements of the MSR Campaign to complete that effort.

After the samples are collected and launched into Low Mars Orbit, ERO-CCRS would rendezvous in Mars orbit with the Orbiting Sample container, capture it, contain it within a redundant set of vessels before returning to Earth and releasing the samples, protected within the EES, to land safely.

9.1. Project Organization

MSR program structure is shown in Figure 21. The figure shows that CCRS interacts with multiple NASA centers and European partners, including ESA and Airbus (ERO spacecraft prime contractor). Besides the intricacy among organizations, the ERO/CCRS mission is part of the MSR Campaign, and its schedule is highly correlated with other campaign projects.

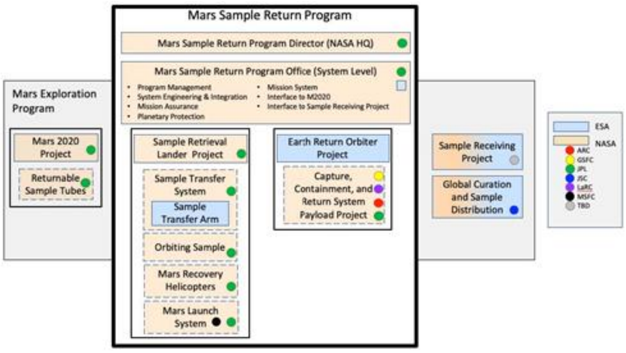

Figure 21. MSR program structure.

9.2. Scientific impacts

The planetary science community has advocated for MSR for decades as an endeavor that would fundamentally advance our understanding of the history and evolution of the solar system, and about the past and current habitability of Mars. The potential benefits of MSR include proven capability to return planetary samples with robots and potentially historic discoveries. These discoveries would be enabled by applying current and future technological capabilities to the analysis of Martian samples through Earth-based laboratory, far beyond what is possible to implement with in-situ instruments. MSR is also expected to provide enormous educational and inspirational benefits to the public.

Acknowledgements

The authors would like to thank the MSR, ERO, and CCRS project teams for their support and dedication to NASA's ongoing efforts to increase humankind's understanding of the universe. A portion of the work described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

The decision to implement Mars Sample Return will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

Appendix A: Abbreviations and Acronyms

AE	Assembly Enclosure
AEDL	Approach Entry, Descent and Landing
ATC	Aero-Thermal Closeout
ATS	Absolute Time Sequence
bPOC	Backup Payload Operation Center
BPP	Backward Planetary Protection
C&C	Capture and Configuration (CCRS Phase)
CCRS	Capture, Containment and Return System
CCS	Capture & Configuration System
CE	Capture Enclosure
CLM	Capture Lid Mechanism
CMD	Command
COP	Containment Phase (ERO phase)
C-OS	Contained OS (OS + SCV)
CSG	Centre Spatial Guyanais (Guiana Space Center)
CSS	Capture Sensor Suite
DSN	Deep-Space Network
DSOC	Deep Space Optical Communications
EAM	Earth Avoidance Maneuver
EAR	Export Administration Regulations
EDL	Entry, Descent, and Landing
EDP	EES Delivery Phase (ERO phase)
EE	End Effector
EES	Earth Entry System
EESA	EES Aeroshell
EESOOA	EES On-orbit Assembly (CCRS Phase)
EIP	Entry Interface Point
ERO	Earth Return Orbiter
ESA	European Space Agency
ESOC	European Space Operations Centre
ESTRACK	European Space Tracking network (ESA analog to DSN)
ETM	Earth Targeting Maneuver
FCM	Final Cleanup Maneuver (to Earth)
FOT	Flight Operation Team
FPP	Forward Planetary Protection
FSW	Flight Software
GDS	Ground Data System
GITL	Ground-in-the-Loop
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
GS&O	Ground System and Operations
HDRM	Hold-Down Release Mechanism
HGA	High Gain Antenna
HIP	Homing Interface Point
IGST	Integrated Ground-Space Test
I&T	Integration and Test
IM	Illumination Module
IMU	Inertial Measuring Unit
ITAR	International Trade in Arms Regulations
ITP	Inbound Transfer Phase (ERO phase)
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LaRC	Langley Research Center
LCOT	Launch, Commissioning, & Outbound Transfer
LED	Light Emitting Diode
LEOP	Launch & Early Orbit Phase (ERO phase)
LMOSP	Low Mars Orbit Support Phase (ERO phase)
LOS	Lid Assembly + OS
LRM	Lid Restraint Mechanism

LRS	Lid Release System
LTM	Linear Transfer Mechanism
LV	Launch Vehicle
M2020	Mars 2020 Rover (Perseverance)
MAV	Mars Ascent Vehicle
MEP	Mars Exploration Program
MDNav	Mission Design & Navigation
MLS	Mars Launch System
MMOD	Micro-meteoroid Orbital Debris
MMG	Micro-meteoroid Garage
MMPS	Micro-meteoroid Protection System
MOC	Mission Operations Center
MOIP	Mars Orbit Insertion Phase (ERO phase)
MOM	Mission Operation Manager
MRN	Mars Relay Network
MRSH	Mars Return Sample Handling
MSA	Mission Support Area
MSFC	Marshall Space Flight Center
MSO	Mars Support Orbit
MSR	Mars Sample Return
NASA	National Aeronautics and Space Administration
NECP	Near Earth Commissioning Phase (ERO phase)
NEPA	National Environmental Policy Act
OBC	On-Board Computer
OBC-MM	OBC Mass Memory
OM	Orientation Mechanism
OMG	Orientation Mechanism Guard
OpHtr	Operation Heater
OS	Orbiting Sample
OTP	Outbound Transfer Phase (ERO phase)
PIE	Pickup, Installation and Encapsulation
PJR	Protection, Jettison and Release (CCRS phase)
POC	Payload Operations Center
POR	Payload Operations Request
PP	Planetary Protection
PRT	Platinum Resistance Thermometer
PSTB	Payload System Testbed
RDVP	Rendezvous Phase (ERO phase)
RD	Restraining Door
RP	Retirement Phase (ERO phase)
RPO	Rendezvous and Proximity Operations
RSCE	Robotic System Control Electronics
RSO	Relay Support Orbit
RSS	Rendezvous Sensor Suite
RSTA	Return Sample Tube Assembly
RTAS	Robotic Transfer Assembly System
RTS	Relative Time Sequence
S/C	Spacecraft
SCV	Secondary Containment Vessel
SDP	Spiraling Down Phase (ERO phase)
SEM	Spin Eject Mechanism
SK	Station Keeping
SMD	Science Mission Division
SOLAR	SCV-OS Latch-Align-Restrain
SpW	Space Wire
SRH	Sample Recovery Helicopter
SRL	Sample Retrieval Lander
SRP	Sample Receiving Project
SSMM	Solid State Mass Memory
STA	Sample Transfer Arm (on SRL)
STRATCOM	U.S. Strategic Command
SUP	Spiraling Up Phase (ERO phase)
SVT	System Validation Test
TC	Telecommand
TCM	Trajectory Correction Maneuver
TDMS	Technical Data Management System
TLM	Telemetry
TPS	Thermal Protection System
UHF	Ultra High Frequency
UTTR	Utah Test and Training Range
UV	Ultraviolet
VS	Vision System