Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

NASA's Capture, Containment, and Return System: Bringing Mars samples to Earth

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ARTICLE INFO

Keywords:
Mars mission
Sample return
Mission design

ABSTRACT

The Mars Sample Return (MSR) campaign is one of the most ambitious and complex planetary science exploration missions ever pursued. With the participation of NASA, ESA, and many industry partners, MSR aims to bring Martian rock and atmosphere samples to Earth with the goal of answering key questions about Mars' geological, climatological and, potentially, biological evolution. To accomplish this ambitious goal, the MSR campaign relies on three distinct flight elements and a ground element. The Earth Return Orbiter mission that would host the Capture, Containment, and Return System (CCRS) is the last flight element of the trio. The mission would capture the orbiting sample in low Mars orbit (launched into orbit by another mission), contain it, and return it to Earth, landing at the Utah Test and Training Range. Since its early architecture, several changes were adopted by CCRS to improve overall payload efficiency and reduce mass. This paper will discuss the CCRS design, how the current CCRS architecture contributes to an improved mission concept, and the next critical steps of the mission toward its launch.

1. Introduction

Mars Sample Return (MSR) is a collaboration between the U.S. National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and several industry partners. The MSR campaign aims to bring Martian rock, regolith (broken rocks and dust), and atmospheric samples to Earth to answer key questions about the geologic and climate history of Mars, as well as the potential for ancient life [1–5]. Several concepts have been formulated over the years, consisting of multiple missions executing specific functions in a relay fashion [6,7]. Under the NASA architecture shown in Figs. 1 and 2, NASA's Capture, Containment, and Return System (CCRS), hosted on ESA's Earth Return Orbiter (ERO), would bring the samples to Earth. The CCRS payload is managed and would be operated by NASA. After capturing the Orbiting Sample (OS) container with the Martian sealed sample tubes in Mars orbit, ERO would journey back to Earth. Several robotic operations within CCRS would allow the OS to be protected in a containment vessel before being assembled into the Earth Entry System (EES) spacecraft. About 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 EES would then enter Earth's atmosphere, flying on a fully passive ballistic trajectory and landing safely on Earth, notionally at the Utah Test and Training Range (UTTR), USA.

This paper describes the purpose of the CCRS payload, its design, and the operation plans of its various subsystems as of the project's Preliminary Design Review (PDR). At the completion of this stage of

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https://doi.org/10.1016/j.actaastro.2024.05.048
Received 30 January 2024; Received in revised form 30 April 2024; Accepted 31 May 2024

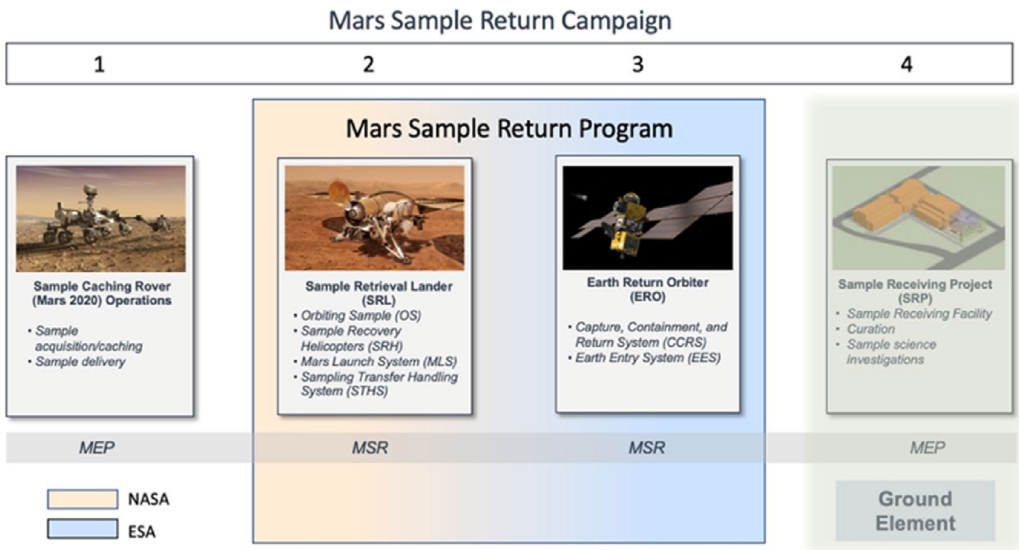


Fig. 1. Planned MSR campaign elements: Mars 2020 in its operational phase, SRL and ERO in their design phase as part of the MSR Program, and the SRP in its formulation phase.

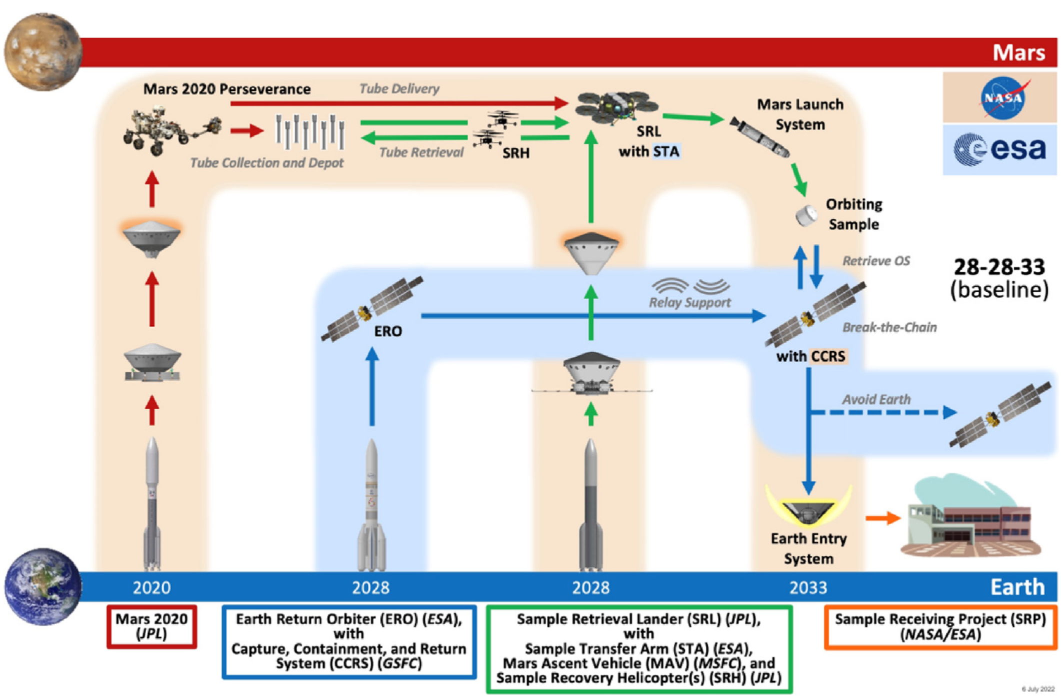


Fig. 2. MSR campaign planning architecture depicting the contributions of ESA and NASA as of late 2023 before the rearchitecture initiated in response to the second Independent Review Board final report [8].

a NASA project's life cycle [9], the design solution meets the mission needs and technology development has been completed to a level sufficient to proceed to critical design. This paper begins with a brief introduction of 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 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 sealed sample tubes would be returned to Earth safely and efficiently.

The purpose of this article is to contribute to the broader scientific and engineering community by showcasing the design elements and processes of an interplanetary mission with an emphasis on inspiring and offering a reference for future Mars sample return missions.

The document is organized in the following manner: Section 2 summarizes the MSR campaign and high-level requirements. Section 3 describes the ERO spacecraft and CCRS payload interface while offering insight into the mission phases and planned trajectory. Section 4 is an overview of the CCRS payload components, and major subsystems. Section 5 describes the details of every CCRS phase with the key events and approximate timelines. Finally, Section 6 summarizes the purpose and design of the CCRS mission.

2. Mars Sample Return campaign overview

MSR's 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 [10]; the NASA-led Sample Retrieval Lander (SRL) mission with the Orbiting Sample (OS) container [11,12], Sample Recovery Helicopter(s) [13], and Mars Ascent Vehicle [14,15]; and the ESA-led ERO mission [16,17], on which CCRS is the payload.

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

- The ERO mission with CCRS,
- The SRL mission to collect and launch sealed sample tubes into low Mars orbit.

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

- The Mars 2020 Perseverance Rover (currently conducting sample collection on Mars),
- The Sample Receiving Project to provide a containment facility for initial characterization of the samples, including a safety assessment [18,19].

Mars 2020/Perseverance and the Sample Receiving Project 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 Fig. 1.

2.1. Campaign timeline overview

Fig. 2 is a high-level illustration of the MSR campaign timeline for the 28-28-33 scenario [2028 = SRL launch, 2028 = ERO launch, and 2033 = Earth return]. This timeline was the nominal plan at the time of CCRS PDR in late December 2023. In case of a contingency, samples could be returned to Earth in 2035.

The MSR campaign began with the Mars 2020 mission [10], 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, acquiring, and caching samples in one or more depot locations on the Mars surface, while retaining a sample set onboard for direct delivery to the SRL [20–22]. As of April 2024, 24 samples have been acquired, with 10 sample tubes cached in the first depot at Three Forks [23].

The campaign timeline considers the launch readiness dates for SRL, ERO, and CCRS as well as the orbital dynamics involved into the Earth-Mars transit, the Mars capture and spiral-down, low Mars orbit operations, the spiral-up, and the Mars-Earth return transit. Each of the aforementioned items plays a role and needs to be concatenated to build the MSR timeline. Key considerations from orbital dynamics are that: Earth-Mars transit takes 1–2 years depending on whether an Earth gravity assist maneuver is employed; spirals down and up take approximately 1 year; Mars-Earth transit takes 1 year; and low Mars orbit depends on the SRL landing date and surface operations duration. In addition, the Earth-Mars orbital resonance is close to 2:1, which dictates optimal launch and return windows. Considering these details, the ERO-CCRS mission was projected (as of CCRS PDR) to launch in 2028 and reach Mars orbit in 2029. After Mars orbit insertion and jettison of its chemical propulsion stage, ERO would use electric propulsion to spiral down to low Mars orbit reaching it in 2030. There it would provide SRL Entry, Descent, and Landing (EDL) communication and relay support of the surface mission. SRL, previously projected to launch in 2028, would perform Mars EDL in July 2030. 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 with the two NASA Sample Retrieval Helicopters deployed from SRL serving as backups, based on the successful Mars 2020 Ingenuity [24]. The samples would then be placed in low Mars orbit and captured by ERO-CCRS in 2031. Once captured, ERO-CCRS would initiate its return to Earth, finish the spiral-up in 2032 and arrive at Earth in 2033.

2.2. Planetary protection requirements

Many drivers for the MSR design and operational concept revolve around the mission planetary protection categorization, which is based on the need to protect Mars from potentially harmful contamination by terrestrial materials to enable scientific exploration (forward planetary protection – FPP) as well as to protect the Earth-Moon system from possible harmful extraterrestrial contamination that may be returned from Mars (backward planetary protection – BPP) [25–28]. In the execution of MSR, NASA and ESA have mutually agreed to apply approaches consistent with their own planetary protection standards to the campaign elements they each provide. As with every planetary mission, each MSR flight element is assigned a planetary protection categorization according to the type of planetary encounter planned (e.g., flyby, orbiter, lander) and the nature of its destination. This section briefly explains the project's BPP and FPP requirements that derive from this categorization and the processes in place to meet them. For further details about the planetary protection strategy of the entire ERO-CCRS mission, the reader is referred to [17].

The ERO spacecraft and CCRS payload are categorized as "Category V(r) Restricted Return" for BPP. To meet the standards for this categorization, CCRS would follow a "Break the Chain" process, which prohibits uncontrolled transmission and release of Mars material of concern into Earth's biosphere. This process consists of a series of operations to be performed throughout the entire mission timeline and is intended to control and contain unsterilized Mars particles to prevent them from being transferred from one step to the next. The "Break the Chain" techniques (1–4), employed by both ERO and CCRS, are shown in Table 1 below along with Earth avoidance by ERO post-release (5), anomaly detection (6), and precision landing (7). Events such as the initiation of Earth return, the Earth targeting maneuver, and the release of the EES may be subject to approvals from federal and international authorities. If the aggregate flight system status or performance does not meet the desired levels, the EES would remain with the ERO in a heliocentric orbit and the samples would not be returned.

ERO and CCRS are classified as "Category III Flyby/Orbiter" for FPP. To comply with the requirements inherent to this category, CCRS would employ different strategies. First, CCRS would comply with ERO-CCRS interface requirements and final disposition of CCRS hardware not returned to Earth would be compliant with Cat. III FPP through trajectories established and maintained by ERO. CCRS would be assembled, integrated and tested in an ISO-8 or better cleanroom; alternatively, hardware would be tested for bioburden directly. CCRS is also required to provide an inventory of all organic materials present on the payload in amounts greater than 1 kg to aid in determining future scientific impacts if the mission inadvertently contacts Mars. Finally, CCRS would archive 50 g of organic materials present on the payload in amounts greater than 25 kg.

3. ERO-CCRS project overview

The ERO-CCRS mission would begin with an expected launch from French Guiana onboard an Ariane 6 rocket. Since CCRS is the payload for the ERO mission, CCRS activities would take place throughout the ERO mission timeline. The major ERO mission objectives are to support CCRS during the transfer to Mars, provide surface communication relay at Mars, detect and rendezvous with the OS in Mars orbit, and return the OS from Mars inside the EES.

The ERO mission is divided into twelve phases, each with its own space environment considerations (thermal, dynamic loads, ground

Table 1
Backward Planetary Protection Processes for the ERO-CCRS mission.

No.	Process	Responsibility
1.	Active UV illumination of the OS	CCRS
2.	Containment of the OS in a Secondary Containment Vessel (SCV) and assembly into the EES	CCRS
3.	Particle management within CCRS	CCRS
4.	Passive heat sterilization on outside of EES during AEDL	Mission design
5.	Active avoidance of Earth by ERO post-release	ERO
6.	Anomaly detection	ERO-CCRS
7.	Precision landing (ETM, EES release)	ERO-CCRS

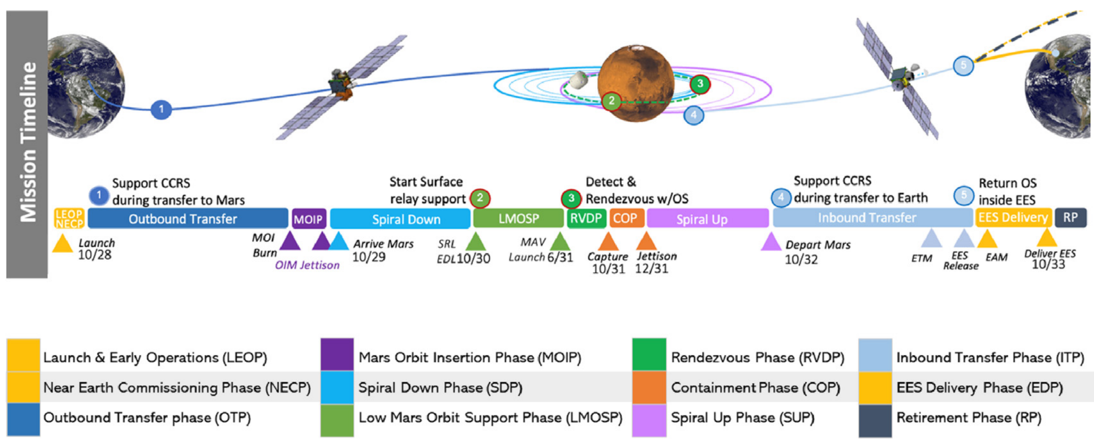


Fig. 3. The timeline for the twelve planned ERO phases and major ERO mission events as it stood prior to the re-architecting effort initiated in late 2023.

communications) due to its trajectory. Fig. 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 overlaps with the ERO timeline, it is broken down into a separate set of project phases, from pre-launch activities through end of mission, which 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)
6. Provide Ground and Operations Support [all CCRS Phases]

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

3.1. ERO spacecraft overview

The ERO spacecraft [16,17] would be composed of two main subsystems, the orbit insertion module and the return module. The orbit insertion module contains the chemical propulsion system that would be used to propel ERO on the outward journey from Earth to Mars, while the return module would be composed of the CCRS payload, a second chemical propulsion system to be used for propelling ERO on the return journey from Mars to Earth, an electric propulsion system used for large Delta-V maneuvers, and the solar power and communication systems. Fig. 5 below shows the ERO flight configuration. ERO would use a hybrid propulsion system consisting of both chemical and electric propulsion to ensure all mission trajectory objectives are met.

3.2. Earth-to-Mars transit

Assuming an ERO launch in 2028 (assumed launch date at CCRS PDR), the trajectory to Mars would require two electric propulsion thrusts arcs, so the total trip time from launch to Mars arrival would be approximately 302 days. As the ERO spacecraft travels farther from Earth, the light time delay increases, resulting in increasingly longer command and response times. This means that most of the CCRS mission activities would have to be completed autonomously without real-time ground-in-the-loop control, using standard flight software functionality. Once ERO has reached Mars orbit and performed the Mars orbit insertion burn, ERO would jettison the orbit insertion module. Fig. 6 below shows a nominal flight trajectory plan for the outgoing flight and the resulting change in light time delay until achieving Mars orbit insertion.

3.3. Mars orbit communication

After completing the orbit insertion module jettison activity, ERO would begin spiraling down to low Mars orbit, where it would support communication relay to Earth during the EDL and surface operation activities of the SRL mission. The spiral-down process would last approximately 10 months, and the duration of the full period from the start of spiral-down activity to the end of spiral-up activity would be approximately 3 years. As the spacecraft spirals down toward Mars, the parameters of the orbit (eclipse, altitude, ground contacts) would naturally change. Fig. 7 shows the changes in ERO's distance from Earth and the associated variations in light time delay during the period of SRL communications relay assuming a 2028 launch.

3.4. Mars-to-Earth transit

Once the OS has been captured by CCRS after being inserted into Mars orbit by SRL, ERO would begin the spiral-up activity in order to begin the return flight to Earth. The inbound transfer phase of ERO

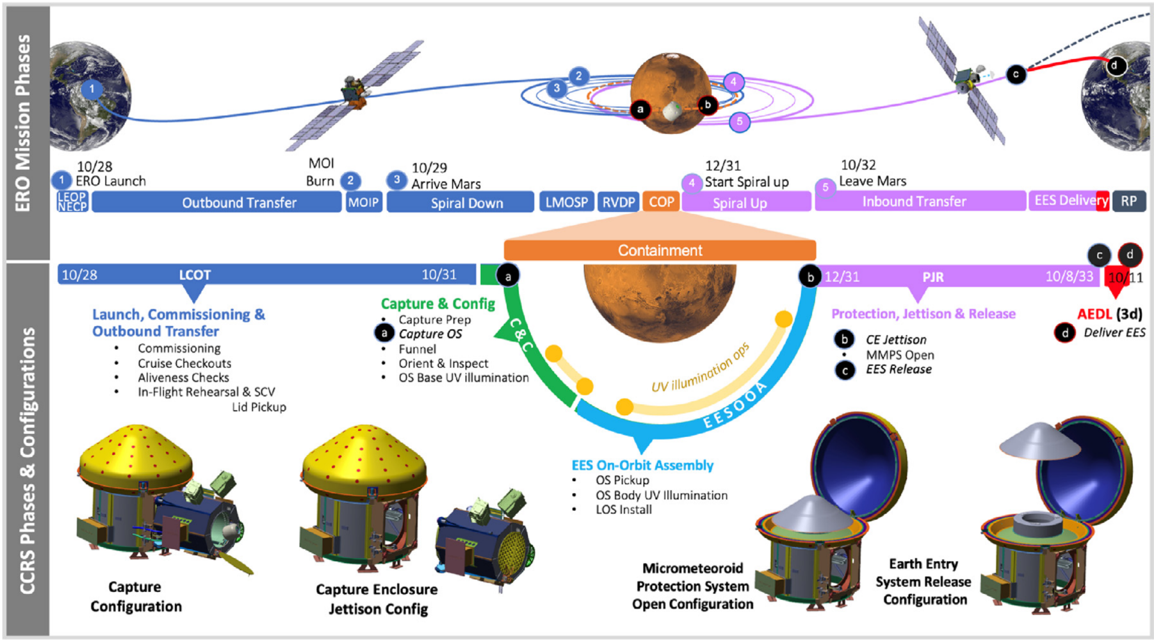


Fig. 4. Planned CCRS and ERO phases with key events and CCRS configurations.

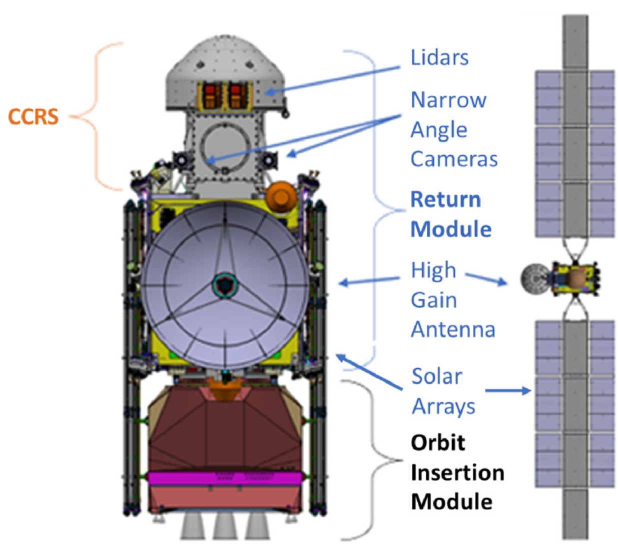


Fig. 5. Stowed and deployed ERO spacecraft configurations.

would take approximately 1 year, from the end of spiral-up through the return flight toward Earth, until the planned start of the EES release operational period. Similar to the Earth-to-Mars transit, as ERO journeys farther from Mars and closer to Earth, the light delay would naturally decrease, resulting in continually reducing ground command and response times. Fig. 8 shows a nominal flight trajectory plan for the return flight and the resulting light time delay change.

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 mission phases (as well as the ground element):

1. Perform overall robotic operation at Mars orbit in a clean and timely manner [all CCRS phases]
2. Capture and 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 and reduce potential contamination [PJR phase]
5. Protect EES from meteorite impacts and release the EES [PJR phase]
6. Release EES on targeted path to selected landing location on Earth [PJR phase]
7. Perform EES approach, entry, descent and landing on Earth [AEDL phase]
8. Provide ground and operations support [all phases]

The following sections will describe the CCRS payload and ground elements, the nominal activities that would take place during each of the CCRS operational phases, and the systems and components used to perform those activities.

4.1. 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 assemble the Earth Entry System (EES) by inserting and sealing the OS in a redundant containment vessel within the return vehicle aeroshell; 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 sample tubes to the landing area. The approximate mass of the CCRS payload is 620 kg. It is composed of the capture, assembly and micrometeoroid enclosures with approximate masses of 240 kg, 280 kg, and 100 kg, respectively.

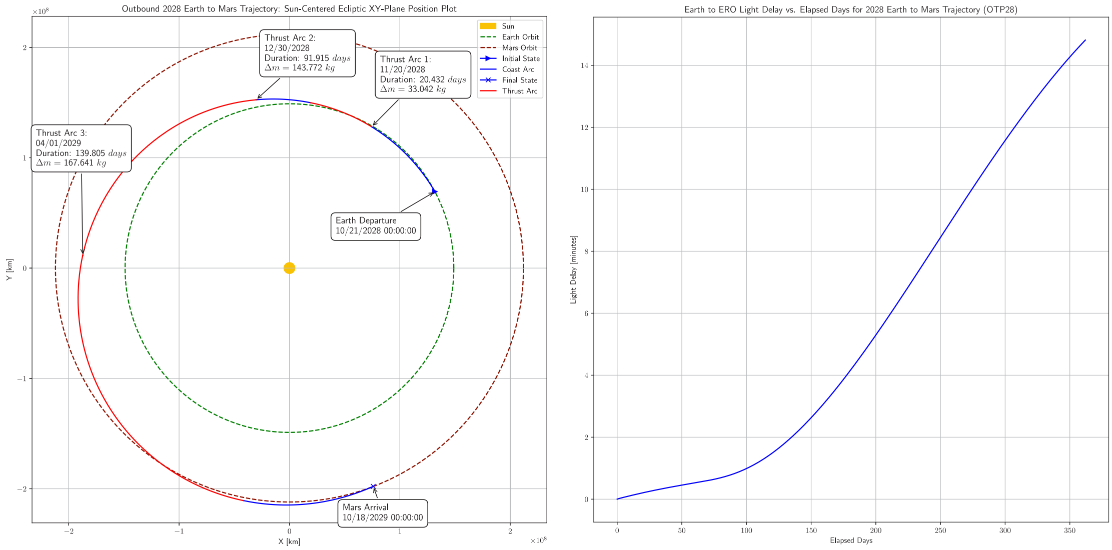


Fig. 6. The 302-day ERO-CCRS Outbound Trajectory from Earth-to-Mars and the Light Time Delay for a 2028 Launch.

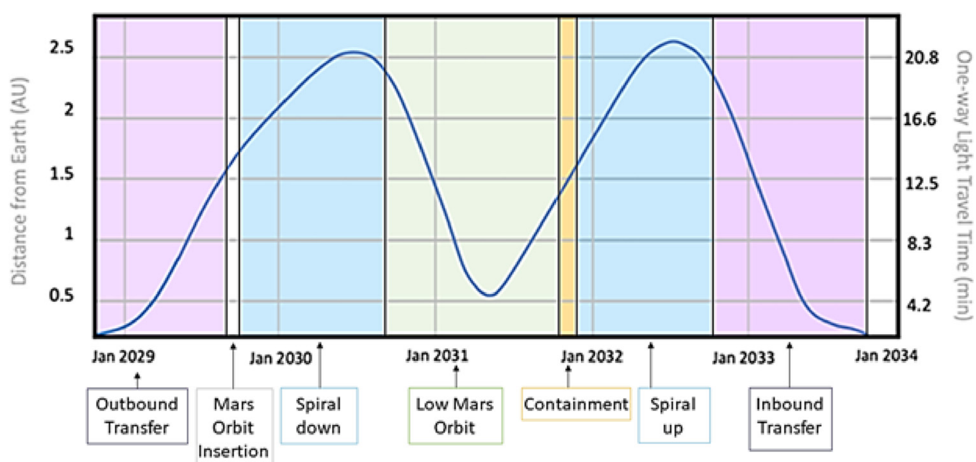


Fig. 7. ERO-CCRS distance from Earth and light time delays during SRL relay for a 2028 Launch. The longest communication delays occur in the summers of 2030 and 2032.

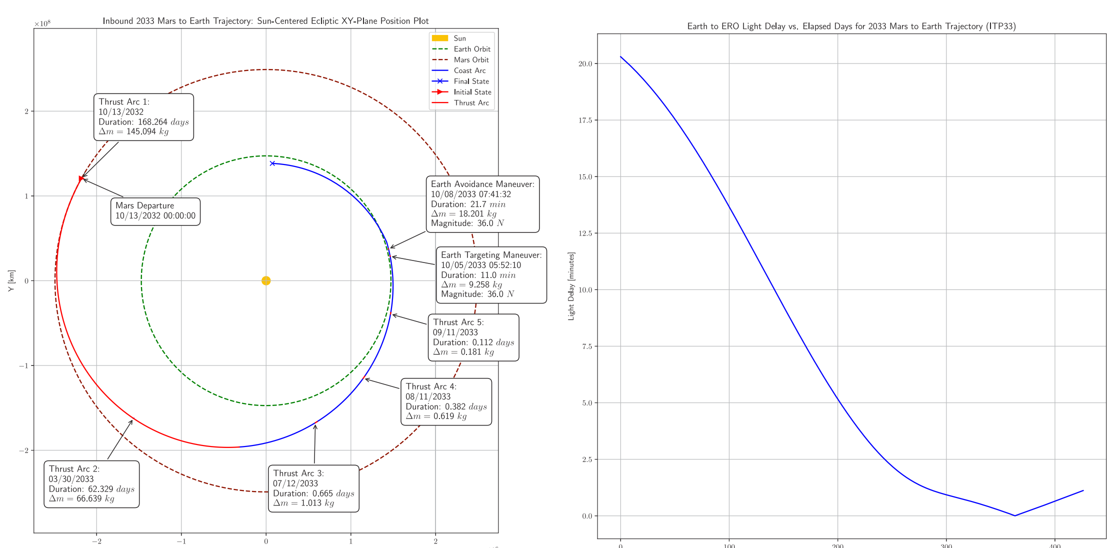


Fig. 8. The Year-Long ERO-CCRS Outbound Trajectory from Mars-to-Earth and the Light Time Delay for a 2028 Launch.

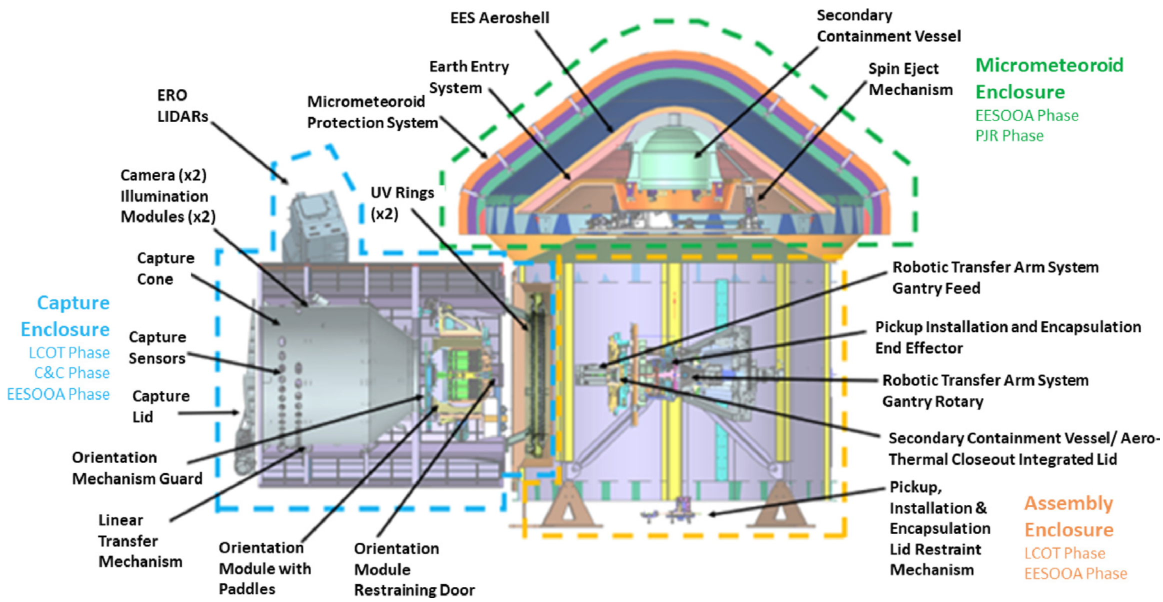


Fig. 9. CCRS payload element displaying the three CCRS element modules and major system components. The overall dimensions of CCRS are approximately $3.4\,\mathrm{m} \times 0.5\,\mathrm{m} \times 2\,\mathrm{m}$.

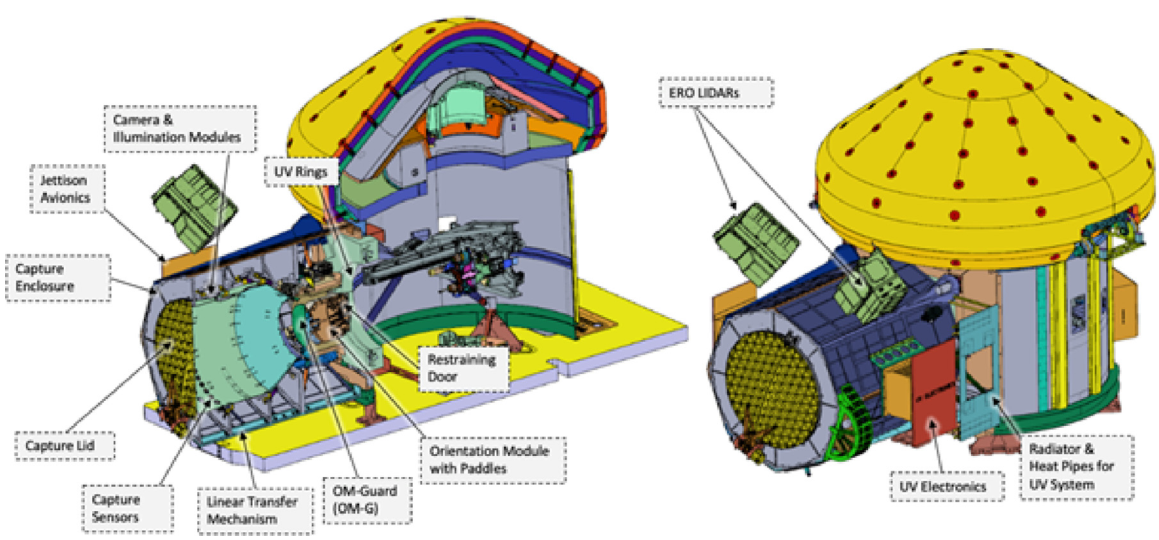


Fig. 10. Model of the capture enclosure components.

Fig. 9 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 the CCRS components and their functions are found in Table 2, Table 3, and Table 4. Corresponding illustrations focusing on the components of each module are shown in Figs 10, 11, and 12.

Previous sample return missions have used similar return vehicle geometries as the EES. The conical shape allows for aerodynamic stability during reentry. Table 5 describes past sample return missions, their reentry vehicle physical components, and the method of reentry [29–33].

While the reentry vehicles between CCRS and former missions have similarities, no other mission has attempted a sample return from a different planet. The nature of the CCRS mission necessitates a novel design to execute its purpose.

4.1.1. *Primary payload functions*

To facilitate the successful execution of all CCRS operations, the payload would perform the following functions:

- Execute direct commands sent from the ground
- Process commands from stored command files, either via Flight System Test and Operations Language (FSTOL) or Relative Time Sequence (RTS), previously loaded to CCRS
- Perform fault management functions as defined by the CCRS Fault Management Architecture & Design Document
- Generate and transmit housekeeping and engineering telemetry and images to ERO (for eventual transmission to the ground)

4.1.2. *Payload power*

All CCRS power is provided by the ERO spacecraft and consists of redundant 28-V and 100-V Power Control and Distribution Units (PCDUs). CCRS power consumption throughout the mission is carefully managed with the ERO spacecraft in each phase, with the payload typically consuming 300 W to 500 W.

4.1.3. *Thermal subsystem*

The CCRS payload thermal system's main design driver is to thermally protect the Mars sample tubes throughout the mission lifetime.

Table 2
CE components, functions, and CCRS mission phases.

Subsystem	Mechanism/Unit	Function	LCOT	C&C	EESOOA	PJR	AEDL
Capture & Containment System (CCS)	**Capture Lid Mechanism**	Serves as a thermal cover to the capture cavity	X	X			
	Linear Transfer Mechanism (LTM) Swing Arm	Cages the OS once it enters the capture cone	X	X			
	LTM Linear Drive	Funnels the OS down the capture cone into the OM	X	X			
	Capture Cone	Designed to handle incoming OS impact loads without damaging OS and supports funneling operations		X			
	Orientation Mechanism (OM)	Orients the OS into the proper orientation using paddles	X	X	X		
	OM - Guard	Protects the OM during OS capture and serves as a registration surface for integrated lid installation	X	X	X		
	OM - Restraining Door	Keeps the OS within the OM volume during orientation. Also seats the OS onto the OM-Guard in preparation for integrated lid installation	X	X			
	Capture Sensor Suite (CSS)	Two beam break layers to detect the incoming OS to trigger the LTM swing arm to deploy and “capture the OS”	X	X			
	CCS Launch Locks	Launch locks holding down CCS mechanisms	X				
Vision System (VS)	**Cameras (x2)**	Placed on the outside of the capture cone with strategic holes placed to allow camera visibility of the OS while constrained in the OM	X	X			
	Illumination Modules (x2)	Visible light LEDs to assist in the image capture	X	X			
Thermal System	**Operational Heaters**	16P + 16R operational heaters in the CE	X	X	X		
	Survival Heaters	3P + 3R survival heater services in the CE	X	X	X		
Avionics	**Jettison Avionics**	Controls the mechanisms and heaters in the Capture Enclosure that are jettisoned	X	X	X		
UV System	**UV Rings**	2 rings, 1 ring with 104 LEDs for OS base illumination, and 1 ring with 104 LEDs for OS body and OS bid illumination.	X	X	X		
	UV Electronics	Controls the UV rings	X	X	X		

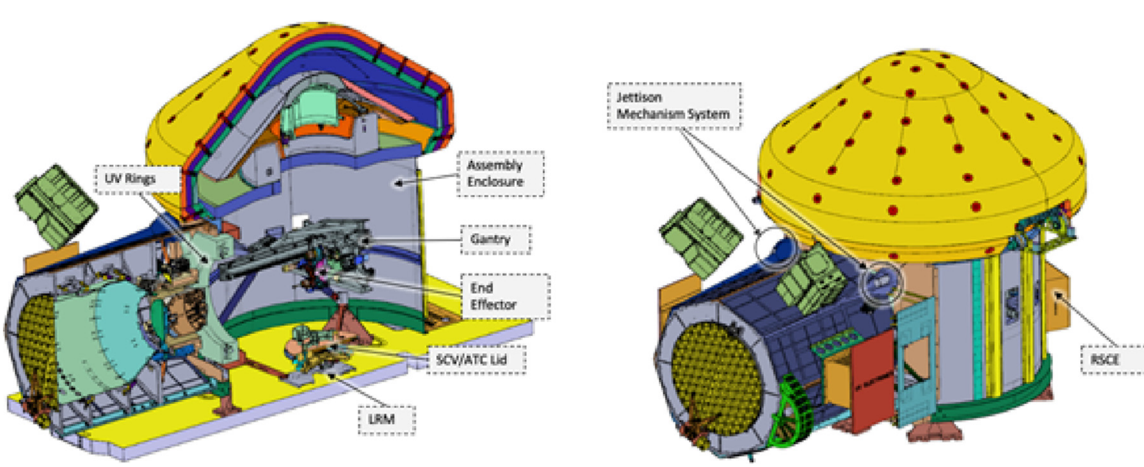


Fig. 11. Model of the assembly enclosure components.

Table 3
AE Components, Functions & Mission Phases.

Subsystem	Mechanism/Unit	Function	LCOT	C&C	EESOOA	PJR	AEDL
Robotic Transfer Assembly System (RTAS)	Gantry	2 degree-of-freedom robotic manipulation platform that positions the End Effector for EES assembly operations	X		X		
	Gantry Launch Locks	They hold down the Gantry	X				
	Robot Servo Control Electronics (RSCE)	Controls the Gantry and End Effector mechanisms and sensors, reports telemetry	X		X		
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 Integrated Lid/ OS to the EES	X		X		
	Lid Restraint Mechanism (LRM)	Set of release devices to hold the Integrated Lid Assembly (composed of SCV Lid and Aero-Thermal Closeout). Released during robotic operations to pick up the Integrated Lid	X				
	SCV-OS Latch, Align, Restrain (SOLAR)	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	X		X		
	SCV Lid	Contains rotary latch mechanism that, when torqued into a latched position after installation into the EES Aeroshell by the EE, forms the Containment Assurance seal for BPP	X		X	X	X
	SCV Body	Secondary containment vessel body, located within the EES Aeroshell. This is the structure that the Integrated Lid and OS are latched into.			X	X	X
EES Aeroshell	Aero-Thermal Closeout (ATC)	Attached to the SCV Lid in the launch configuration. Acts as a Hot Gas Barrier for EDL. SCV Lid & ATC make up the Integrated Lid Assembly			X	X	X
Thermal System	Operational Heaters	16P + 16R operational heaters in the AE	X	X	X		
	Survival Heaters	5P + 5R survival heater services in the AE	X	X	X	X	
Avionics	Main Avionics	Distributes power from ERO, controls HDRMs, Thermal control in the AE, manages data collection and platform for CCRS flight software	X	X	X	X	
Structure & Deployables	Cable Cutters	Severs connection between the Capture and Assembly Enclosure electrical components				X	
	Jettison Mechanism System	4 NEAs are released to jettison the Capture Enclosure from the Assembly Enclosure				X	

In addition to safeguarding sample integrity, the thermal system would actively keep all CCRS mechanisms and units within their operational temperature ranges, while hardware is in use and protected during non-operational times throughout the different mission phases (Table 6).

4.1.4. UV illumination subsystem

The goal of the UV illumination subsystem is to support the "Break the Chain" process by minimizing the quantity of potentially hazardous Mars particles transported on the OS from the capture enclosure to the assembly enclosure. MSR has defined potentially hazardous Mars material as particles of diameters ≥ 50 nm that would encompass any potential Mars biology that might proliferate and compromise the integrity of Earth's biosphere (note that host-specific pathogenesis is considered the lowest likelihood hazard [34]). For a detailed discussion on why Mars is a challenging environment for active biology or biomolecules and why the samples being collected by Perseverance pose a low likelihood hazard, the reader is referred to [17].

Active UV radiation is the proposed sterilization strategy. The efficacy of UV sterilization is subject to verification through ongoing biological testing at the Jet Propulsion Laboratory under appropriate environmental conditions (vacuum, temperature, presence of dust particles) and using flight-like illumination parameters. The MSR Program has been conducting a parallel effort to demonstrate overkill sterilization values for solar UV. It is important to note that any sterilization method used for a NASA mission would meet the technical standards for planetary protection, which include overkill sterilization method validation in accordance with ISO 11138-7 standards [35]. The MSR Program has identified penetrating sterilization methods (e.g., heat) as a risk to future sample science whereas a surface sterilization such as UV imposes little to no risk to the samples protected inside the OS. The proposed UV sterilization system is expected to have lower mass than with the previous heat sterilization approach [36]. Additional details on this proposed UV sterilization system can be found in [37,38], while a summary of its concept of operations (ConOps) is found below.

The UV illumination subsystem is responsible for providing UV light exposure for a given time to particles that are not contained within the OS. The subsystem consists of:

Table 4
Micrometeoroid Enclosure Components, Functions & Mission Phases.

Subsystem	Mechanism/Unit	Function	LCOT	C&C	EESOOA	PJR	AEDL
Structures & Deployables (S&D)	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.				X	
	MMPS HDRMs	Hold Down Release Mechanisms securing the MMPS Lid closed until time to open for EES release				X	
Spin Eject Mechanism (SEM)	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.				X	
Earth Entry System (EES)	Aeroshell	The structure that protects the EES with the OS inside during entry, descent and landing.				X	X
	Thermal Protection System (TPS)	The thermal protection layer on top of the EES Aeroshell				X	X
Orbiting Sample (OS)	Orbiting Sample	Captured in Low Mars Orbit and is Contained with the SCV Body of the EES for Entry, Descent and Landing on Earth		X	X	X	X

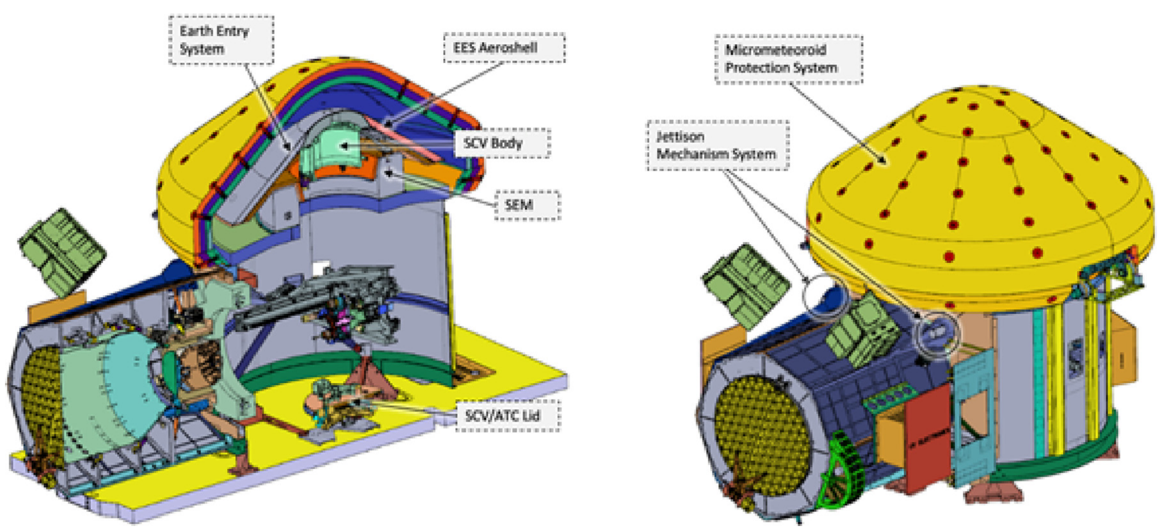


Fig. 12. Model of the micrometeoroid enclosure components.

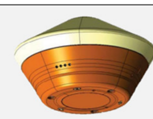
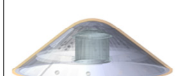
- Two separate rings on one single structure located between the AE and CE structures:
  - Ring-1 includes 104 LEDs with positions specific for OS base exposure
  - Ring-2 includes 104 LEDs with position specific for OS body and OS lid exposure
- Dedicated UV electronics box located on the CE structure, controlled by jettison avionics
- UV thermal radiator and heat pipes

The UV rings are planned to be operated in a pulse-like fashion, with the effects of the UV illumination being cumulative. Pulse operation allows for duty cycle of diodes to control average power and heat dissipation. The UV illumination subsystem is being designed to operate concurrently with ERO electric propulsion thrusting operations to minimize operational constraints on the mission. Further optimization is still needed to ensure UV operations during eclipse are feasible given ERO's battery performance.

The concept of operations for the UV subsystem is broken into UV illumination steps, of which there are 12 currently planned: one for the OS base and 11 steps for the body and lid. In order to meet a flux target at the OS surface of 375 W/m^2 and a total dose of 20 kJ [37], the UV rings would be powered "on" for 97 h for the OS base step, and 70 h for each of the 11 illumination steps for the body and lid (assuming illumination through eclipse periods). The concept of operations includes Ground-In-The-Loop checks after each UV illumination step, to ensure completion of the previous step and to command the repositioning of RTAS/PIE to move the OS into its next position prior to starting the next UV illumination step.

UV illumination step "Base", shown in Fig. 13, is performed at the end of the C&C phase (Section 5.2). The UV illumination, performed in 25-mm steps lengthwise, occurs in the EESOOA phase after OS pickup by the RTAS/PIE (Section 5.3).

Table 5
Previous Sample Return Reentry Vehicle Details.

Mission	Science Objective	Launch Date	Sample Return Date	Earth Return Capsule	Components of Return Capsule	Release time from Earth	Method of Reentry	Landing Success
Stardust [29]	Comet sample	February 1999	January 2006		- Heat shield - Backshell - Sample canister - Parachute - Avionics	4 hours	Parachute	- Landed within the landing zone - High winds caused drift
Genesis [30]	Solar wind sample	August 2001	September 2004		- Heat shield - Backshell - Sample canister - Parachute - Avionics	4 hours	Parachute	- Drogue parachute did not deploy causing unplanned hard landing - Capsule was damaged and contaminated
Hayabusa 1 [31]	Asteroid sample	May 2003	November 2005		- Heat shield - Sample canister - Parachute	12 hours	Parachute	Successful parachute descent at the nominal location
Hayabusa 2 [32]	Asteroid sample	December 2014	December 2020		- Heat shield - Sample canister - Parachute	12 hours	Parachute	Ballistic re-entry and successful parachute descent
OSIRIS-REx [33]	Asteroid sample	September 2016	September 2023		- Heat shield - Backshell - Sample canister - Parachute - Avionics	4 hours	Parachute	Drogue parachute did not deploy, main parachute provided sufficient drag to allow for a successful landing
CCRS [This paper]	Mars sample	No earlier than 2028	No earlier than 2033		- Heat shield - Sample canister	3 days	Ballistic hard landing	TBD

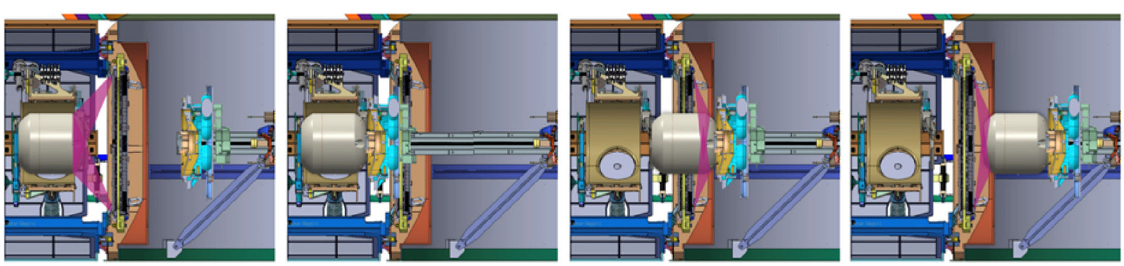


Fig. 13. OS movement and mechanism operations during UV illumination. The pink beams represent the UV illumination rays irradiating the OS.

4.1.5. *Flight software subsystem*

CCRS Flight Software (FSW) is based on the modular, open-source Core Flight System (CFS) framework. Software components are referred to as "apps". All flight software, including the robotics software, is compiled into a single executable running on a single processor in the main avionics (Fig. 14). This software interfaces with four main endpoints:

- Hub Cards: Control capture enclosure hardware
- Robot Servo Control Electronics (RSCE): Control assembly enclosure mechanisms
- Housekeeping Card: Other hardware interfaces
- ERO Interface: SpaceWire interface with ERO flight computer

FSW apps with a notable role in operations include:

- **Flight STOL (FSTOL):** Onboard implementation of the System Test and Operations Language (STOL) scripting language. FSTOL scripts are loaded separately from the underlying flight software. They interface with the system in the same way as a ground operator, by checking telemetry and sending commands. This capability allows for simple onboard automation that can be easily modified during testing or contingencies.
- **Stored Command:** Allows execution of Relative Time Sequences (RTSs) which are stored sequences of command used for fault responses and precisely timed activities.
- **Limit Checker:** Used for fault management to monitor telemetry and trigger RTS responses.
- **Robot Software:** A FSW app that provides logic for command and control of the RSCE and AE mechanisms.
- **Thermal Control:** Provides monitoring of thermal sensors and control of operational heaters.

Table 6
CCRS Thermal ConOps.

Objective	Description	Concept of Operations
Keep Sample Temperature Cold	Ensure the Return Sample Tube Assembly (RSTA) stays below the allowable flight temperature of -20°C (except for periods of unavoidable operational transients for which the AFT is +30°C) • Unavoidable op transients: UV illumination & AEDL activities	Passive thermal design
Maintain Op Temps during Active CCRS Ops	The CCRS system includes 32P + 32R operational heaters throughout both the AE and CE structures: • 16P + 16R operational **heaters** (28V) controlled by the Jettison Avionics within the CE • 16P + 16R operational heaters (80-100V) controlled by the Main Avionics within the AE	Operational heaters are enabled for one section at a time based on OS location, remaining sections would be thermally protected by surrounding survival heaters
Maintain Survival Temps during Idle/OFF CCRS	The CCRS system includes a total of 8P & 8R survival heater services spread across the AE and CE structures. Each heater service is its own ERO LCL, with multiple heater circuits. Both primary and redundant survival heaters are controlled by thermostats. • 4P + 4R heater **services** on AE • 4P + 4R heater **services** on CE • 80V-100V at the ERO-CCRS electrical interface for powering on Survival Heaters during CCRS non-operational modes (including CCRS Power OFF)	All survival heaters would be enabled for the duration of the mission, including launch
Monitor Temperature Sensors	All CCRS provided temperature sensors are Platinum Resistance Thermometers (PRTs) and are only monitored by CCRS when CCRS is powered ON. ERO provides 18 temperature sensors for thermal control and payload monitoring that are monitored by ERO at all times. • 12 thermistors • 6 PRTs	18 ERO-provided temperature sensors would be monitored at all times (CCRS Active/Idle/OFF) When CCRS is powered OFF, CCRS temperature sensors would be polled every 4 months during Aliveness Checks
Accommodate UV Illumination Operations	The UV system is the most power and thermal intensive part of the CCRS payload and requires a dedicated radiator & heat pipes	The size of the radiator panel contributes to the operational constraints of the UV illumination process.

4.1.6. CCRS data

Most of the data CCRS generates on-board is classified as housekeeping data and is solely intended to be downlinked to the ground to be assessed by operators in the Mission/Payload Operations Centers to confirm CCRS activities successfully executed. The other four categories of CCRS data generated on-board are described below and visually shown in Fig. 15.

1. **Housekeeping Data**: Encompasses the majority of CCRS data from main and jettison avionics, FSW, mechanisms, temperatures and subsystem data. These data are transmitted via a SpaceWire interface to ERO and formatted in CCSDS packets.
   a. Average transmit rate to ERO per orbit: 15 kbps (idle), 50 kbps (active, mechanisms moving)
   b. On-board storage: ERO packet stores in OBC-MM
   c. Downlink ConOps: Small subset available in real-time stream (VC0) and rest included in the playback stream (VC1)
2. **Critical Data**: A subset of housekeeping data that if lost could jeopardize the mission.
   a. On-Board Storage: 2 MB in CCRS Proc Card MRAM (NVM)
   b. Downlink ConOps: Only playback in the event of a processor reset
3. **Image Data**: CCRS camera images.
   a. Transmit rate to ERO: 20 Mbps
   b. Image data flow: The current ConOps is to write images to ERO's two logical address locations (0x50/0x51) in a round robin like fashion. Once the CCRS is finished writing an image file to one address, it would send a file completion event that would trigger ERO to save off that file and queue is up for downlink based on priority. Once the file completion event message is sent for one address location, CCRS may begin writing to the other logical address without delay.
   c. On-board Storage: The ERO spacecraft includes a 5-GB non-volatile data storage capacity (Solid State Mass Memory) allocated to CCRS and would store CCRS files until successful transmission to Earth is achieved.
   d. Downlink ConOps: Request ERO to playback file.
4. **Diagnostic Data**: FSW data for troubleshooting purposes, subsystem data sampled at a faster rate.
   a. Transmit Rate to ERO: 20 Mbps
   b. On-board Storage: 5-GB ERO SSMM (as a file)
   c. Downlink ConOps: Only playback in the event of an anomaly

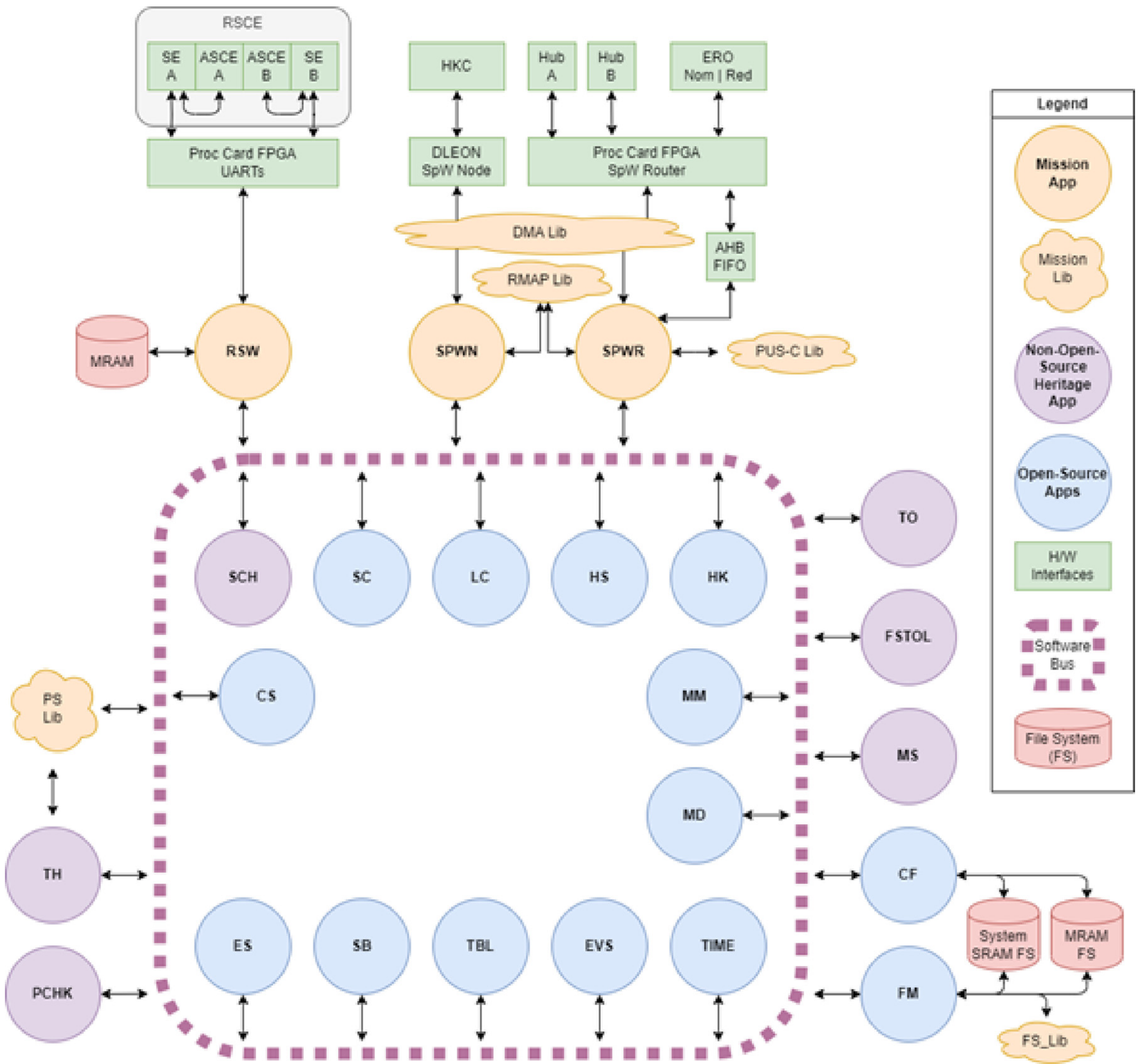


Fig. 14. Flight software component context diagram.

5. **PUS-C Compliant Packets:** Only a very small set of telemetry is transmitted to ERO for use by on-board software to support fault detection and response. That telemetry is formatted in PUS-C compatible CCSDS packets, and is also available for downlink to the ground.

It should be noted that the CCRS-to-ERO transmit rates listed above are not limitations of ERO's SpaceWire design, but instead an attempt to fit all (non-file) data on the order of the radio downlink capability (250 kbps at 2.2 AU) within a single playback during a 40-minute downlink pass to enable quick data transfer to Earth. Since most CCRS operations would be executed out of view, the playback of these data during ground contacts in a timely manner to support Ground-In-The-Loop decisions is paramount.

CCRS would have 16 GB of flash storage for uploading software and parameter changes only, but it is not intended for any local telemetry storage.

4.2. 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 located at GSFC in Maryland. 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. The MOC would verify and store the payload operations requests 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. In addition, CCRS would maintain a secondary operations facility at ESOC. This facility serves a backup

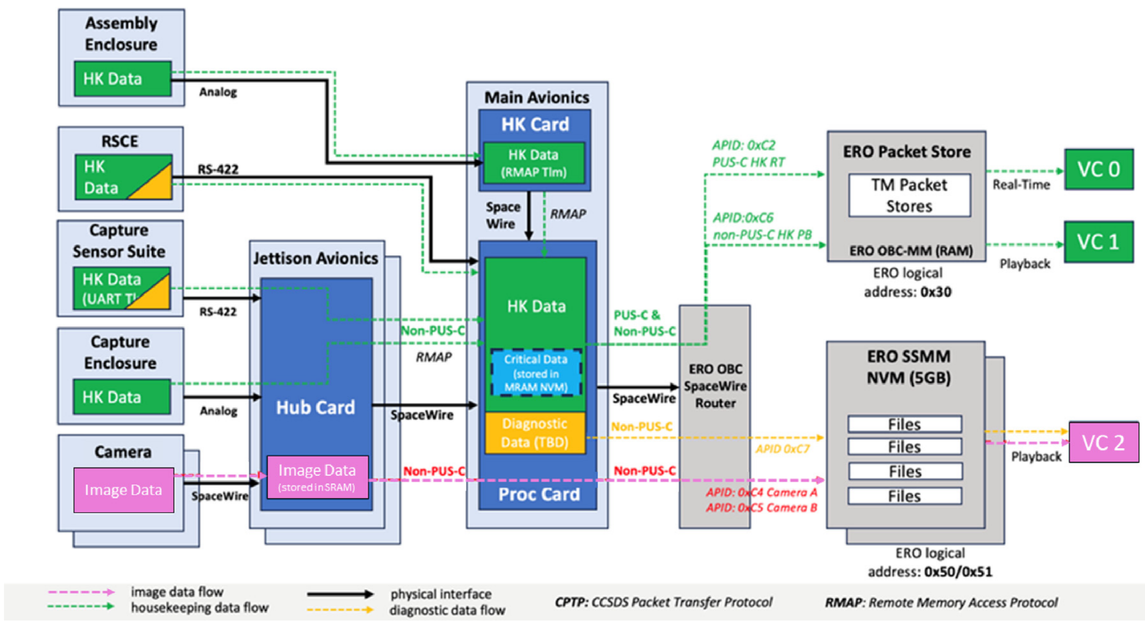


Fig. 15. CCRS on-board data flow to ERO.

Table 7
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 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.

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 Fig. 16. High-level summaries of the functions of each of the ground facilities are in Table 7, Table 8, and Table 9.

4.3. CCRS key events

Certain key events have been identified for the CCRS payload. Since a majority of CCRS activities are considered “critical” to mission success, each activity was also evaluated based on the following criteria for a “key event” classification.

- **Executed During Ground Contact:** Specific activities that would be executed during a ground contact
- **CCRS Time Critical:** An event that has tight timing constraints and minimal backup opportunities if the event/activity is missed
  - The bPOC would be staffed and operational at the MOC
  - Requires backup ground coverage
- **Irreversible:** An event that is not reversible (e.g., launch lock release, SOLAR latching OS)
- **Critical Joint Activities:** Specific activities that require both sides to have time tight coordination, with the ERO platform significantly affected
  - CCRS representatives would be present at the MOC
  - Staffing of the POC would be increased
- **ERO FDIR Deferred:** An event that requires ERO FDIR to enter a Deferred Recovery Mode, which means a combination of:
  - ERO would not power off the CCRS jettison avionics in the event of a fault
  - ERO would not fire any thrusters
  - ERO would not perform any slew maneuvers (except attitude control)
- **CCRS FSW Message to ERO:** Specific CCRS activities that the ERO spacecraft has requested to be alerted of by a FSW generated message
- **MSR Key Program Checkpoint:** Specific activities that are critical to the success of the MSR campaign and requires coordination across multiple projects and/or agencies

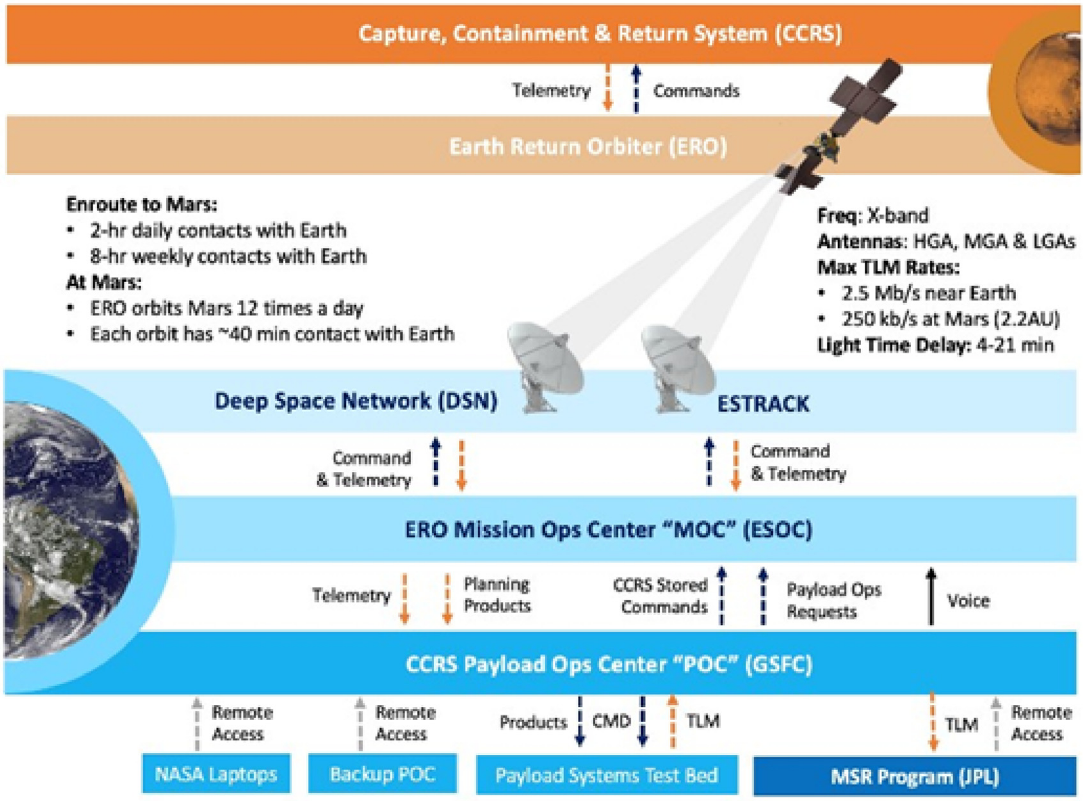


Fig. 16. CCRS ground system architecture through DSN and ESTRACK.

Table 8
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 9
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.

Table 10
CCRS Key Events.

	CCRS Key Event	Executed during Grnd Contact	Time Critical	Irreversible	Critical Joint Activities	MSR Key Program Checkpoints	CCRS FSW Message to ERO	ERO FDIR Deferred	CCRS Phase
1	Initial CCRS Power ON after Launch	☒							LCOT
2	Launch Lock Releases (& LRM Release)	☒		☒					LCOT
3	Open Capture Lid						☒		LCOT/C&C
4	Relative Navigation Go/No-Go (HIP)					☒			C&C
5	OS Capture Go/No-Go (SK4)				☒	☒			C&C
6	Deploy Linear Transfer Mech to Capture OS	☒	☒				☒	☒	C&C
7	Initiation of OS Base UV Illumination Go/No-Go					☒			C&C
8	Verification of OS Base UV Sterilization Complete					☒			C&C
9	Latch OS to Integrated Lid			☒			☒		EESOOA
10	Verification of OS Body UV Sterilization Complete					☒			EESOOA
11	LOS Radially Aligned to EES Aeroshell			☒					EESOOA
12	SCV Latch hardstop Engaged (EESA Closeout)			☒			☒		EESOOA
13	Sever Cables Between CE & AE			☒			☒		PJR
14	Jettison Capture Enclosure	☒		☒	☒		☒		PJR
15	Departure of Mars Sphere of Influence Go/No-Go					☒			PJR
16	Earth Return Plan Approval					☒			PJR
17	Earth Targeting & Final Cleanup Maneuver Go/No-Go					☒			PJR
18	Open MMPS Lid	☒		☒			☒		PJR
19	EES Release & Earth Avoidance Maneuver Go/No-Go					☒			PJR
20	Release EES	☒	☒	☒	☒		☒		PJR

Table 10 containing a complete list of CCRS key events is below. Additional detail for the key events is described in the relevant phase subsection. It happens that every active CCRS mission phase includes the execution of key events. Since all AEDL phase events are passive, they are not included in the table below. All critical activities would implement FSW and ground safeguards to limit the possibility of an inadvertent execution.

4.4. Containment timeline allocation

To ensure ERO can return to Earth and meet its mission objective of delivering the EES in 2033, the CCRS containment timeline duration is controlled with two separate timing constraints:

- Total time from OS capture until CE Jettison = 73 days
- Total time for dedicated CCRS operations (i.e., no concurrent electric propulsion thrusting) = 10 days

CCRS operations would not be particularly time constrained. As a consequence, operations have been planned as a sequence of steps separated by ground loops, during which success of a step is confirmed and the subsequent command string activated. This enables the design to limit autonomy and complexity required in the flight system.

This containment timeline allocation is given with the following assumptions:

- The operational timeline allocation period starts after confirmation that the linear transfer mechanism is fully deployed (and OS is unable to escape) and ends with jettison of the capture enclosure.
- The 73 days until jettison assumes that CCRS illumination operations can (1) proceed in parallel with ERO electric propulsion thrusting, (2) proceed during eclipse portions of the low Mars orbit.
- Operational activities do not require specific relative times between them, and thus the 10 days of dedicated CCRS operations (no electric propulsion thrusting) are cumulative and do not need to be consecutive. These 10 days may be divided into periods that allow minimum of 12 continuous hour of electric propulsion thrust by ERO. This gives ERO usable and predictable time to plan spacecraft thrusting activities.
- The 10 days of dedicated CCRS operations does not preclude CCRS activities during ERO thrusting.
- Sequences are pre-planned on the ground and uplinked to the spacecraft following review and confirmation of preceding activities via telemetry. A Command Authorization Meeting process provides authorization prior to operations.
- As of CCRS PDR: From the 73-day requirement, the CCRS project is allocating a maximum of 56 days (4 days for dedicated ops, and 52 days for ops concurrent with ERO electric propulsion thrusting) as shown in Fig. 17 below.
  - An additional 11 days are earmarked as system-held margin for growth during post-PDR development (20% of 56 days):
    - 2 of the 11 days are reserved for dedicated CCRS ops time,
    - 9 of the 11 days are reserved for concurrent ops with ERO electric propulsion thrusting.
  - An additional 6 days are earmarked as flight-held margin for minor issues encountered during operations (i.e., ground network issues causing unavailability of required contact data):
    - 4 of the 6 days are reserved for dedicated CCRS ops time,
    - 2 of the 6 days are reserved for concurrent ops with ERO electric propulsion thrusting.
- Additional operational timeline margin for major anomalies is held at the MSR Program level.

5. CCRS phases

The CCRS project plan is divided into operational phases similar to the ERO mission phases, but defined according to the CCRS project activities rather than ERO mission events. CCRS is actively commanded in every phase except for the fully passive AEDL phase. Most of the operations would require extensive use of stored command sequences since communication delays at Mars can range from 4 to 22 min

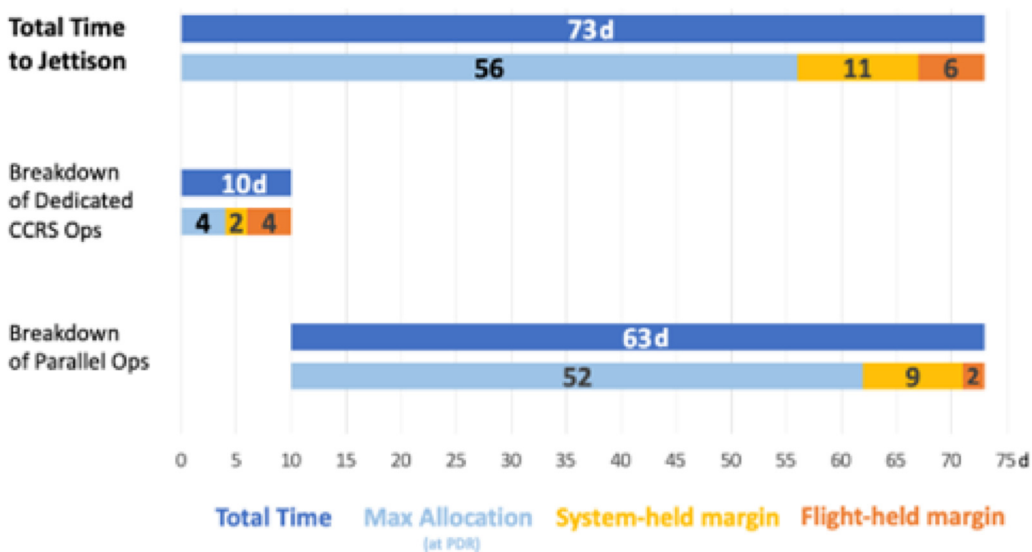


Fig. 17. Jettison timeline allocation of CCRS and ERO with system and flight margins.

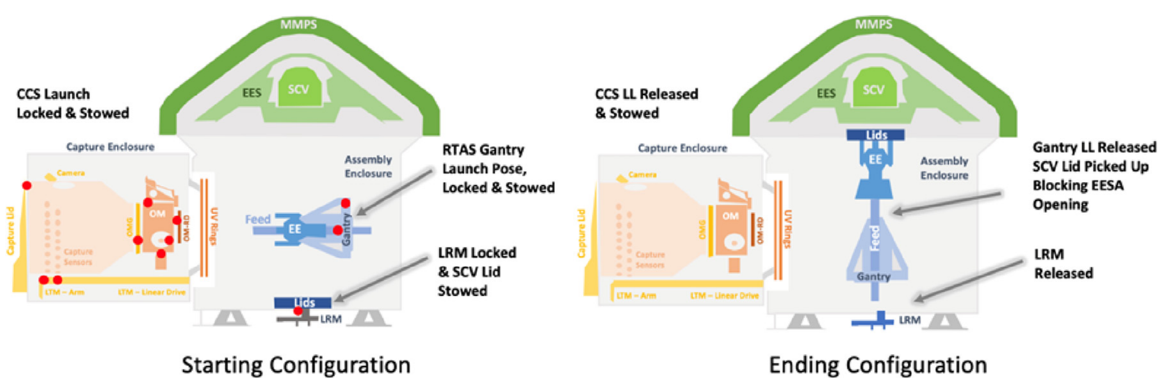


Fig. 18. LCOT phase starting configuration during launch and ending configuration approaching Mars.

(one-way light delay). Ground-In-The-Loop checks are required to both initiate a stored command sequence and then verify execution success. Each of the project phases are described in more detail in the following sections.

5.1. Launch, commissioning, and 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. Releasing the CCS and RTAS launch locks and the PIE Lid Restraint Mechanism (LRM) Hold Down Restraint Mechanisms (HDRMs) are the only irreversible events executed during the LCOT phase. 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 Fig. 18. Table 11 defines the six subphases of the LCOT phase.

Fig. 19 shows a graphical representation of the top-level CCRS activities that would be executed during the LCOT phase, along with a notional schedule of when those activities would occur.

As shown in Table 11, 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: The pre-launch subphase would begin with arrival of ERO and CCRS at the ESA launch site. This subphase includes system aliveness checks on the launchpad, confirming CCRS is ready for launch, and powering CCRS survival heaters on before powering CCRS off for launch.

Launch: Launch starts with the switch to spacecraft internal power on the launch pad (expected to occur near L-3 hr). CCRS would remain in the “off” configuration through ERO's Launch and Early Orbit Phase (LEOP) and until ERO has completed mission critical events (approximately L+7 days). CCRS survival heater telemetry would be available in telemetry after launch vehicle separation and telemetry is routed to the ground using the low gain antenna on ERO.

Commissioning: Commissioning is the term for the initial set of system checkout operations that would be performed to ensure that CCRS survived launch and 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. All commissioning operations would be initiated through a ground command during real-time contact following review of telemetry and a Go/No-Go decision to proceed to the next step in the operations plan. During this phase of the mission, ground contacts with ERO are expected every day for around 8 h.

Table 11
LCOT Subphases.

CCRS Phase	Launch, Commissioning & Outbound Transfer (1458 d)					
CCRS Subphase	Pre-Launch	Launch	Commissioning	Cruise Alive	Cruise Checkout	In-Flight Rehearsal
Key Functions	1. Aliveness tests on launch pad 2. Power OFF CCRS	1. Survive launch 2. No CCRS commanding	1. Release launch locks 2. Range of motion (ROM) on actuators (Open Capture Lid) 3. Full functional checkout of system	1. Temperature & sensor polling	1. Small moves on reversible actuators 2. Limited checkout	1. ROM on actuators 2. Full functional checkout 3. LRM HDRM release 4. Integrated lid pickup to block EESA
Approximate Subphase duration	Arrival at launch site to L-3 hrs	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
Subphase Starting Condition	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
Subphase Ending Condition	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 start of C&C

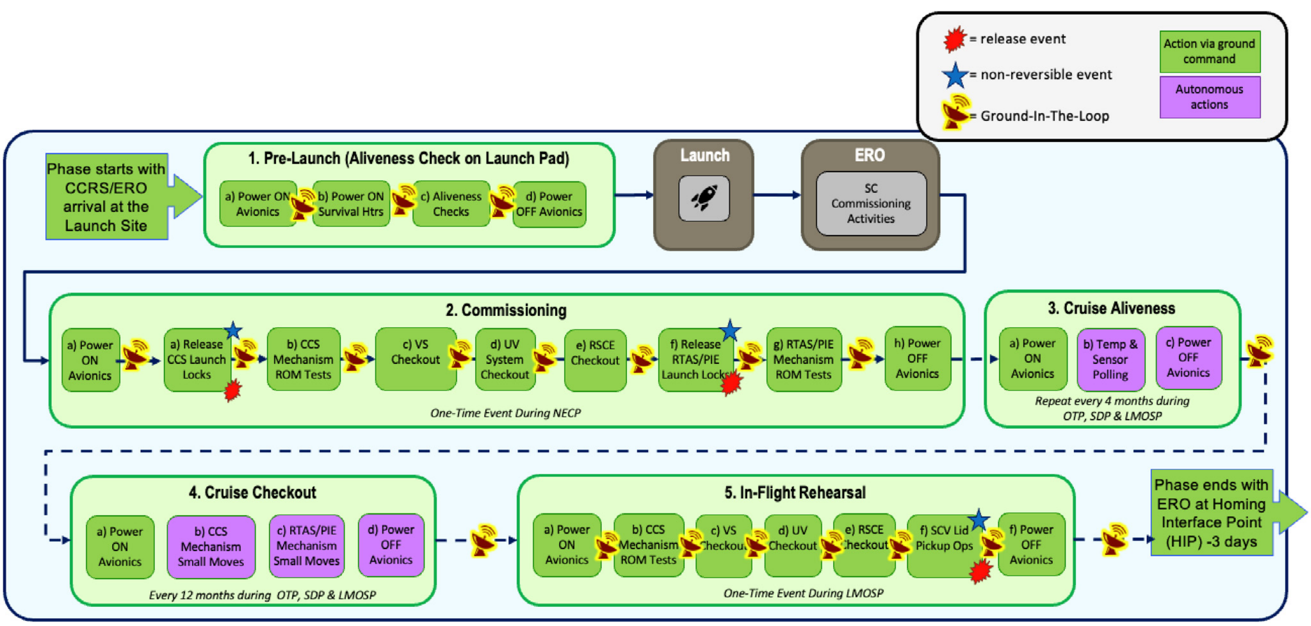


Fig. 19. CCRS workflow during LCOT phase. LCOT phase has two irreversible events and three release events.

Major activities include:

1. Initial power on CCRS (Main, Jettison and RSCE) – CCRS Key Event #1
2. Temperature and sensor polling
3. Heater calibrations (as required)
4. Launch locks releases - CCRS Key Event #2
5. Perform operational range of motion on reversible actuators and back to stow
    - Includes opening the capture lid – CCRS Key Event #3
6. Checkout UV system
7. Checkout vision system and camera calibration
8. Power off CCRS

The CCRS payload is secured during the mission using a variety of different Hold Down Restraint Mechanisms (HDRMs). The HDRMs specifically used to protect CCRS against launch loads are referred to as launch locks. The rest of the HDRMs for CCRS are referred to as release devices. The Critical Services on the CCRS avionics operates all release devices. Critical Services distinguishes the power services tied to components executing irreversible operations or are classified as safety critical and require two independent commands for enabling them. Secondary telemetry from a device such as a temperature sensor as well as first motion of actuators would be the ground's indication of successful launch lock release. PIE's lid restraint mechanism is planned

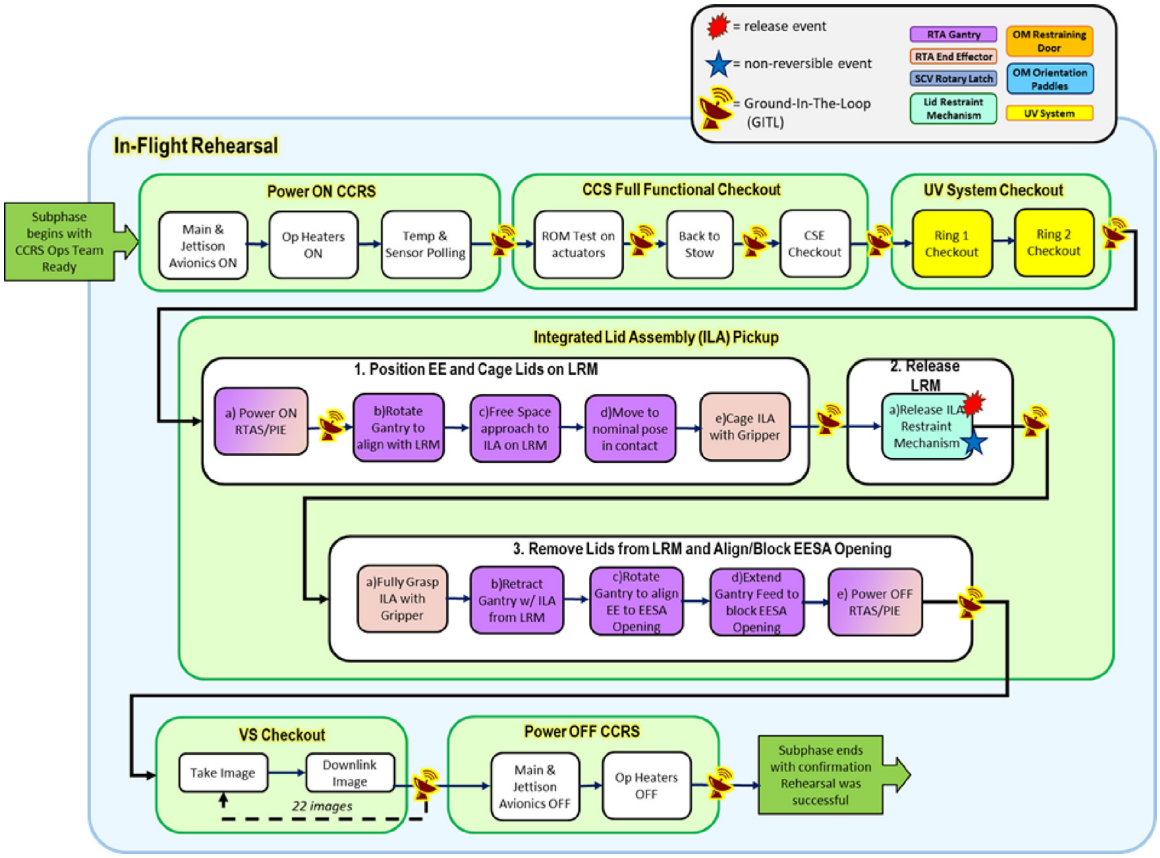


Fig. 20. CCRS activity workflow during in-flight rehearsal of LCOT.

to be released during the in-flight rehearsal. It is the only non-launch lock that would be fired during LCOT operations.

Cruise Aliveness: Aliveness checks would be performed approximately every four 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. These checks are vital due to the lack of telemetry on-board CCRS while the payload is powered "off"; the only telemetry available would be from 18 temperature sensors used by ERO to ensure CCRS remains within survival temperature limits. The spacecraft's trajectory and orientation during ERO's outbound transfer phase is thermally dynamic; therefore, it is recommended to perform a cruise aliveness check once every four months throughout the LCOT phase. The timing of the checks would be coordinated with the spacecraft in advance to ensure no disruption of ERO activity. Cruise aliveness checks would be designed to accommodate execution even while out of contact with the ground. At the contact following the check, the telemetry would be downlinked with enough time for the ops team to analyze and assess the health and safety of CCRS.

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. All cruise checkouts would be designed not to require Ground-In-The-Loop and could occur out of contact with the ground. The ground would have plenty of time to analyze and assess the state of CCRS mechanisms via telemetry downlink. For a 2028 Launch, there are two cruise checkout operations planned:

- Post orbit insertion module jettison (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). It would be coordinated with ERO to ensure no disruption of spacecraft activity.

An additional activity occurring during this subphase would be the Integrated Lid Assembly (ILA) pickup. This sequence of operation includes the following operations:

1. Rotate and extend gantry to cage lids on LRM
2. Release the LRM HDRM – CCRS Key Event #2
3. Retract, rotate and extend gantry to block EES aeroshell opening

The rationale for performing this operation during LCOT and prior to OS capture is to use the ILA to block the opening to the EES to assist in shielding loose Martian particles from entering the EES during capture and orientation of the OS. Since the nature of the ILA operations requires the use of the Robotic Transfer Assembly System (RTAS) Gantry, the Pickup Installation & Encapsulation (PIE) End Effector, Robot Servo-Control Electronics (RSCE), and the heaters, this activity would double as a full checkout of the RTAS and PIE subsystems which is the objective for this subphase. A detailed operational sequence and gantry poses are shown below in Figs. 20 and 21.

5.2. Capture and configuration phase

The Capture & Configuration (C&C) phase would be the second CCRS phase, starting after the OS is detected in orbit and ERO is 3 days out from the homing interface point in ERO's rendezvous phase. The phase would end when ground control confirms that the OS base endcap has completed its UV illumination and is ready for OS pickup by RTAS/PIE.

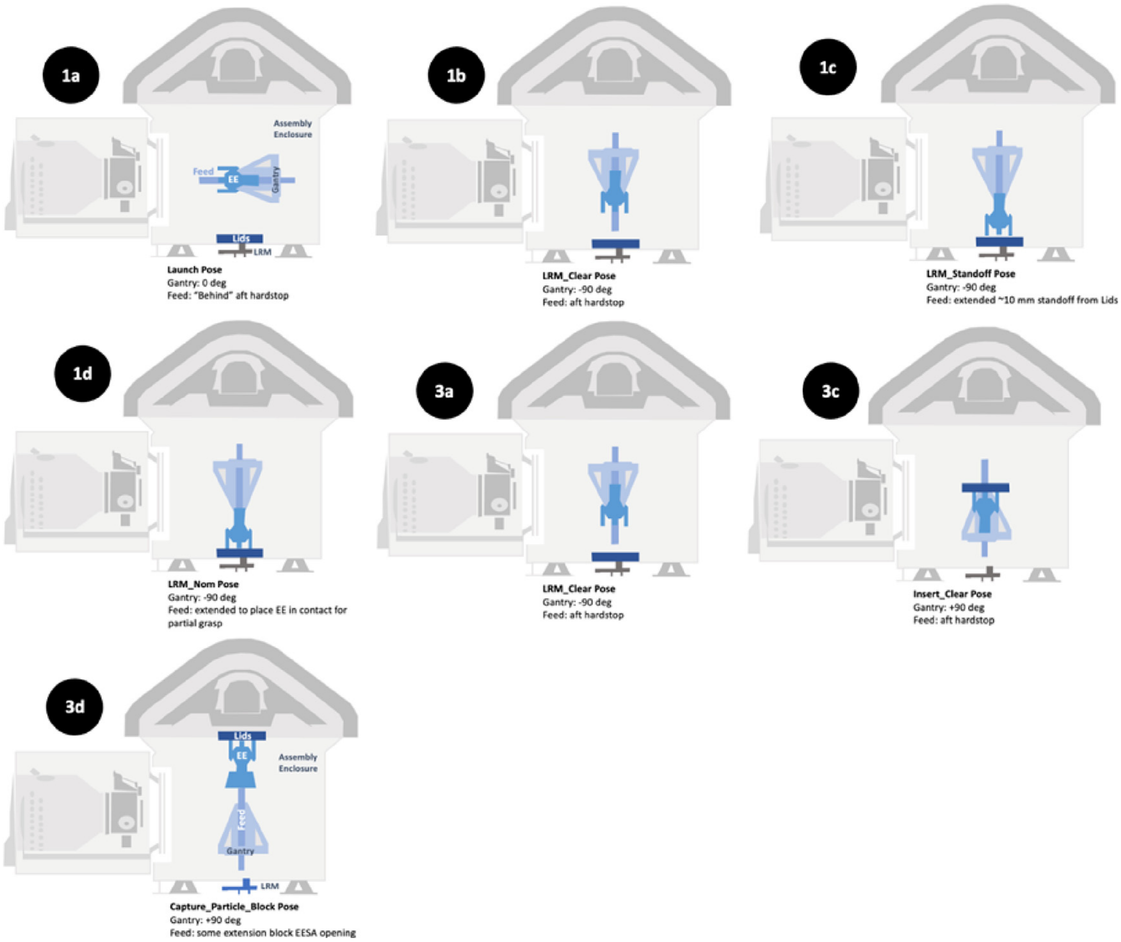


Fig. 21. Integrated lid pickup gantry poses to protect EES from loose debris during capture.

Table 12
C&C Subphases.

CCRS Subphase	Pre-Capture	Capture	Funneling	Orientation	Inspection	Endcap Illumination
Key Functions	**1. Open capture lid** 2. LTM capture maneuver checkout **3. Go for relative** nav 4. Arm hubs for capture **5. Go for capture**	1. OS trigger sensor arrays, actuation of LTM swing arm & lid **2. LTM arm fully deployed (OS captured)**	1. Capture lid closed 2. LTM funnels OS thru the capture cone; stops at OM bulkhead	1. OM grasps OS and manipulates it into correct orientation 2. Move LTM to beginning of travel	1. Take image of OS base 2. Confirm orientation	**1. Initiate UV illumination on OS base** **2. Verify UV illumination on OS base**
Approximate Subphase duration	About 2.5 days plus 8 hrs ground reviews	40 min + 4 hrs ground review	186 min	8 hrs	3.5 min + 4 hrs ground review	UV step #1 = ~30 hrs + ground review
Subphase Starting Condition	ERO is at HIP – 3 days	Ground "go" for capture at SK 4	Ground confirms OS is within capture cone	LTM reaches end of travel with OS within OM	OM-G is rotated clear	Ground verifies OS orientation via images

As shown in Table 12, the C&C phase would be composed of six subphases: Pre-capture, capture, funneling, inspection, orientation, and OS endcap illumination. The first few days of the C&C phase (from arrival at HIP to capture of the OS) are not a part of the Containment phase timeline allocation. Within the six subphases, there are six CCRS key events. Brief summaries of each C&C subphase are included in the next several sections.

Fig. 22 shows a graphical representation of the CCRS activities that are expected to execute in the C&C phase. This figure maps to the below subsections where additional details are provided.

Pre-Capture: Once the orbit of the OS has been detected, ERO would begin maneuvering the spacecraft to match the orbit on its way to the homing interface point (HIP). Prior to arriving at HIP (~3 days earlier), CCRS would be powered "on" with capture sensors and capture operational heaters enabled. The CCRS Operations team would then verify CCRS looks nominal and wait for the capture lid mechanism to warm up. Once at temperature, the ground would open the capture lid (CCRS Key Event #3). Once the capture lid has been opened, there would also be a check-out of the linear transfer mechanism maneuver and calibration of capture sensors to ensure CCRS is capture-ready. When ERO arrives at HIP, the same orbit altitude as the OS but offset along track by ~30 km, there would be a Program decision for Go/No-Go Relative Navigation at HIP (CCRS Key Event #4). Once the ground gives the "Go", ERO would continue approaching the OS, from homing through closing, and to final approach with a series of hopping maneuvers using its reaction control system thrusters to decrease the

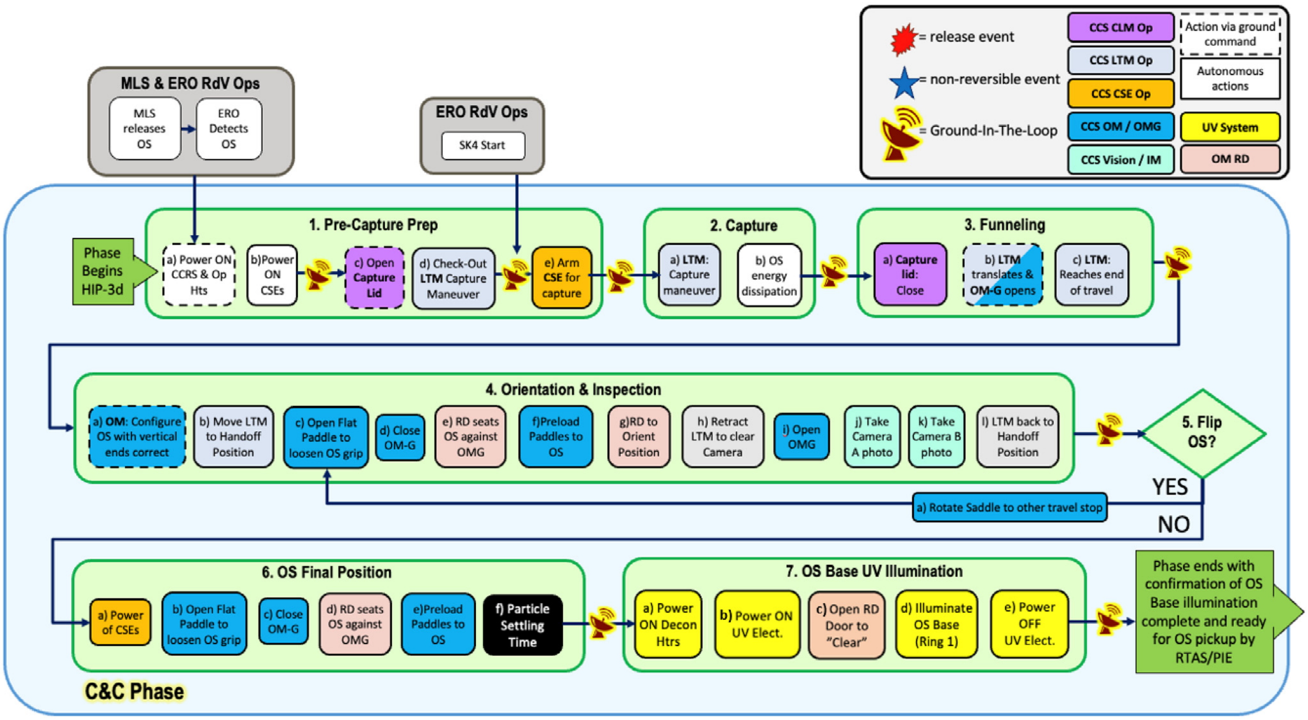


Fig. 22. CCRS activity workflow in C&C phase.

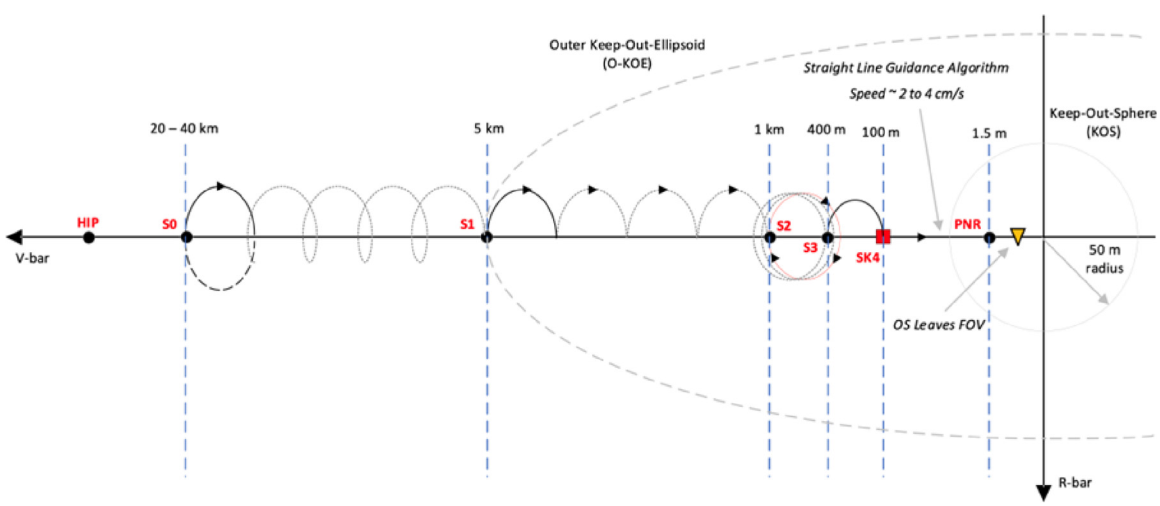


Fig. 23. ERO and OS rendezvous timeline. ERO lowers to the OS altitude until within 5 km where hopping maneuvers begin.

ERO-OS distance. ERO would command a final hop maneuver to get to SK4, where the OS is within 100-m range from ERO (Fig. 23). At this point, there would be another Program decision for Go/No-Go for capture of the OS (CCRS Key Event #5), and a handover to the next C&C subphase. The activities in this subphase do not count toward the containment timeline duration requirement. For additional context into the rendezvous timeline, Fig. 23 has been included.

Capture: This subphase begins with CCRS Key Event #5: OS capture Go/No-Go when ERO is at SK4 (Fig. 23). For CCRS, the ground would arm the capture sensors and HUB for capture. Once CCRS and the MSR Program confirm "Go" for capture, the ERO would begin terminal rendezvous with the OS. Upon ERO's arrival at the point of no return about 1.5 m out from the OS, ERO's Failure, Detection, Isolation, and Recovery (FDIR) is deferred until capture completes. In the event of a failure pre-capture that leads to an abort, CCRS would allow for a maximum of three capture operation attempts.

ERO monitoring cameras are expected to capture the moment the OS enters the capture cone. Once inside, the OS would trigger the capture sensor beams (consisting of 14 P+R LED emitters and phototransistor detector pairs), which are only triggered if the following are true:

- Top (close to lid) capture sensor plane indicates no break, AND
- Bottom (away from lid) capture sensor plane indicates break (by OS), AND
- A history pattern of (Top, Bottom) beam break sensors indicate: (Top, Bottom) = (NB, NB) → (B, NB) → (B, B) → (NB, B), where NB=No Break, and B=Break.

That trigger event autonomously actuates CCRS Key Event #6: linear transfer mechanism arm swinging to the deployed position to capture the OS. This event is a (relative) time critical event that is planned to occur during ground contact. Once the linear transfer

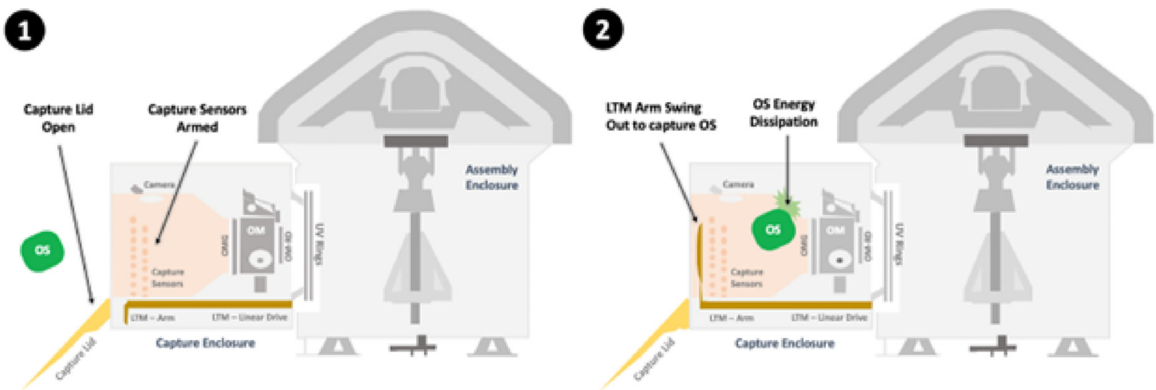


Fig. 24. Capture subphase configurations before and after OS entry into capture cone. Kinetic energy imparted from the OS is dissipated via collisions in the capture cone.

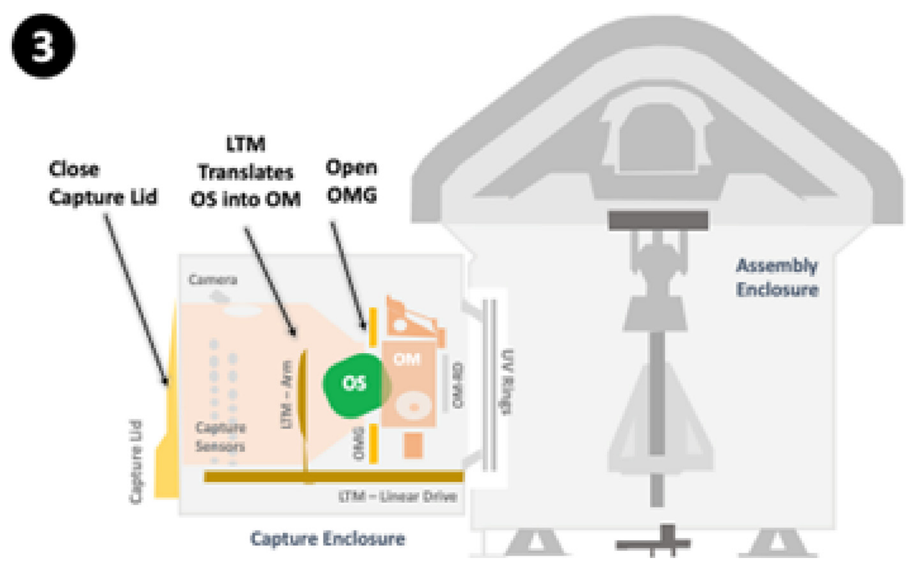


Fig. 25. Funneling subphase configuration with the translating LTM after the initial OS energy dissipation.

mechanism deploys, CCRS would send a message to ERO which would alert ERO to autonomously re-enable their FDIR. If that message is never received, ERO would autonomously re-enable their FDIR 3 min after the point of no return.

Once the OS is captured, the Containment operational timeline clock starts. The OS then is expected to take on the order of 5 min to bounce in the capture cone and dissipate energy, during which time ERO would re-enable their FDIR. ERO automatically re-enables FDIR 1 min after LTM deployment, or 3 min after the point of no return, whichever comes first. Once back in contact, the ground would confirm that the OS is within the capture cone and is ready to begin the next subphase operations (funneling). Fig. 24 shows a cartoon depiction of the capture subphase starting and ending configurations.

Funneling: The funneling subphase picks up in the same ground contact as above, ready to command the capture lid closed, the Orientation Module (OM) guard open and starting the LTM funneling of the OS through the capture cone, which could take as long as 3 h before it reaches its end of travel at the OM bulkhead. Once at the end of travel, the LTM remains stationed there during the orientation sub-phase, followed by another Ground-In-The-Loop to confirm the subphase objectives were successful. Fig. 25 shows a cartoon depiction of the 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 OM guard being commanded to open in preparation for the inspection subphase. Fig. 26 shows the orientation subphase operations.

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 toward the CCRS capture cone, the ground would initiate a re-orientation operation, which would flip the OS 180 degrees before proceeding to UV illumination phase. Once the OS is correctly oriented, the OM guard and restraining door would be closed to in order to precisely align the OS to the orientation mechanism in preparation for OS endcap illumination in the next subphase. The beginning and ending OS configuration are shown in Fig. 26.

OS Base Illumination: The OS base illumination 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 structures. Operation of the UV system would be split between the C&C and EESOOA phases:

- Ring-1 would include 104 LEDs in positions specific for OS base exposure (C&C phase)
- Ring-2 would include 104 LEDs in positions specific for OS body & OS lid exposure (EESOOA phase)

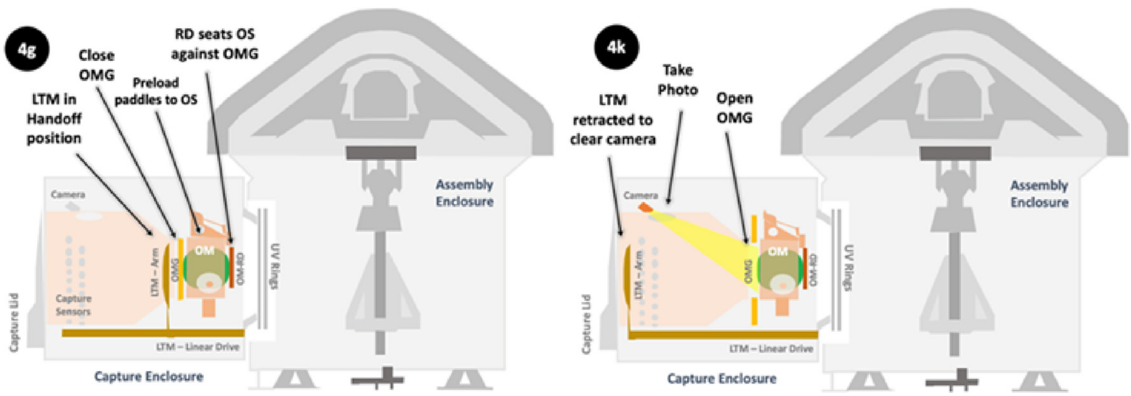


Fig. 26. C&C orientation and inspection subphase configurations. Proper OS orientation is checked using a camera at the front of the capture cone.

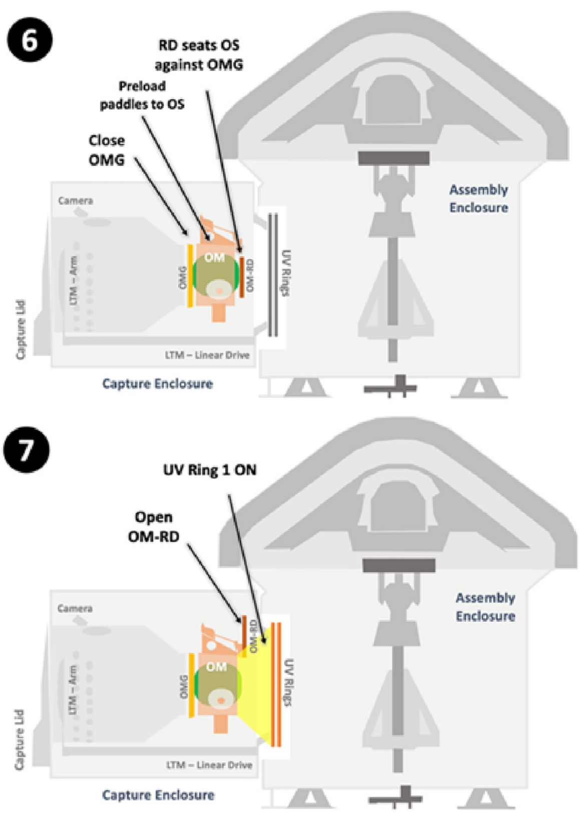


Fig. 27. C&C OS base illumination subphase configurations. The C&C phase ends with the completion of the UV illumination of the OS Base and the OM-RD Open.

The OS base illumination subphase of the C&C phase would begin with the OS constrained by the OM paddles. The UV illumination system ring 1 would then be powered up to perform the first illumination step: sterilizing the restraining door. The restraining door would then be cleared so that the first UV illumination subphase, the OS base illumination, can begin. Once that subphase is complete, ring 1 would be powered off for the duration of the ERO mission. The OS base illumination subphase is depicted in Fig. 27.

5.3. EES on-orbit assembly phase

The third phase of the CCRS mission is the Earth Entry System (EES) On-Orbit Assembly phase. This phase would start at the completion of UV illumination of the OS base endcap and end when the ground confirms successful assembly of the EES into its landing configuration. This phase would be composed of three subphases, as shown in Table 13: OS pickup, UV illumination, and installation.

Fig. 28 shows a graphical representation of the CCRS activities that are expected to be executed in this phase.

OS Pickup: When this phase begins, the UV illumination system ring 1 would have completed the UV exposure of the OS base and is powered down. The steps for this subphase are as follows, correspond to the workflow number above and the graphical representation of the gantry poses in Fig. 29:

1. Power on assembly mechanism
2. Assembly mechanism latches EES lid to OS
3. OS retracted to standoff

UV Illumination: The UV illumination subphase, shown in Fig. 30, would be focused on completing the UV exposure of the OS before it is installed into the EES aeroshell. Fig. 30 shows a cartoon depiction of the events that would unfold during the UV illumination subphase.

Installation: This is the subphase where the autonomous construction of the EES would be accomplished in four major steps, as listed below. Step 1 and step 4 are illustrated in Fig. 31 and Fig. 32, respectively. This phase includes four Ground-In-The-Loop checks to ensure successful execution along the way.

1. Position for installation (rotate)
2. Angularly and axially align OS to EES
3. Assemble EES into landing configuration
4. Retreat and stow assembly mechanism

5.4. Protection, jettison, and release phase

This phase would begin after the assembly of the EES in Mars orbit, continue through jettison operations and the return flight to Earth, and end with the release of EES for landing. The duration of the PJR phase would last slightly under two years. A 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 Micrometeoroids and Orbital Debris (MMOD) for the assembled EES. This phase would include two major release events: jettison of the Capture Enclosure and the EES release. As shown in Table 14, the PJR phase is broken into three subphases: Jettison, transit, and EES release.

A graphical representation of the CCRS activities executed in the PJR phase is provided in Fig. 33.

Jettison: Once the OS has been successfully contained within the EES, CCRS would jettison the capture enclosure to reduce return mass, leaving only the assembly enclosure, micrometeoroid protection system, and EES attached to ERO for the return trip to Earth. The jettison activity would require particularly tight coordination with ERO, as it

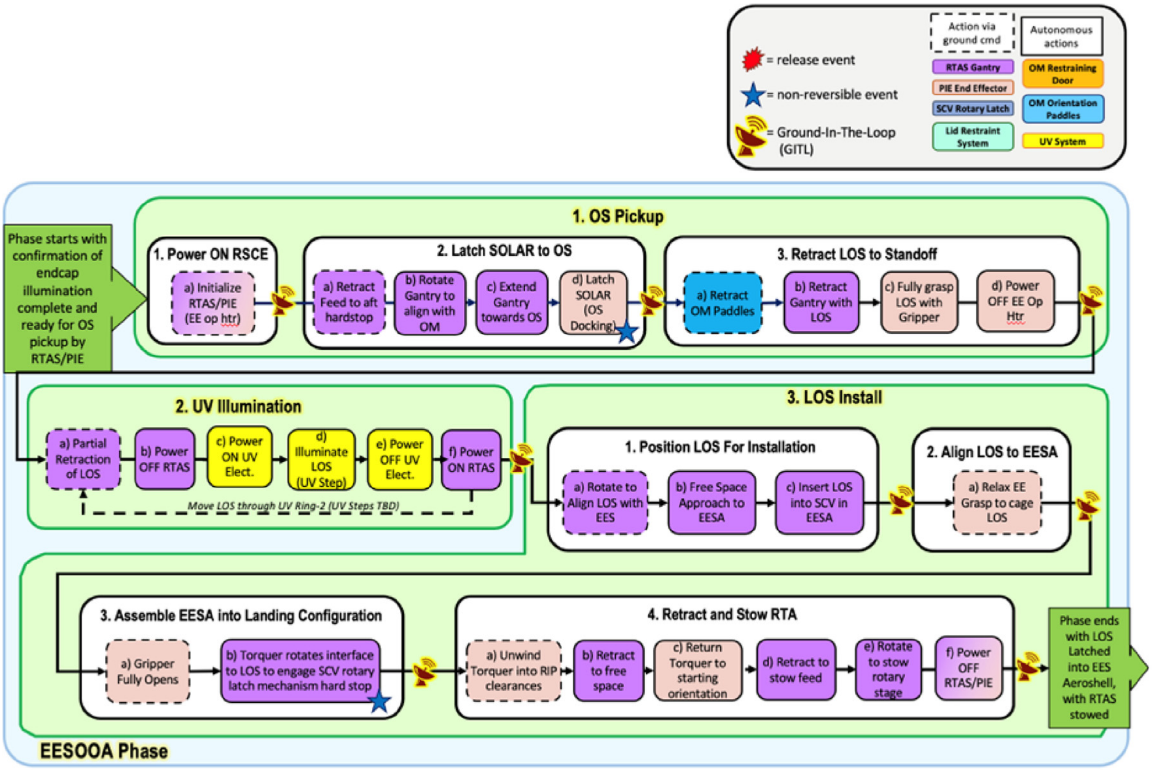


Fig. 28. CCRS activity workflow in the EES assembly phase.

Table 13
EES On-Orbit Assembly Subphases.

CCRS Phase	EES On-Orbit Assembly		
CCRS Subphase	OS Pickup	UV Illumination	Installation
Key Functions	1. Power on assembly mechanism **2. Latch lid assembly to OS** 3. Retract OS+lid	1. Stepwise illumination of OS+lid **2. Confirm illumination**	1. Position OS+lid for installation into EES 2. Assemble EES into landing configuration **1. Radially align OS+lid with EES aeroshell** **2. Engage latch to close out EES** 3. Retract and stow installation mechanism
Approximate Subphase duration	2.5 hours + 3 ground loops	Non-thrusting time: ~178 hours Orbit razing allowed: TBD duration for 12 Ground-In-The-Loop checks	2.5 hours + 3 Ground-In-The-Loop
Subphase Starting Condition	OS Base has completed UV illumination	OS is gripped by assembly mechanism	Ground Confirms UV illumination of OS body is complete. Installation mechanism is in final position

Table 14
PJR Phase Subphases.

CCRS Phase	Protection, Jettison & Release		
CCRS Subphase	Jettison	Transit	EES Release
Key Functions	1. Cut cable connections between the CCRS enclosures, and between the ERO rendezvous sensors and the ERO spacecraft 2. Separate the capture enclosure 3. Kick capture enclosure away from the spacecraft	1. Provide protection against MMOD 2. CCRS Aliveness checks (every 4 months)	1. Open micrometeoroid protection lid 2. Release EES
Approximate Subphase duration	30 days	708 days	7 days
Subphase Starting Condition	Telemetry confirms of successful completion of EES assembly	Telemetry confirms successful jettison of the capture enclosure	ERO reaches planned release location

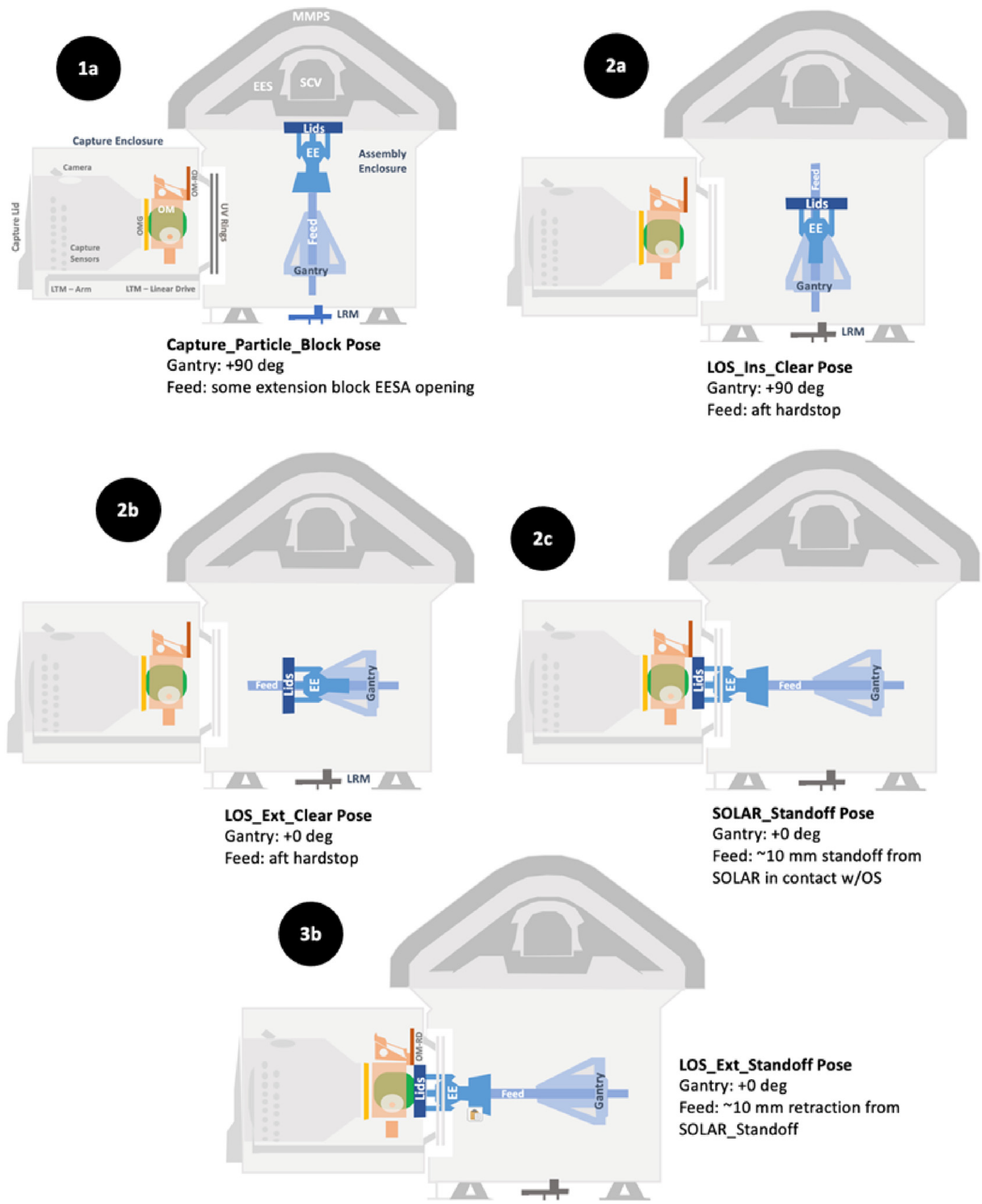


Fig. 29. OS pickup subphase: Assembly mechanism (gantry) poses moving the OS lid assembly from the particle closeout position to the standoff position.

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 re-acquisition afterwards.

The separation activity would start by powering down the capture enclosure and physically separating the cable connection between it and the rest of CCRS using a cable cutter system composed of cutter mechanisms, a cable retraction system, and associated sensors. The severed cables would be immediately pulled and twisted away from both the cutters and the side walls of the assembly enclosure, leaving the capture enclosure physically connected only by the bipod structures and release mechanisms. After confirming successful cable disconnection, the ground would command the release mechanisms to fire, ejecting the capture enclosure away from the spacecraft. The jettison subphase is illustrated in Fig. 34.

Sequence of events:

- Power down the capture enclosure
- Sever cable cutters (CCRS Key Event #13)
- Confirm sensor readout
- Fire release mechanisms to jettison the capture enclosure (CCRS Key Event #14)

Transit: After jettison, ERO would use electric propulsion thrusting to spiral up as shown in Fig. 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. These aliveness checks would occur every four months. The EES would be protected from MMOD during transit by the micrometeoroid protection system, which includes shield and lid. After completing the spiral-up activities, there would be a Program Go/No-Go decision to depart

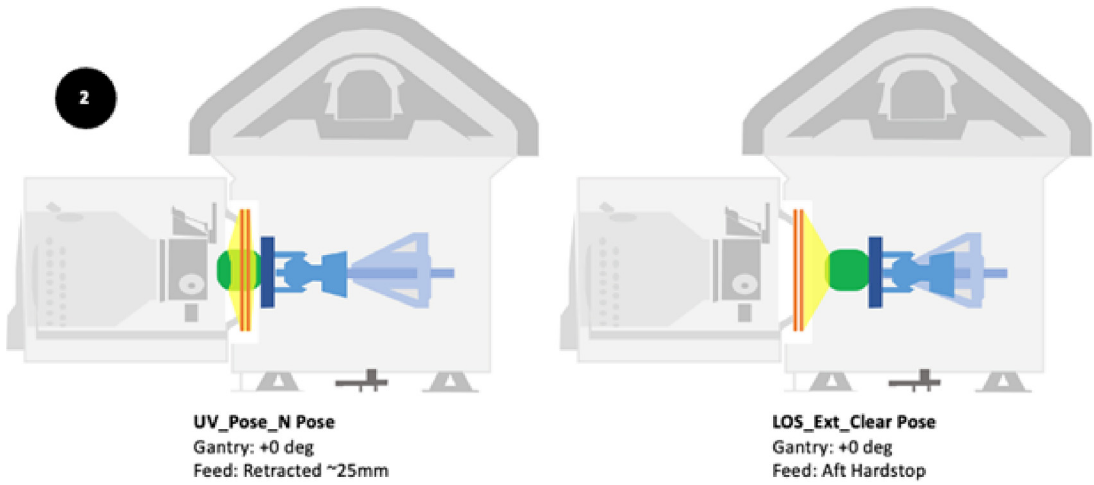


Fig. 30. UV illumination subphase gantry poses as it moves the OS through the UV ring in 25-mm steps.

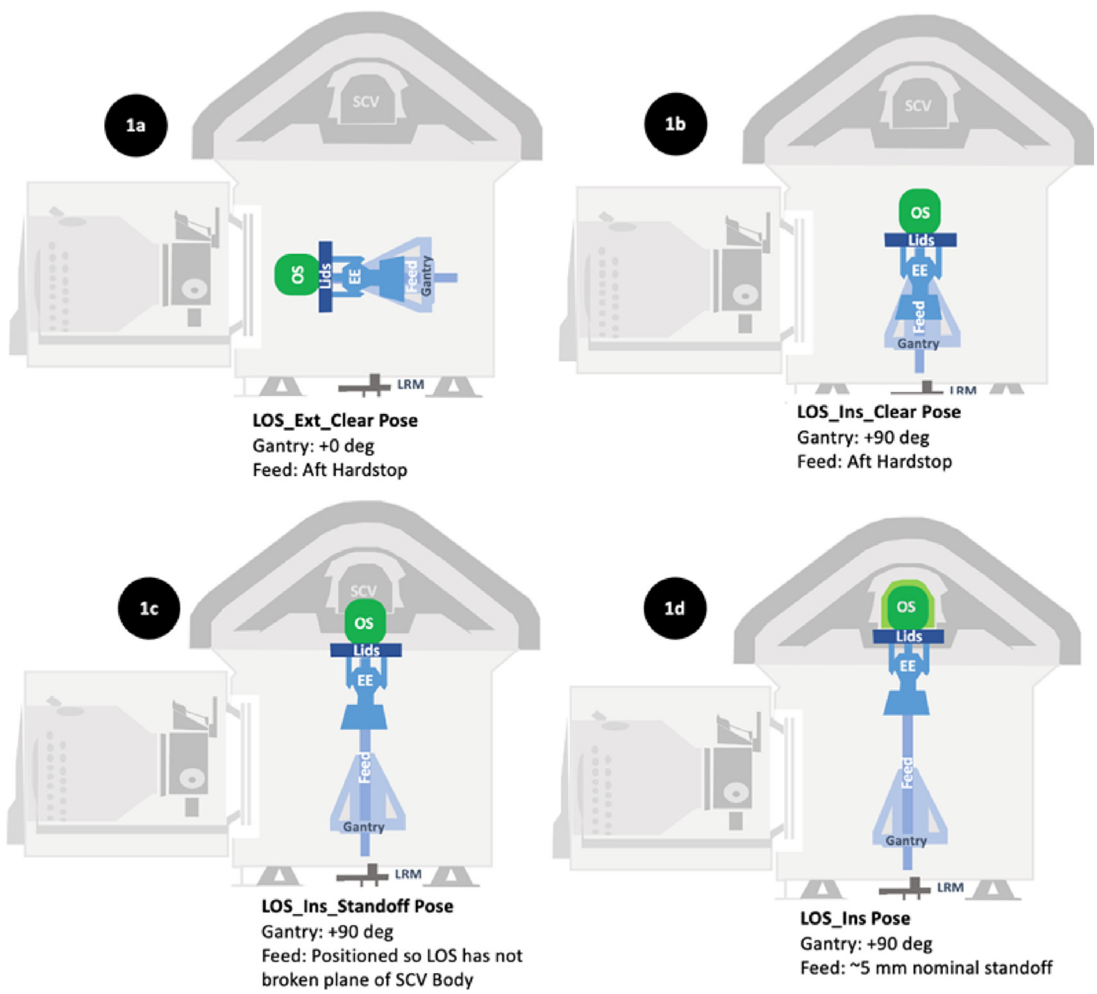


Fig. 31. Gantry poses as it positions the LOS for installation in the EES.

Mars' sphere of influence (CCRS Key Event #15). At the completion of the inbound transfer, approximately 90 days before EES release preparations start, the Program would require approval for Earth return (CCRS Key Event #16).

EES Release: The final PJR subphase would begin roughly eight days before reaching the Earth entry interface point, which is defined at an altitude of 125 km above Earth's surface, and nominally five days before EES release. This is the point at which the ground would upload the EES release commands to CCRS. The end of the PJR phase would be defined as the point at which the EES has been released on its trajectory toward UTTR. Nominal EES release is planned for three days prior to Earth entry, 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 h later at E-1.5 days.

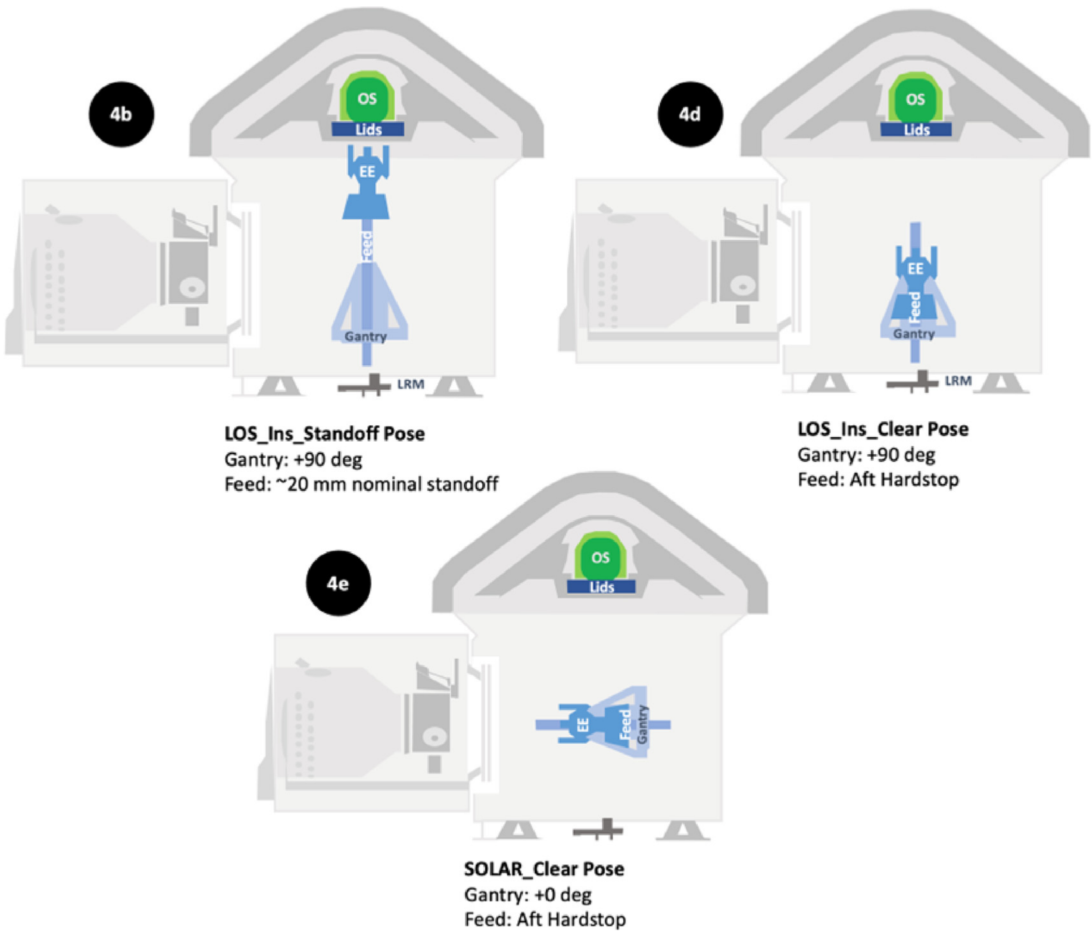


Fig. 32. Gantry poses after assembling the EES as it retreats and stows RTAS.

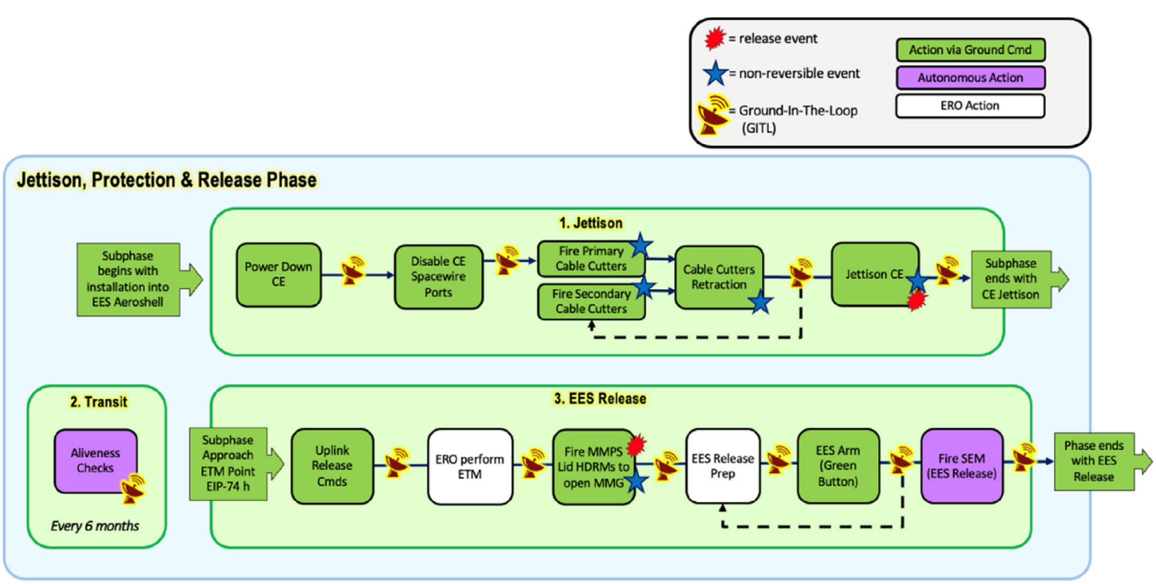


Fig. 33. CCRS workflow in PJR phase. PJR phase has five irreversible and release events.

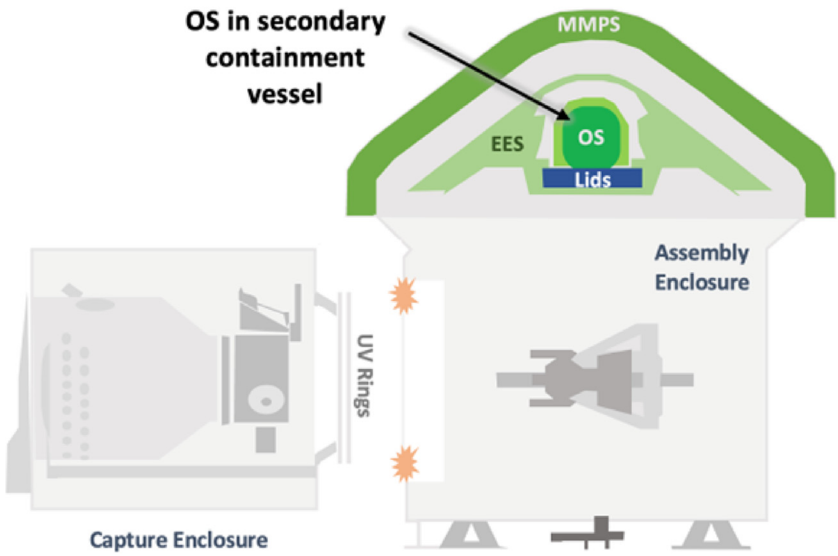


Fig. 34. CCRS configuration just after jettison.

Table 15
EES Release Subphase Timeline.

Entry Interface (EI)-Time	EES Release -Time	Activity	CCRS Key Event
EI- 8 d	Release - 5 d	Ground Uploads CCRS command sequence for EES Release	
EI- 7 d	Release - 4 d	Go/No-Go for Earth Targeting Maneuver **ERO performs Earth Targeting Maneuver (ETM)** • CCRS provides system heath status data	**Key Event #17**
EI- 96 h	Release - 1 d	ERO performs Final Cleanup Maneuver **optional* • CCRS provides system heath status data	
EI- 82 h	Release - 10 h	**Ground commands Micrometeoroid Lid Open** **Go/No-Go for EES Release & Earth Avoidance Maneuver**	**Key Event #18** **Key Event #19**
EI- 81 h	Release - 9 h	CCRS Enables EES Release Sequence	
EI- 72 h	Release - 0 h	**Nominal EES Release (with a backup release plan 36 h later)**	**Key Event #20**

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 before the final communications latency point ~7 s prior to release, MOC would uplink an immediate "Red Button" command, which would terminate the release sequence and reestablish release inhibits. Additionally, while the EES release command sequence is active, it would continually perform safety checks to ensure flight software can detect a parameter out of range and stop the execution.

Approximately ten hours before EES release, the ground would command the micrometeoroid protection lid to open, and verify overall CCRS system functionality. Following the previous command, the ground would enable the EES release (Green Button activation), with the actual release happening once inside the ±5 min release window. The EES would be released through the operation of the spin-eject mechanism using a two-stage release execution:

- Stage 1 = 3 release devices on ejection mechanism nodes
- Stage 2 = 1 release device on the ejection mechanism ring

The ejection mechanism would impart a controlled spin on the EES, allowing the EES to be spin-stabilized during its free-flight transit to Earth's atmosphere.

A high-level overview of the release timeline of events is included in Table 15.

Fig. 35 illustrates the configuration of CCRS at the start and the completion of the subphase.

5.5. Approach, entry, descent, and landing phase

The AEDL phase would be the final phase of the CCRS mission. This is the phase where the EES would approach, enter, and descend through Earth's atmosphere, landing on Earth nominally at the Utah Test and Training Range. The AEDL phase begins immediately following the EES release and would include the 36-h 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 landing site (Table 16). The CCRS mission ends upon EES landing.

Notably, planning for AEDL must consider:

1. The EES forebody would no longer be protected from micrometeoroid damage, after deployment of the protection system lid.
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 is no opportunity to abort the landing, or alter the entry trajectory.

AEDL timeline of events: During this phase, the ground team would coordinate closely with the MSR Mission Design & Navigation team to reconstruct the precise release trajectory (timing, angles, dynamics

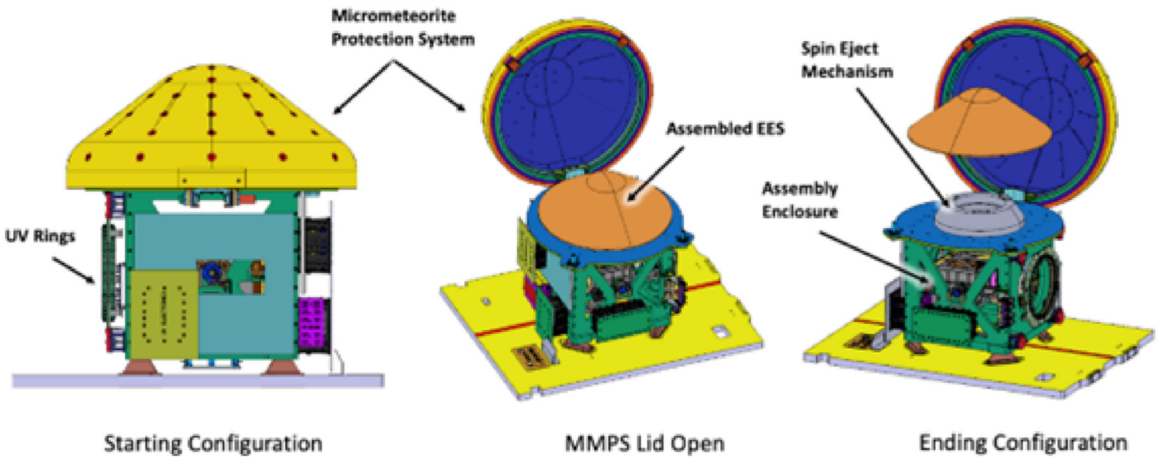


Fig. 35. Configurations for the EES release. The major mechanism operations for release include opening the micrometeoroid lid, and initializing the spin eject mechanism.

Table 16
AEDL Subphase.

CCRS Phase	**Earth Approach, Entry, Descent & Landing**
CCRS Subphase	Approach & EDL Subphases
Key Functions	Deliver EES on free-flight through space until atmospheric entry and landing at the landing site
Approximate Subphase duration	3 days
Subphase Starting Condition	Immediately after EES release

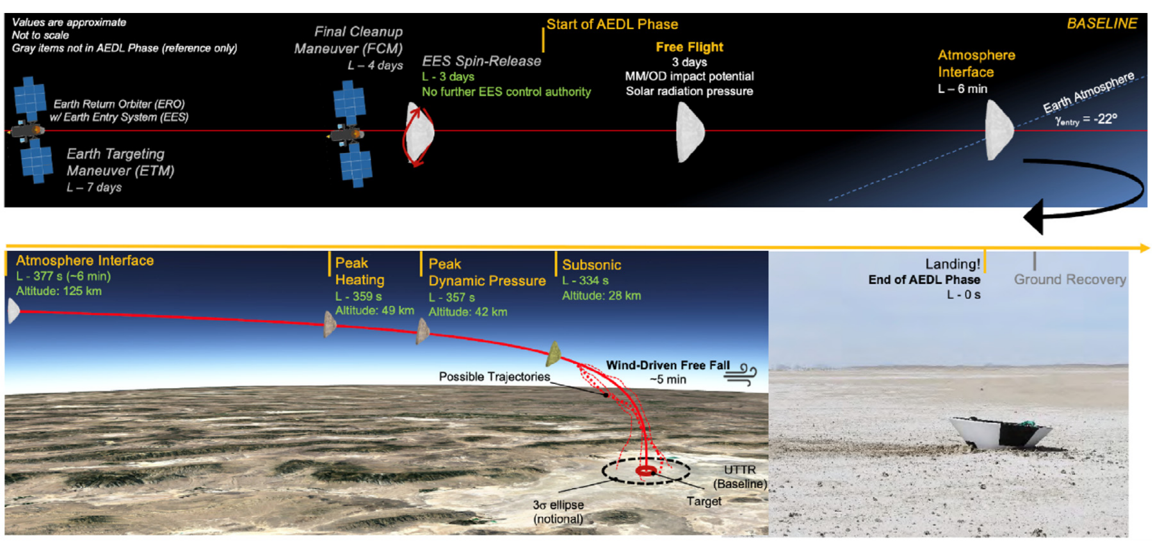


Fig. 36. AEDL phase timeline of events. EES is in free flight for three days before reaching Earth atmosphere interface.

response) and update the predicted landing location. EES landing predictions would be provided by CCRS to the MSR Program to inform ground recovery activities. Since the AEDL phase has no active control or monitoring systems, the AEDL phase has no subphases. Fig. 36 shows the timeline of events of the AEDL phase, beginning with the EES release at the end of the PJR phase. Table 17 demonstrates the phase timeline with event details.

The components of the EES are shown in Fig. 37, for overall context in how the OS fits inside.

6. 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. 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.

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

Table 17
Timeline of Events during AEDL.

Entry Interface (EI) - Time	Landing (L) -Time	Event Details
EI – 72 h		EES release is confirmed and ERO pulls all power to CCRS • ERO and EES drift apart for 1-2 hours
EI– 70 h		ERO performs Earth Avoidance Maneuver
(No later than) EI- 12 h		ERO provides release telemetry (timing, angles, dynamics response) to Program Mission Design & Navigation team • Joint Navigation team predictions of expected entry point and time, including dispersions provided to AEDL team by MSR. • AEDL team predictions of landing ellipse location, orientation, size, and hazard impact probability (incorporating weather balloon data) provided to the landing site & Ground Recovery team by MSR
EI – 8 h to EI – 4 h		U.S. Strategic Command and UTTR range asset acquisition of EES; data provided to Ground Recovery Team by MSR
EI – 1 h		Updated EES Entry Interface predictions provided to MSR • MSR provides expected entry point and time, including dispersions, to AEDL team. • AEDL team performs final AEDL landing ellipse location, orientation, and size prediction and hazard impact probability; provided to Ground Recovery team by MSR
EI – 0 h	L – 6m	(Atmospheric) Entry Interface Point
	L – 359 s	Peak Heating (Altitude 49 km)
	L – 357 s	Peak Dynamic Pressure (Altitude 42 km)
	L – 334 s	Subsonic (Altitude 28 km)
	L – 0	Landing & Ground Recovery • UTTR tracking assets track EES to final landing location and provides location to Ground Recovery team.

effort. The system is projected to launch on ERO and collect the samples launched into low Mars orbit by rendezvousing with the Orbiting Sample container. After capture, CCRS would contain the OS within a redundant set of vessels before returning to Earth and releasing the samples, protected within the EES, to land safely.

The work presented here has demonstrated a CCRS design that addresses the requirements levied in the system by the MSR Program as well as the interface requirements with ERO. Among these, it is worth noting that the CCRS design shows a robust system that addresses the backward planetary protection requirements and the demanding AEDL environment. This also includes accuracy on the release, as well as micrometeoroid protection and resilience. CCRS operates under a large international team shared across agencies, the success of its preliminary design review demonstrates the effectiveness and commitment of the team.

7. Notes and acknowledgments

This document is being made available for information purposes only. The decision to implement Mars Sample Return will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. In addition, as stated earlier in this document, as part of the NASA response to the recent MSR Independent Review Board's report [8] and in light of the current budget environment, the MSR Program is undergoing a consideration of changes in its mission architecture. This document is based upon MSR architecture in which ERO-CCRS would return the OS to Earth within approximately five years of landing on Mars to retrieve samples collected by the Perseverance rover. The CCRS project completed system development to a PDR level of maturity in mid-December 2023, after which the project was stopped indefinitely pending the results of a re-architecting effort. As such, any design information included in here should be viewed as notional.

Funding provided by the National Aeronautics and Space Administration and the European Space Agency is gratefully acknowledged. Portions of the research were carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

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.

CRediT authorship contribution statement

Bruno Sarli: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing, Supervision. **Emily Bowman:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Giuseppe Cataldo:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. **Brendan Feehan:** Project administration, Resources, Writing – review & editing. **Thomas Green:** Formal analysis, Investigation, Methodology. **Kerry Gough:** Formal analysis, Investigation, Writing – original draft. **Andria Hagedorn:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. **Paul Hudgins:** Formal analysis, Methodology, Software. **Justin Lin:** Formal analysis, Investigation, Methodology. **Mark Neuman:** Formal analysis. **Erfan Parvez:** Conceptualization, Writing – original draft, Writing – review & editing. **Julien Rondey:** Formal analysis, Methodology. **Christine Szalai:** Formal analysis, Investigation, Methodology. **Calinda Yew:** Formal analysis, Investigation, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

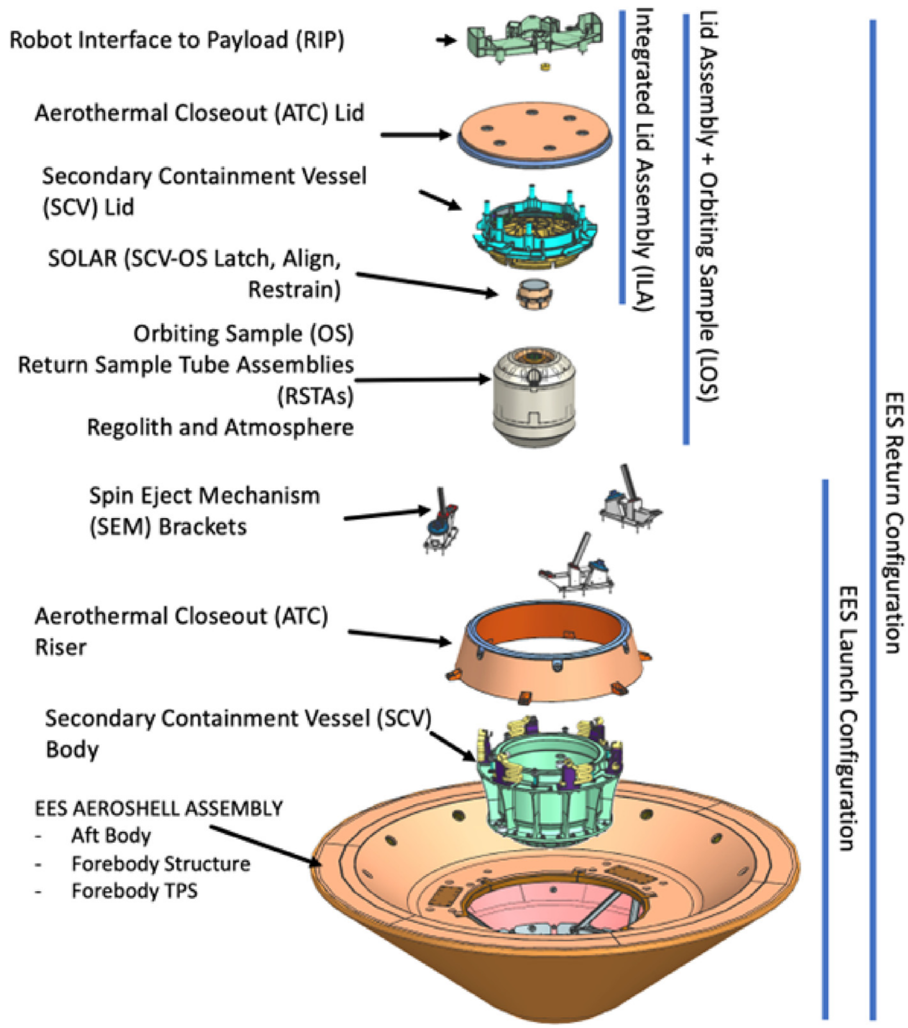


Fig. 37. Earth Entry System (EES) components with the assembled OS inside.

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
BTC	Break the Chain
C&C	Capture and Configuration (CCRS Phase)
CCRS	Capture, Containment and Return System
CCS	Capture & Configuration System
CE	Capture Enclosure
CFS	Core Flight System
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
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
HK	Housekeeping

IGST	Integrated Ground-Space Test
I&T	Integration and Test
ILA	Integrated Lid Assembly
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)
LMO	Low Mars Orbit
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)
PCDU	Power Control and Distribution Unit
PIE	Pickup, Installation and Encapsulation
PJR	Protection, Jettison and Release (CCRS phase)
POC	Payload Operations Center
POR	Payload Operations Request
PP	Planetary Protection
PROD	Protruding/Retracting OS Disruptor
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	Robot Servo 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)
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

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