

Planetary Protection Trades and Lessons Learned from Designing Mars Sample Return's Capture, Containment, and Return System

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Abstract

This paper describes the trades carried out and lessons learned while performing the preliminary design of the Capture, Containment, and Return System as part of the Mars Sample Return campaign, before the re-architecture studies initiated after December 2023. Mars Sample Return is an effort to bring to Earth rock cores, regolith, and atmospheric samples from Mars inside sealed tubes. The importance of these samples lies in their potential to provide valuable information about Mars' geological and climate evolution, its potential ability to have harbored life in the past, and the risks posed to future human exploration by the Martian environment. The trades and lessons learned presented in this paper refer to the preliminary design solutions generated in response to the constraints levied on the payload design by backward planetary protection requirements, which impose the protection of the Earth-Moon system from any potential negative effects the returned Mars material might cause. Topics include jettison of the payload capture enclosure, replacement of the aseptic transfer system with an ultraviolet illumination system, and leveraging different design options to augment the micrometeoroid protection system to improve shielding performance.

Keywords: Planetary protection, Sterilization, Particle control, Containment, Micrometeoroids, Orbital debris.

1. Introduction

This manuscript presents the trades and lessons learned while designing the Capture, Containment, and Return System (CCRS) [1], a payload designed as part of the Mars Sample Return (MSR) campaign, which intends to deliver Martian rock cores, regolith (broken rock and dust) and atmospheric samples to Earth. Inspection and analysis of these samples will guide insights about the geological history of Mars, its climate evolution, the possibility of having harbored ancient life [2, 3, 4, 5, 6], and the risks the Martian environment could pose to future human exploration. Specifically, this manuscript describes the design solutions proposed in response to the constraints imposed on the CCRS design by backward planetary protection requirements, which address the protection of Earth's biosphere and the Moon from any potential adverse effects caused by returned Mars material [7, 8]. In addition, the design presented here was carried out during the preliminary design phase and represents a snapshot in time.

The MSR campaign is accomplishing this endeavor through a series of missions, one operational and others in the formulation phase, through an international collaboration between NASA, the European Space Agency (ESA) and several industry partners associated with each agency. This paper is based on the MSR architecture as it had been conceived of until December 2023 [1], after which challenges identified by the second MSR Independent Review Board (IRB-2) [9] triggered re-architectural studies that are still ongoing at the time of this work and may end up altering this approach.

The MSR campaign started with the Mars 2020 mission [10], carrying to Mars the Perseverance rover and Ingenuity helicopter. To date, Perseverance has collected and sealed 25 of 38 samples (22 rock cores, 2 regolith samples, 1 atmospheric sample) and 3 of 5 witness tubes [11, 12, 13]. Perseverance also left 10 of these sealed tubes at the Three Forks depot in Jezero Crater as a contingency reserve for a possible safe return to Earth [14].

Under the architecture mentioned above, the Sample Retrieval Lander [15, 16] would subsequently land on Mars to retrieve the sealed sample tubes and launch them into Mars orbit for future pick-up and return. Specifically, the Sample Retrieval Lander would use a sample transfer arm [17] and a sample transfer system with cameras [18] to transfer the sealed sample tubes from Perseverance into a container called the Orbiting Sample (OS). The OS would be located inside the Mars Ascent Vehicle [19, 20], a rocket that would launch the OS into Mars orbit. Should Perseverance be unable to approach the Sample Retrieval Lander to deliver the sealed sample tubes, two sample recovery helicopters, based on Mars 2020's Ingenuity [21], but with wheels and gripping capabilities, would pick up the cached sample tubes left on the surface by Perseverance and transport them to the Sample Retrieval Lander.

The Earth Return Orbiter (ERO) [17, 22], provided by ESA, would launch prior to the Sample Retrieval Lander to provide communication relay support in Mars orbit. Once the OS container is launched and orbiting around Mars, ERO, through the NASA-provided CCRS [1], would detect and capture the OS, sterilize its external surface to comply with backward planetary protection requirements [7], enclose it in an additional container for redundancy, and safely bring it back to Earth via an Earth entry system (EES). The EES is a capsule that would reenter the Earth's atmosphere passively (i.e., without a parachute) while guaranteeing structural integrity during entry, descent and landing. In addition, it would protect the contained OS from any damage that might be caused by micrometeoroids and orbital debris (MMOD) after its release from ERO.

Once landed, the sealed sample tubes would be transported to the Sample Receiving Facility [23, 24]. This would be a maximum containment facility, where the returned samples would be kept following protocols similar to those commonly applied to the management of known infectious agents in biological research laboratories, while sample safety assessments are performed. At the same time, the facility would prevent the samples from being contaminated with terrestrial materials that might undermine future scientific discoveries.

The manuscript is organized as follows: Section 2 provides background on the CCRS payload and how its preliminary design as of December 2023 responds to planetary protection requirements. Section 3 describes the trade of heat and ultraviolet (UV) radiation sterilization¹. Section 4 describes the trades involved with managing micrometeoroid impacts. Section 5 presents the trade between full and partial jettison. Finally, Section 6 summarizes the main findings and provides perspectives on future efforts.

2. Payload overview and planetary protection

Many aspects of the design of the ERO-CCRS mission are dictated by both forward and backward planetary protection requirements from NASA and ESA [7, 8, 25], following current international law and policies [26, 27]. These requirements aim to protect Mars from harmful terrestrial contamination to enable the mission's science objectives as well as the Earth-Moon system from potential harmful Martian contamination that might be returned to Earth. Note, however, that under Article 19 of the MSR NASA-ESA Memorandum of Understanding, NASA and ESA apply planetary protection measures based on their respective applicable policies and requirements.

A summary of the key reference ERO-CCRS mission parameters can be found in Ref. [17], while updated details on the mission itself as well as the mission compliance to planetary protection requirements are described extensively in Ref. [22]. The focus here is on the CCRS payload which, under the MSR architecture considered in this paper, is required to break the chain of contact between Mars and Earth to eliminate the possibility of uncontrolled transmission and release of Martian material of concern into Earth's biosphere. This material of concern is defined as any particle with a diameter ≥ 50 nm that would include any potential Mars biology capable of propagating and negatively interacting with Earth's biosphere, resulting in harm. It is worth reminding the reader that host-specific pathogenesis remains the lowest likelihood hazard [28].

The implementation of the planetary protection requirements for CCRS translates into three main functions:

1. Particle control – Controlling particle paths through design features that minimize the amount of potentially hazardous Mars material being brought back to Earth;
2. Sterilization – Inactivation of such particles;
3. Containment – Robust encapsulation through redundant vessels that create multiple layers of protection.

¹The 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.

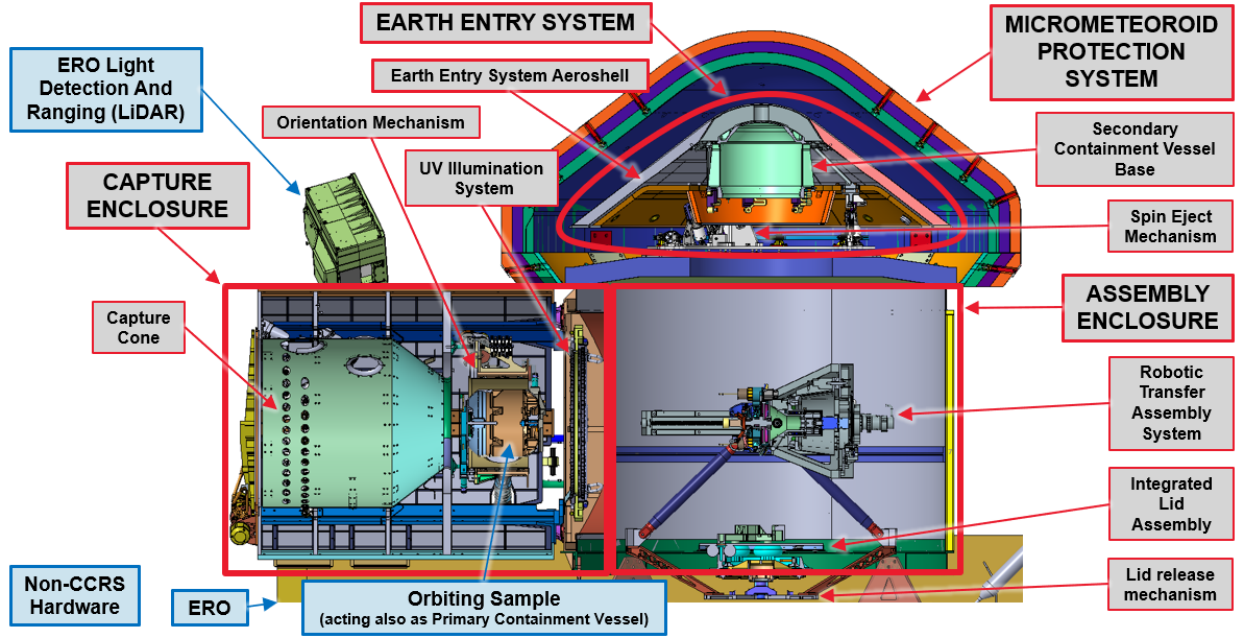


Figure 1: CCRS architecture with UV sterilization and OS providing PCV function (baseline preliminary design as of December 2023).

The preliminary design of CCRS is responsive to all of these functions through the following elements, depicted in Fig. 1:

1. Particle-control barriers such as multilayer insulation blankets or minimization of gaps that could lead to undesired lines of sight (i.e., gap size, number of particle bounces, etc.) or minimization of hardware returned to Earth that might have been in contact with unsterilized Martian particles;
2. A UV illumination system delivering a minimum flux of 375 W/m^2 and a minimum dose of 2 MJ/m^2 of UV radiation to the external surface of the OS container [29, 30];
3. A secondary containment vessel to encapsulate the sterilized OS before placing it inside the EES [1];
4. A micrometeoroid protection system (MMPS) to protect the EES from MMOD damage that might cause release of unsterilized particles [1, 31].

The next few sections will describe in detail trades and lessons learned while designing CCRS to accomplish these functions, which led to the preliminary design shown in Fig. 1.

3. Trade 1: Heat vs UV sterilization

A summary of the trade on methods of sterilization is shown in Table 1 with specific metrics. Each metric is assigned a plus, minus or equal sign to indicate the relative merits of the preliminary design options under consideration.

In the preliminary design described in Ref. [32] and shown in Fig. 2, the sterilization function would be accomplished through heat and a primary containment vessel (PCV) within the aseptic transfer and encapsulation system. Following the different steps illustrated in Fig. 3, the OS would be attached to the PCV lid in the capture enclosure (considered to be exposed to Martian material), rotated by 180° , and inserted inside the PCV base after the PCV base rim has been heated to $> 500^\circ\text{C}$ to expand. At this point, the PCV base would cool and form a joint that is robust enough to remain sealed when subject to the landing loads. After insertion of the OS into the PCV, the seam line between the PCV lid and base would be sterilized being heated to temperatures $> 500^\circ\text{C}$ for 5 seconds. This

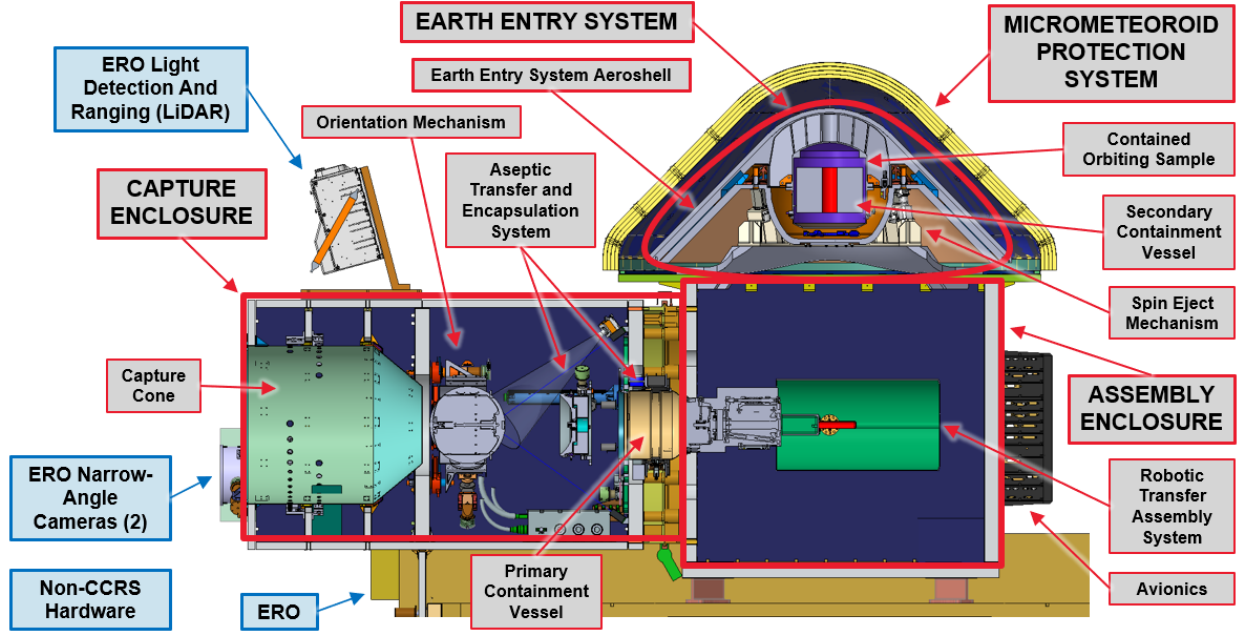


Figure 2: Early candidate CCRS architecture with heat sterilization and separate PCV hardware.

Table 1: Summary of trade metrics for heat vs UV sterilization.

	Heat	UV
Mass	-	+
Risk to sample integrity	-	+
Operational flexibility	-	+
Fault tolerance	-	+
Methodology efficacy	=	=

would sterilize particles of concern on any remaining exposed surface of the PCV lid or base and complete the barrier between the Mars-exposed capture enclosure and the clean assembly enclosure.

Heat sterilization presents several disadvantages. First, it increases mass due to system's complexity and the need for a dedicated containment vessel (here in the form of a PCV). In addition, sample integrity could be compromised at sterilization temperatures $> 500^{\circ}\text{C}$, since the samples inside the sealed tubes would be unable to stay below the required temperature of $+30^{\circ}\text{C}$. This would diminish or destroy their potential to address key science objectives for astrobiology and geology. Sample properties most sensitive to temperature-driven alteration include biosignatures, organic molecules/chemistry, volatiles and isotopic composition.

On the other hand, the UV sterilization approach of the preliminary design described in Ref. [1] and shown in Fig. 1 presents more flexibility from several points of view, since it is a cumulative, non-time-critical process, which opens the implementation option space substantially. The goal of the UV system is to deliver UV radiation with a dose of 2 MJ/m^2 at a flux of 375 W/m^2 , as required by the MSR Program [29]. The UV system is designed as two rings of light emitting diodes. Following the different steps illustrated in Fig. 4, the first ring would irradiate the base of the OS closest to the robotic transfer assembly system (RTAS). RTAS, being already clean, would then attach itself to the sterilized OS base and pull the OS through the rings. Here, the second ring would irradiate the OS surface and the other base over 11 discrete steps.

With UV radiation, discontinuous doses can be utilized in flight due to biological stasis enforced by the flight environments either through a reduction in water activity ($W_a < 0.5$) or temperature past specific thresholds ($T \leq -28^{\circ}\text{C}$). As a result, the delivery of UV radiation can be administered intermittently over days, weeks or months, as

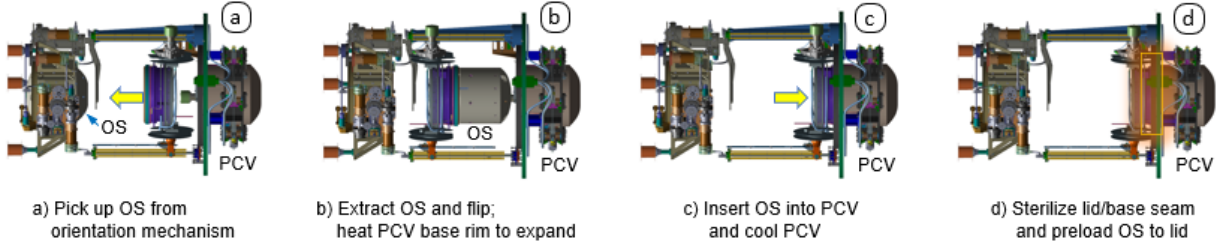


Figure 3: Heat-shrink fit approach executed by the aseptic transfer and encapsulation system.

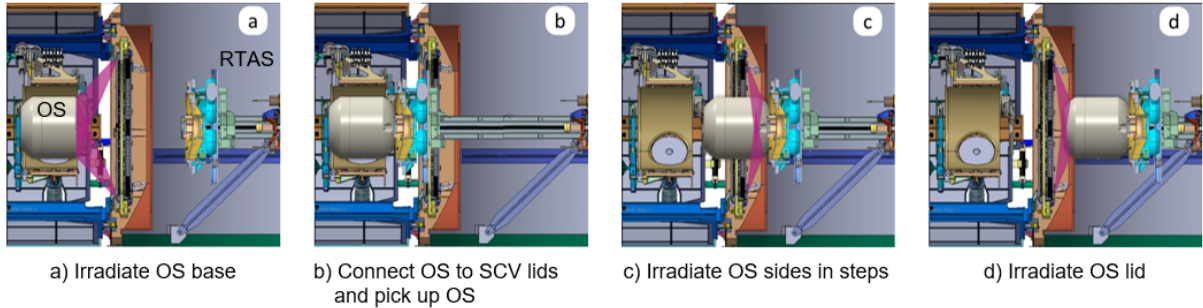


Figure 4: UV illumination approach executed by the UV illumination system. Image adapted from [29].

opposed to one large-power event. Cycling this active UV system enables therefore a better control of the thermal environment.

With the UV sterilization approach, sample integrity is no longer affected, because the UV system generates a much more benign thermal environment. Since the OS acts as PCV itself, the overall mass is also reduced.

In terms of operations, for the UV system these could be automated, managed through ground-in-the-loop, or a combination of both, providing more flexibility than for the heat sterilization, which cannot be stopped once started or repeated. However, while the UV system could in principle be turned on/off at any time, it would need to be coordinated with ERO's electrical propulsion thrusting. The heat sterilization approach, on the other hand, retains the flexibility to be started whenever ready. However, significant spacecraft coordination is needed: favorable Sun pointing, fully charged battery, suspension of spacecraft activity (which has to be for far longer than the actual heat shrink fit operation, due to communication latency). UV sterilization can truly be done any time and is much more operationally flexible.

As far as fault tolerance is concerned, the UV sterilization approach enables maintaining the supremacy of the ERO bus safety by powering CCRS off as necessary.

Finally, in terms of methodology efficacy, since this would be the first in-flight sterilization taking place during a sample return mission, both methods need to be shown to meet industry standards (e.g., ISO 11138-7 [33]). Currently, the expected efficacy of UV sterilization is undergoing verification testing at the Jet Propulsion Laboratory.

Specific technical details about lessons learned in designing this proposed UV sterilization system are available in Ref. [29], where a summary can also be found of other sterilization options that were investigated (for example, chemical, plasma/ion, radiation, active surfaces, etc.) but not selected due to their drawbacks.

4. Trade 2: Inspection vs protection

This trade considers the management of damage caused by MMOD to the EES, which could lead to a containment not assured of the Martian samples. This can either occur directly through an impact with sufficient energy to puncture the containment vessels (unlikely) or by creating sufficient damage to the EES that, through damage progression on entry, containment not assured occurs during entry or landing (more likely). Note, containment not assured is

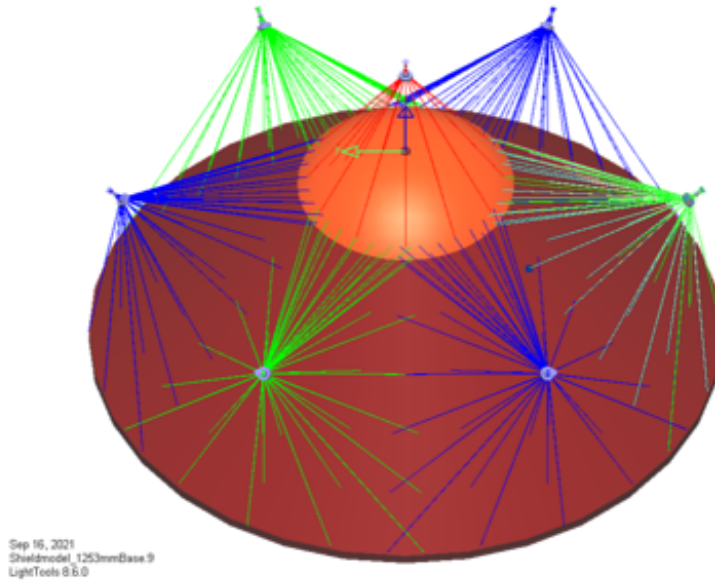


Figure 5: Concept of a visual inspection system for critical damage.

defined as the state in which one or more requirements for ensuring containment of Mars material have not been met. Containment not assured does not necessarily equate to Mars material release. If the probability of containment not assured exceeds a target probability, additional analyses and/or mitigation measures may be undertaken to more precisely determine when assurance is lost.

In contrast with past missions focused on Earth orbit operations where micrometeoroids and orbital debris are similarly considered critical (e.g., Space Shuttle, International Space Station, etc.), micrometeoroid impact is the dominant risk contributor for Mars Sample Return due to the long exposure duration to the micrometeoroid environment, both for the multi-year long cruise phase and the 3-day unshielded Earth-approach phase. The altitude range through which orbital debris might be encountered is traversed within minutes. Micrometeoroid impact velocities range from approximately 7 km/s to 72 km/s, much higher than average orbital debris impact velocities, bounded above at about 12 km/s.

Damage, either due to an impact of the MMPS resulting in debris-cloud damage to the EES or a direct impact of the EES during Earth approach, can result in one of three failure modes: 1) damage to the EES aeroshell that progresses on entry and leads to loss of structural integrity, 2) modified aerodynamic/mass properties leading to unacceptable vehicle dynamics or orientation at landing, or 3) a direct containment breach of the OS. The consequence of these failure modes can be gated by subsequent analyses: ground containment/sterilization, and break-up/burn-up in the case of structural damage progression. Note that ground containment/sterilization after a CNA event remains risk reduction and containment can never be (re)assured because some material would likely be lost to the wind. Critical damage is defined as damage sufficient to invoke the necessity of a subsequent analysis or containment operation (e.g., break-up/burn-up, sterilization). Critical damage does not, by itself, indicate loss of containment, unless the probability of loss of containment due to all serial subsequent events is unity.

The initial design (prior to the one shown in Fig. 2) considered a visual inspection system to check for critical damage through assessment of crater severity (Fig. 5). In this case, critical damage is defined in terms of a depth of penetration and crater area, that is, loss of a critical volume of the thermal protection system's thickness in the neighborhood of the impact. The thermal protection system, constructed of 3-dimensionally woven mid-density carbon phenolic (3MDCP) material, is designed to protect the EES from the environment encountered during entry and descent, characterized by a short period of high pressure and high heating environments generated by the EES' high initial velocity through the atmosphere.

Protection and detection capabilities could be balanced so that acceptable containment assurance could be achieved

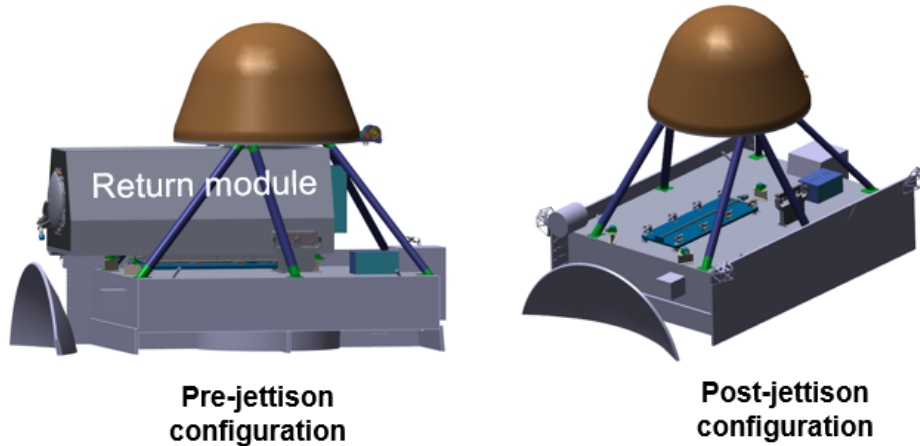


Figure 6: Pre- and post-jettison configurations of CCRS for the jettison of the entire return module.

at reasonable mass, without excessive decrease in likelihood of mission loss due to detection of critical damage (which would preclude release of the EES). The MMPS would be designed to mitigate the damage from most impacts, so that the likelihood of critical damage would remain below the level acceptable for loss of mission. The detection system would detect critical damage, in the rare event that it occurs, with reliability sufficient to satisfy targets for containment not assured, and would limit the false positive rate for reporting critical damage, to avoid unnecessary prevention of EES release and consequent loss of mission.

Several detection systems were considered. Cameras with an illumination system were deemed the more mature and reliable. Among those it is worth mentioning: a mesh that would detect impacts by running a current through it and measuring the output of the individual electric channels, and acoustic sensors placed on the most interior layer of the MMPS.

Study and analysis identified a degree of uncertainty of the detection system capability to capture images and for on-image interpretation. This uncertainty could lead to false positives and false negatives, which can either reduce the probability of science return or increase the risk, respectively. In parallel, it was assessed what additional protection could be provided if the inspection system mass were to be applied to the MMPS to add more layers of shielding. This assessment included optimization of the shape of the MMPS and its stand-off distance from the EES' outer surface, to maximize protection without needing to accommodate inspection system hardware and provide broad fields of view.

Results showed a 100-fold increase in the protection level when the inspection system mass was reallocated to the MMPS, which put the predicted MMOD probability of critical damage during the shielded portion of the mission (approximately 6 years) in the same range as the prediction for the unshielded portion of the mission (3 days). The trade indicated that acceptable containment not assured would be delivered more efficiently with a pure protection approach, which eliminated the complexity associated with precise determination of damage levels that would be needed in a suitably reliable detection system. For additional discussion and technical details, the reader is referred to Ref. [34].

5. Trade 3: Full vs partial jettison

This trade concerns the jettison of all or part of the CCRS hardware other than the MMPS and EES prior to leaving Mars orbit, with the goal of reducing the return mass and the amount of hardware potentially contaminated with Mars material that would be flying back with ERO. A summary of the trade on jettison methods is shown in Table 2 with specific metrics that were assigned a plus or minus sign based on the relative merits of the preliminary design options under consideration.

As can be seen in Fig. 6, the jettison of the entire return module requires additional structure (e.g., legs) to support the MMPS and EES, with consequent increase in the system launch mass. This structural configuration, after loads are applied (such as those, for example, deriving from launch, Mars orbit insertion or jettison), also makes it more

Table 2: Summary of trade metrics for full vs partial jettison.

	Full jettison	Partial jettison
Structural efficiency	-	+
Maintenance of alignment tolerances for EES assembly	-	+
MMOD protection post-jettison	-	+
Contamination	-	+
System launch mass	-	+
Return mass	+	-

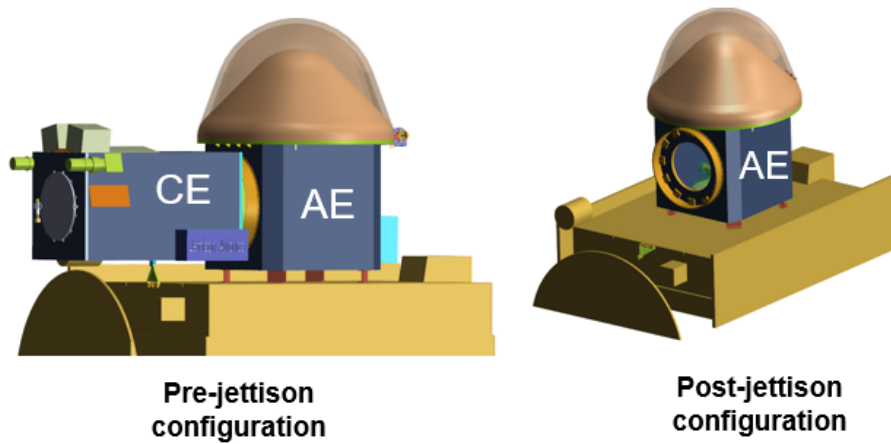


Figure 7: Pre- and post-jettison configurations of CCRS for the jettison of the capture enclosure (CE) while the assembly enclosure (AE) remains.

challenging to maintain the necessary release alignment of the EES, especially given the accuracy required, through the mission life-cycle when considering launch, Mars orbit insertion, and thermal loads.

The lack of a return module underneath the EES would leave it more exposed to MMOD damage, decreasing EES protection in the interface area with ERO after jettison. At the same time, it would increase exposure of the EES to contamination from Mars particles, which would be able to travel more freely between ERO and the bottom of the MMPS opening. This, in turn, would give the particles access to the entire EES surface, albeit at varying probability of contamination. Finally, full-jettison also presents issues with respect to the thermal cycle the EES would experience. Requirements on the temperature gradient that the samples can be exposed at are difficult to meet without an enclosure, considering the ever-changing Sun angle. As an advantage, this full-jettison configuration would minimize the return mass by eliminating most of the unneeded hardware. On the other hand, it increases the launch mass by requiring the addition of the tripod structure.

As can be seen in Fig. 7, the jettison of the capture enclosure only eliminates the need of additional structure for the MMPS, leading to a net reduction in system launch mass, but increases the return mass due to the assembly enclosure flying back with ERO from Mars to Earth. Leaving the assembly enclosure below the EES improves the drawbacks related to MMOD risk, alignment, contamination control, and thermal gradient mentioned for the full-jettison configuration.

Overall, the partial jettison solution provides a balance of performance and mass optimization and was selected for preliminary design.

6. Conclusions

This work provides an overview of trades and lessons learned while designing Mars Sample Return's Capture, Containment, and Return System in the context of planetary protection. Specifically, it refers to the preliminary design phase of the ERO-CCRS mission and represents a snapshot in time before the re-architecture studies of 2024. To comply with the backward planetary protection requirements imposed for this restricted sample return mission, CCRS must be able to perform specific functions to break the chain of contact between Mars and Earth. These functions would be implemented through a series of on-orbit operations including control, sterilization and containment of potentially hazardous Mars material.

The two main sterilization options that were investigated in detail and brought to the design stage include heat and ultraviolet radiation. The latter was preferred due to its reduced mass, a better thermal profile that allows maintaining sample integrity, and the ability to provide better fault tolerance by allowing CCRS to be powered off and ERO to retain its bus safety.

The control of the MMOD-induced damage initially entailed a combination of protection through the MMPS and inspection via cameras. Large uncertainties on the camera system to capture the images and interpret them correctly showed that a 100-fold increase in the protection level could be achieved by reallocating the inspection system mass to the MMPS. This was retained as the main means of MMOD damage control.

Finally, splitting the Earth return module in a capture and an assembly enclosure brought benefits in terms of reduced launch mass, structural efficiency and maintenance of alignment tolerances for the EES by having the assembly enclosure support the EES and MMPS. This increased MMOD protection along the interface with ERO, while decreasing contamination from Mars particles.

Overall, these trades enabled CCRS to advance to a preliminary design stage, that was reviewed and approved in December 2023 as a potential solution to the MSR paradigm, after which challenges identified by the MSR IRB-2 triggered re-architectural studies that are still ongoing at the time of this work and may alter this approach.

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 part of the NASA response to the recent MSR IRB-2 report [9] and in light of the current budget environment, the MSR Program is undergoing a consideration of changes in its mission architecture. This work is based upon the previous baseline 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 Preliminary Design Review level of maturity in mid-December 2023, after which it was stopped indefinitely pending the results of the re-architecture effort.

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References

- [1] B. Sarli, E. Bowman, G. Cataldo, T. Feehan, T. Green, K. Gough, A. Hagedorn, P. Hudgins, J. Lin, M. Neuman, E. Parvez, J. Rondey, C. Szalai, C. Yew, NASA's Capture, Containment, and Return System: Bringing Mars Samples to Earth, *Acta Astronautica* 223 (2024) 270–303. doi:10.1016/j.actaastro.2024.05.048.
- [2] D. Beaty, M. Grady, H. McSween, E. Sefton-Nash, B. Carrier, F. Altieri, Y. Amelin, E. Ammannito, M. Anand, L. Benning, J. Bishop, L. Borg, D. Boucher, J. Brucato, H. Busemann, K. Campbell, A. Czaja, V. Debaille, D. des Marais, M. Dixon, B. Ehlmann, J. Farmer, D. Fernandez-Remolar, J. Filiberto, J. Fogarty, D. Glavin, Y. Goreva, L. Hallis, A. Harrington, E. Hausrath, C. Herd, B. Horgan, H. Humanyun, T. Kleine, J. Kleinhenz, R. MacKelprang, N. Mangold, L. Mayhew, J. McCoy, F. McCubbin, S. McClennan, D. Moser, F. Moynier, J. Mustard, P. Niles, G. Ori, F. Raulin, P. Rettberg, M. Rucker, N. Schmitz, S. Schwenzer, M. Sephton, R. Shaheen, Z. Sharp, D. Schuster, S. Siljestrom, C. Smith, J. Spry, A. Steele, T. Swindle, I. ten Kate, N. Tosca, T. Usui, M. van Kranendonk, M. Wadhwa, B. Weiss, S. Werner, F. Westall, R. Wheeler, J. Zipfel, M. Zorzano, The Potential Science and Engineering Value of Samples Delivered to Earth by Mars Sample Return, *Meteoritics and Planetary Science* 54 (3) (2019) 667–671.

- [3] T. Haltigin, E. Hauber, G. Kminek, M. Meyer, C. Agee, H. Busemann, B. Carrier, D. Glavin, L. Hays, B. Marty, L. Pratt, A. Udry, M.-P. Zorzano, D. Beaty, B. Cavalazzi, C. Cockell, V. Debaille, M. Grady, A. Hutzler, F. McCubbin, A. Regberg, A. Smith, C. Smith, R. Summons, T. Swindle, K. Tait, N. Tosca, T. Usui, M. Velbel, M. Wadhwa, F. Westall, Rationale and Proposed Design for a Mars Sample Return (MSR) Science Program, *Astrobiology* 22 (S1) (2022) S-27–S-56, pMID: 34904885. doi:10.1089/ast.2021.0122.
- [4] M. Grady, R. Summons, T. Swindle, F. Westall, G. Kminek, M. Meyer, D. Beaty, B. Carrier, T. Haltigin, L. Hays, C. Agee, H. Busemann, B. Cavalazzi, C. Cockell, V. Debaille, D. Glavin, E. Hauber, A. Hutzler, B. Marty, F. McCubbin, L. Pratt, A. Regberg, A. Smith, C. Smith, K. Tait, N. Tosca, A. Udry, T. Usui, M. Velbel, M. Wadhwa, M.-P. Zorzano, The Scientific Importance of Returning Airfall Dust as a Part of Mars Sample Return (MSR), *Astrobiology* 22 (S1) (2022) S-176–S-185, pMID: 34904884. doi:10.1089/ast.2021.0111.
- [5] T. Swindle, S. Atreya, H. Busemann, J. Cartwright, P. Mahaffy, B. Marty, A. Pack, S. Schwenzer, Scientific Value of Including an Atmospheric Sample as Part of Mars Sample Return (MSR), *Astrobiology* 22 (S1) (2022) S-165–S-175, pMID: 34904893. doi:10.1089/ast.2021.0107.
- [6] B. Carrier, D. Beaty, A. Hutzler, A. Smith, G. Kminek, M. Meyer, T. Haltigin, L. Hays, C. Agee, H. Busemann, B. Cavalazzi, C. Cockell, V. Debaille, D. Glavin, M. Grady, E. Hauber, B. Marty, F. McCubbin, L. Pratt, A. Regberg, C. Smith, R. Summons, T. Swindle, K. Tait, N. Tosca, A. Udry, T. Usui, M. Velbel, M. Wadhwa, F. Westall, M.-P. Zorzano, Science and Curation Considerations for the Design of a Mars Sample Return (MSR) Sample Receiving Facility (SRF), *Astrobiology* 22 (S1) (2022) S-217–S-237, pMID: 34904886. doi:10.1089/ast.2021.0110.
- [7] NASA Office of Safety and Mission Assurance, Planetary Protection Provisions for Robotic Extraterrestrial Missions, NASA Procedural Requirements (NPR) 8715.24 (2021).
- [8] NASA Office of Safety and Mission Assurance, Implementing planetary protection requirements for space flight, NASA Technical Standard 8719.27 (2022).
- [9] O. Figueroa, S. Kearns, N. Boll, J. Elbel, Mars Sample Return (MSR) Independent Review Board-2 Final Report, NASA, 1 September 2023 <https://www.nasa.gov/wp-content/uploads/2023/09/mars-sample-return-independent-review-board-report.pdf>, (Accessed: 4 December 2023) (2023).
- [10] K. Farley, K. Williford, K. Stack, R. Bhartia, A. Chen, M. de la Torre, K. Hand, Y. Goreva, C. Herd, R. Hueso, Y. Liu, J. Maki, G. Martinez, R. Moeller, A. Nelessen, C. Newman, D. Nunes, A. Ponce, N. Spanovich, P. Willis, L. Beegle, J. Bell III, A. Brown, S.-E. Hamran, J. Hurowitz, S. Maurice, D. Paige, J. Rodriguez-Manfredi, M. Schulte, R. Wiens, Mars 2020 Mission Overview, *Space Science Reviews* 216 (142) (2020). doi:10.1007/s11214-020-00762-y.
- [11] E. Scheller, J. Hollis, E. Cardarelli, A. Steele, L. Beegle, R. Bhartia, P. Conrad, K. Uckert, S. Sharma, B. Ehlmann, W. Abbey, S. Asher, K. Benison, E. Berger, O. Beyssac, B. Bleefeld, T. Bosak, A. Brown, A. Burton, S. Bykov, E. Cloutis, A. Fairén, L. DeFlores, K. Farley, D. Fey, T. Fornaro, A. Fox, M. Fries, K. Hickman-Lewis, W. Hug, J. Huggett, S. Imbeah, R. Jakubek, L. Kah, P. Kelemen, M. Kennedy, T. Kizovski, C. Lee, Y. Liu, L. Mandon, F. McCubbin, K. Moore, B. Nixon, J. Núñez, C. R. Sanchez-Vahamonde, R. Roppel, M. Schulte, M. Sephton, S. Sharma, S. Siljeström, S. Shkolyar, D. Shuster, J. Simon, R. Smith, K. Stack, K. Steadman, B. Weiss, A. Werynski, A. Williams, R. Wiens, K. Williford, K. Winchell, B. Wogsland, A. Yanchilina, R. Yingling, M.-P. Zorzano, Aqueous alteration processes in Jezero crater, Mars—implications for organic geochemistry, *Science* 378 (6624) (2022) 1105–1110. doi:10.1126/science.abo5204.
- [12] R. Wiens, A. Udry, O. Beyssac, C. Quantin-Nataf, N. Mangold, A. Cousin, L. Mandon, T. Bosak, O. Forni, S. McLennan, V. Sautter, A. Brown, K. Benzerara, J. Johnson, L. Mayhew, S. Maurice, R. Anderson, S. Clegg, L. Crumpler, T. Gabriel, P. Gasda, J. Hall, B. Horgan, L. Kah, C. Leggett, J. Madariaga, P.-Y. Meslin, A. Ollila, F. Poulet, C. Royer, S. Sharma, S. Siljeström, J. Simon, T. Acosta-Maeda, C. Alvarez-Llamas, S. Angel, G. Arana, P. Beck, S. Bernard, T. Bertrand, B. Bousquet, K. Castro, B. Chide, E. Clavé, E. Cloutis, S. Connell, E. Dehouck, G. Dromart, W. Fischer, T. Fouchet, R. Francis, J. Frydenvang, O. Gasnault, E. Gibbons, S. Gupta, E. Hausrath, X. Jacob, H. Kalucha, E. Kelly, E. Knutsen, N. Lanza, J. Laserna, J. Lasue, S. L. Mouélic, R. Leveille, G. L. Reyes, R. Lorenz, J. Manrique, J. Martinez-Frias, T. McConnochie, N. Melikechi, D. Mimoun, F. Montmessin, J. Moros, N. Murdoch, P. Pilleri, C. Pilonget, P. Pinet, W. Rapin, F. Rull, S. Schröder, D. Shuster, R. Smith, A. Stott, J. Tarnas, N. Turenne, M. V., D. Vogt, B. Weiss, P. Willis, K. Stack, K. Williford, K. Farley, T. S. Team, Compositionally and density stratified igneous terrain in Jezero crater, Mars, *Science Advances* 8 (34) (2022) eabo3399. doi:10.1126/sciadv.abo3399.
- [13] S. Sharma, R. Roppel, A. Murphy, L. Beegle, R. Bhartia, A. Steele, J. Hollis, S. Siljeström, F. McCubbin, S. Asher, W. Abbey, A. Allwood, E. Berger, B. Bleefeld, A. Burton, S. Bykov, E. Cardarelli, P. Conrad, A. Corpolongo, A. Czaja, L. DeFlores, K. Edgett, K. Farley, T. Fornaro, A. Fox, M. Fries, D. Harker, K. Hickman-Lewis, J. Huggett, S. Imbeah, R. Jakubek, L. Kah, C. Lee, Y. Liu, A. Magee, M. Minitti, K. Moore, A. Pascuzzo, C. Rodriguez Sanchez-Vahamonde, E. Scheller, S. Shkolyar, K. Stack, K. Steadman, M. Tuite, K. Uckert, A. Werynski, R. Wiens, A. Williams, K. Winchell, M. Kennedy, A. Yanchilina, Diverse organic-mineral associations in Jezero crater, Mars, *Nature* 619 (2023) 724–732. doi:10.1038/s41586-023-06143-z.
- [14] A. Czaja, M.-P. Zorzano, G. Kminek, M. Meyer, D. Beaty, E. Sefton-Nash, B. Carrier, F. Thiessen, T. Haltigin, A. Bouvier, N. Dauphas, K. L. French, L. Hallis, R. Harris, E. Hauber, L. Rodriguez, S. Schwenzer, A. Steele, K. Tait, M. Thorpe, T. Usui, J. Vanhomwegen, M. Velbel, S. Edwin, K. Farley, D. Glavin, A. Harrington, L. Hays, A. Hutzler, M. Wadhwa, Report of the science community workshop on the proposed first sample depot for the mars sample return campaign, *Meteoritics & Planetary Science* 58 (6) (2023) 885–896. doi:10.1111/maps.13981.
- [15] B. Muirhead, A. Karp, Mars sample return lander mission concepts, in: 2019 IEEE Aerospace Conference, IEEE, 2019, pp. 1–9.
- [16] P. Bhandari, R. Kandilian, K. Novak, J. Miller, S. Morellina, J. Lyra, R. Somawardhana, K. Singh, Overall thermal architecture & design of the mars sample return lander mission, 51st International Conference on Environmental Systems, 2022.
- [17] K. Geelen, O. Sutherland, P. Baglioni, F. Spoto, J. Huesing, A. Haldemann, F. Beyer, P. Schoonejans, A. Accomazzo, T. Loureiro, L. Afentranter, D. Nicolis, C. Steiger, E. Yau, Mars Sample Return Campaign – Status of the ESA provided Elements, in: Proceedings of the International Astronautical Federation, 72nd International Astronautical Congress, Dubai, United Arab Emirates, 2021.
- [18] N. Mavrakis, T.-H. Pham, P. Bailey, Pose Estimation for Rover-to-Lander Tube Transfer for Mars Sample Return, in: 2023 IEEE Aerospace Conference, 2023, pp. 1–10. doi:10.1109/AERO55745.2023.10115908.
- [19] L. McCollum, A. Schnell, D. Yaghoubi, Q. Bean, R. McCauley, A. Prince, Development Concepts for Mars Ascent Vehicle (MAV) Solid and Hybrid Vehicle Systems, in: 2019 IEEE Aerospace Conference, 2019, pp. 1–10. doi:10.1109/AERO.2019.8741965.
- [20] G. Story, A. Karp, B. Nakazono, G. Ziliac, B. Evans, G. Whittinghill, Mars Ascent Vehicle Hybrid Propulsion Effort, in: AIAA Propulsion and Energy 2020 Forum, 2020, p. 3727. doi:10.2514/6.2020-3727.

- [21] J. Balaram, M. Aung, M. Golombek, The Ingenuity Helicopter on the Perseverance Rover, *Space Science Reviews* 217 (56) (2021). doi:10.1007/s11214-021-00815-w.
- [22] G. Cataldo, L. Affentranger, B. Clement, D. Glavin, D. Hughes, J. Hall, B. Sarli, C. Szalai, The planetary protection strategy of Mars Sample Return's Earth Return Orbiter mission, *Journal of Space Safety Engineering* 11 (2024) 374–384. doi:10.1016/j.jsse.2024.04.013.
- [23] D. Beaty, C. Allen, D. Bass, K. Buxbaum, J. Campbell, D. Lindstrom, S. Miller, D. Papanastassiou, Planning Considerations for a Mars Sample Receiving Facility: Summary and Interpretation of Three Design Studies, *Astrobiology* 9 (8) (2009) 745–758, PMID: 19845446. doi:10.1089/ast.2009.0339.
- [24] K. Tait, F. McCubbin, C. Smith, C. Agee, H. Busemann, B. Cavallazzi, V. Debaille, A. Hutzler, T. Usui, G. Kminek, M. Meyer, D. Beaty, B. Carrier, T. Haltigin, L. Hays, C. Cockell, D. Glavin, M. Grady, E. Hauber, B. Marty, L. Pratt, A. Regberg, A. Smith, R. Summons, T. Swindle, N. Tosca, A. Udry, M. Velbel, M. Wadhwa, F. Westall, M.-P. Zorzano, Preliminary Planning for Mars Sample Return (MSR) Curation Activities in a Sample Receiving Facility (SRF), *Astrobiology* 22 (S1) (2022) S–57–S–80, PMID: 34904890. doi:10.1089/ast.2021.0105.
- [25] European Cooperation for Space Standardization, Space Sustainability – Planetary Protection, ECSS-U-ST-20C (2019).
- [26] United Nations General Assembly, 2222 (XXI). Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, Article IX (1967).
- [27] COSPAR Panel on Planetary Protection, COSPAR Policy on Planetary Protection, *Space Research Today* 211 (2021) 12–25. doi:10.1016/j.srt.2021.07.010.
- [28] W. Ammann, J. Baross, A. Bennett, J. Bridges, J. Fragola, A. Kerrest, K. Marshall-Bowman, H. Raoul, P. Rettberg, J. Rummel, M. Salminen, E. Stackebrandt, N. Walter, Mars Sample Return backward contamination – Strategic advice and requirements. Report from the ESF-ESSC Study Group on MSR Planetary Protection Requirements, European Science Foundation (2012).
- [29] D. Hughes, G. Cataldo, F. Pellerano, T. Hardwick, F. Micalizzi, V. Chambers, B. Bean, B. Braley, W. Cook, R. Day, T. Emmett, C. Hovis, S. Ioana, D. Johnstone, A. Kaur, W. Morgenstern, N. Nicolaeff, L. Ong, L. Seals, R. Schnurr, L. Seide, G. Shaw, K. Smith, O. Ta, W. Thomes, H. Yum, Lessons Learned in Designing a Proposed Ultraviolet Sterilization System for Space, *Aerospace* 11 (2024) 538. doi:10.3390/aerospace11070538.
- [30] T. Hardwick, O. Ta, G. Cataldo, F. Micalizzi, L. Seide, T. Emmett, D. Johnstone, H. Yum, L. Seals, L. Ackman, M. Batkis, B. Bos, V. Chambers, C. He, A. Hernandez-Pellerano, A. Kaur, N. Nicolaeff, J. Patel, W. Thomes, M. Quijada, M. Vitullo, F. Pellerano, Technical Design of a Proposed Ultraviolet Sterilization System for Space, *Aerospace*, In prep. (2025).
- [31] B. Sarli, M. Squire, W. Schonberg, G. Cataldo, J. Williamsen, B. Tulaba, V. Cabrera, C. Cline, S. Dellinger, K. Hoffman, J. Hyde, A. Jenkin, Q. McKown, J. Needels, G. Peterson, R. Stein, K. Steward, J. Warner, T. White, Micrometeoroid and orbital debris risk assessment and mitigation strategies for NASA's Capture, Containment, and Return System, *Journal of Spacecraft and Rockets*, In prep. (2025).
- [32] G. Cataldo, B. Childs, J. Corliss, T. Feehan, P. Gage, J. Lin, S. Mukherjee, M. Neuman, F. Pellerano, B. Sarli, C. Szalai, L. Teeney, J. Vander Kam, T. White, C. Yew, C. Zumwalt, Mars Sample Return – An Overview of the Capture, Containment and Return System, in: *Proceedings of the International Astronautical Federation, 73rd International Astronautical Congress, Paris, France, 2022*.
- [33] International Organization for Standardization, ISO 11138-7:2019, Sterilization of health care products, Biological indicators, Part 7: Guidance for the selection, use and interpretation of results (2019).
- [34] P. Gage, G. Cataldo, Probabilistic Allocations for Structural Integrity for Mars Sample Return's Earth Entry System, *Journal of Spacecraft and Rockets*, Submitted (2025).