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Mars Sample Return: From collection to curation of samples from a habitable world

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NASA's Mars 2020 mission has initiated collection of samples from Mars' Jezero Crater, which has a wide range of ancient rocks and rock types from lavas to lacustrine sedimentary rocks. The Mars Sample Return (MSR) Campaign, a joint effort between NASA and ESA, aims to bring the Perseverance collection back to Earth for intense scientific investigation. As the first return of samples from a habitable world, there are important challenges to overcome for the successful implementation of the MSR Campaign from the point of sample collection on Mars to the long-term curation of the samples on Earth. In particular, the successful execution of planetary protection protocols adds well-warranted complexity to every step of the process from the two MSR Program flight elements to the ground element at the sample receiving facility (SRF). In this contribution, we describe the architecture of the MSR Campaign, with a focus on infrastructure needs for the curation (i.e., the clean storage, processing, and allocation) of pristine Martian samples. Curation is a science-enabling and planetary protection-enabling activity, and the curation practices described in this contribution for the SRF and any long-term curation facility will enable the sample safety assessment, initial scientific investigations of the samples, and establish the MSR collection as a scientific resource that will enable generations of science and discovery through studies of the returned Mars samples. The planetary protection and curation processes established for MSR will provide critical insights into potential future sample return missions from other habitable worlds like Enceladus and Europa.

Jezero Crater | astromaterials | astrobiology | planetary protection | Martian

The origin and history of the solar system, as well as the origin and history of its distinct parent bodies, are chronicled within the solar system rock record. That rock record could hold clues about some of the most interesting phenomena that humanity seeks to understand, such as the origin of life and the process of abiogenesis, the processes that have led to the diversity in parent bodies across the solar system, and the sources of material that comprise our solar system. For centuries, humans have used the Earth's rock record to understand Earth's natural history and to understand life's origins. The latter remains one of the most important unanswered questions of our time. Although we have excellent access to Earth's surface and near-surface rocks, Earth represents only one of many planetary bodies that comprise the solar system.

Extraterrestrial samples enable comparisons between Earth and other worlds, allowing us to further develop an understanding of natural processes beyond Earth. Furthermore, the ubiquitous secondary overprint of Earth's crustal rocks coupled with active plate tectonics has further limited what can be gleaned about early Earth from its own rock record. Our access to other portions of the solar system rock record is limited to the extraterrestrial samples we can collect on Earth such as meteorites and cosmic dust, as well as material that we collect on other parent bodies and return to Earth through robotic and human space exploration. Analyses of these astromaterials have led to unprecedented advances in our understanding of Earth and the solar system broadly, including the development of models for the origin of the Earth–Moon system (1–4), the age of our solar system (5), the bulk compositions of planets and the solar system (6, 7), and identification of many of the fundamental processes that have governed and shaped the solar system and its parent bodies to this point (8–14). However, much remains unknown, and each new extraterrestrial sample or set of samples we acquire helps to further elucidate the formation and evolution of our solar system and its parent bodies, including Earth. One lesson learned through decades of planetary sample science is that the scientific value of any sample from the solar system is impactful beyond the parent body from which it was derived and adds to our overall knowledge of the solar system rock record.

Meteorites and cosmic dust represent our most bountiful resource for understanding the solar system rock record. These samples represent a valuable and renewable scientific resource that continues to yield a wealth of information about the formation and evolution of our solar system and its parent bodies. These materials naturally rain down upon the Earth, and a subset is collected, curated, and allocated for scientific study. However, as a consequence of their delivery mechanism, these materials have a high degree of terrestrial contamination and lack a priori context about

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their point of origin. Both of these factors limit the scientific utility of meteorites to answer scientific questions that are dependent upon context and limited terrestrial contamination (e.g., 15).

Sample return missions offer an alternative approach to astromaterials acquisition where samples from another parent body can be deliberately collected and returned to Earth in a controlled and prescribed manner to a controlled environment, designed with specific scientific questions in mind (16–18). The first example of such an endeavor is the Apollo 11 mission to the Moon, where astronauts landed on the Moon, collected 21.55 kg of samples from the lunar surface, and returned to Earth with those samples. These samples were delivered to a curation facility that was designed to keep the samples in a pristine "as returned" state in perpetuity. One of the biggest benefits of sample return missions is the ability to curate samples in an environment that can preserve the scientific integrity of the samples over many years. The careful curation and conservation of samples allows for their availability when new scientific questions arise. Furthermore, as technology advances and new generations of scientists emerge, the samples can be used to answer questions that were not possible to answer, or even conceived of, at the time of sample return.

In total, humans have successfully executed 15 sample return missions, 10 from the Moon, three from asteroids, one from the coma of a comet, and one that collected solar wind at Earth-Sun Lagrange point one (18–21). Other than the first few Apollo missions, there was little concern about the potential for extraterrestrial life to be within the returned samples and/or for the returned samples to pose a threat to life on Earth. This lack of concern was motivated by the fact that all of the parent bodies or collection points thus far are not considered to be habitable. However, NASA's Mars 2020 mission, through the Perseverance Rover, has initiated collection of samples from the planet Mars (22) in Jezero Crater. A joint effort between NASA and ESA referred to as the Mars Sample Return (MSR) Campaign is designed to bring the Perseverance collection back to Earth by 2040 (23). This endeavor would be humanity's first return of samples to Earth from another planet and the first return of samples from a habitable world.

The MSR Campaign was described as the highest scientific priority of NASA's robotic exploration efforts for the last two Planetary Science Decadal Surveys (24, 25). The MSR Campaign consists of the Mars 2020 mission, two MSR Program flight elements, and one ground element (Fig. 1). Each of these portions of the MSR campaign architecture has immense, but not insurmountable, challenges that must be overcome, from sample collection to long-term curation. In this contribution, we highlight the functional steps in the MSR architecture, with a focus on aspects related to planetary protection and the curation of the samples after they arrive on Earth. Although we highlight curation activities that occur in an SRF and in a long-term curation facility, we focus on the aspects of curation that will best enable the sample safety assessment, initial scientific investigations of the samples, and establish the MSR collection as a scientific resource that will allow generations of science and discovery through studies of the returned Mars samples.

Collection of Scientifically Compelling Samples and Considerations for Their Curation

The Mars 2020 mission is tasked with collecting a scientifically compelling set of samples that are worth delivering to Earth for intense scientific examination (22). The processing, subdivision, and handling of these samples, prior to allocation for scientific study or for life-detection studies associated

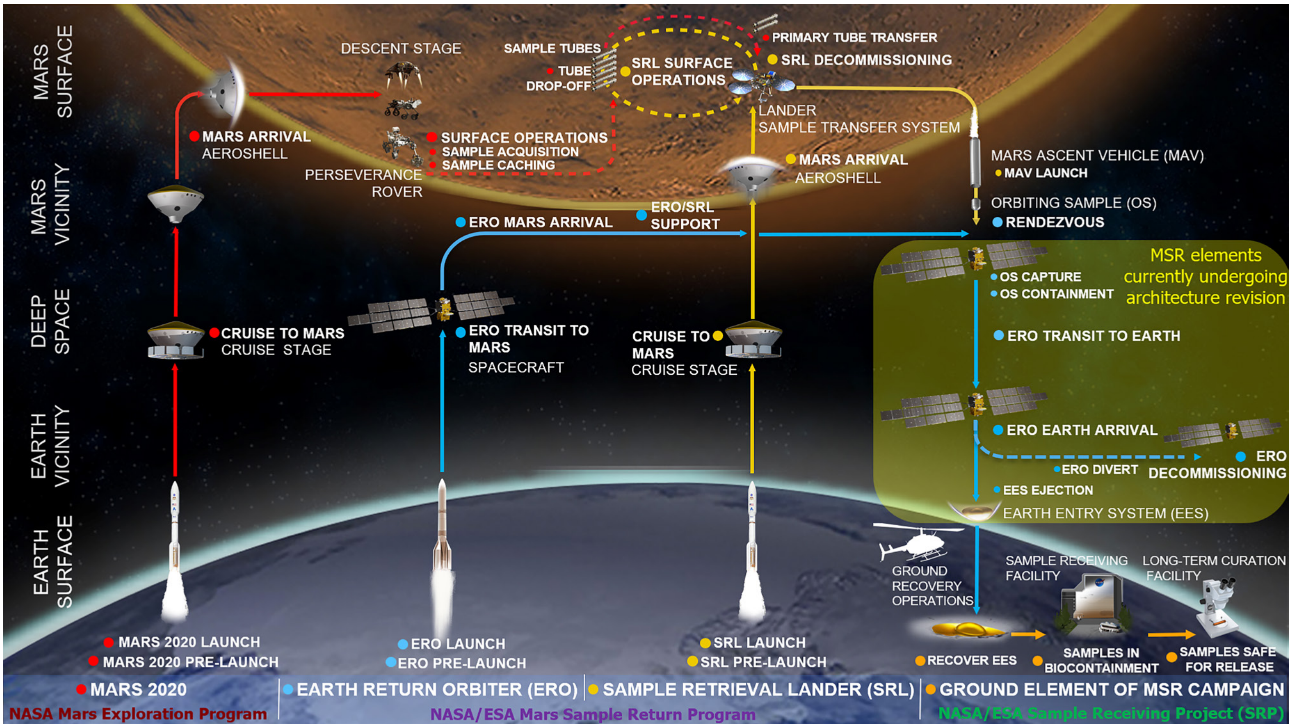

Fig. 1. Notional MSR Campaign architecture (Image Credit: Adapted with permission from ref. 26). The cartoon is intended to demonstrate functional steps for the MSR Campaign and, other than the Mars 2020 Mission, may not represent the final campaign mission architecture.

with planetary protection requirements, will be done by curation personnel. Planning for curation activities in the SRF and in a long-term curation facility requires knowledge about the types of samples that will be returned and the types of scientific investigations that will be prioritized. All of the samples collected by the Perseverance rover are in sealed sample tubes, but these tubes host a wide variety of sample types that need to be considered when designing and planning for curation infrastructure. As of Spring 2024, the Perseverance Rover has collected and sealed a total of 21 rock cores (8 igneous and 13 sedimentary), two regolith samples, one sample of Martian atmosphere, and three witness tubes designed to document Earth-sourced contamination (27). The rover holds 17 of these samples, and 10 of them have been placed in the Three Forks sample depot on the Martian surface to provide flexibility to the plans to return the samples.

Based on the samples collected thus far, the sample processing infrastructure in any MSR curation facility (i.e., SRF or long-term curation facility) will need the capability to process rock cores, unconsolidated regolith (and partially broken or disintegrated rock cores), and gas samples (including headspace gases in all the sample tubes). Furthermore, there is substantial diversity in the rock types being returned that will also have important implications for curation infrastructure needs for handling and processing the returned samples. Samples collected from the floor of Jezero Crater by the Perseverance rover during the Crater Floor Campaign include basaltic lava flows from the heavily cratered Máaz Formation and an older igneous olivine cumulate lithology that underlies the lava flows, referred to as the Séítah Formation (28). Both of these lithologic units have experienced varying degrees of aqueous alteration (29–31) that could prove challenging for sample processing if the aqueously altered portions of the samples are friable or result in partial or full disintegration of the core samples before opening or during extraction and subsequent processing. Understanding the state of the samples prior to opening, through methods such as X-ray computed tomography (XCT), will be crucial for understanding the state of each sample tube before it is opened and to develop a sample processing plan for each sample tube (32, 33).

In addition to the igneous samples collected from the floor of Jezero Crater, the Perseverance rover has also collected 13 sedimentary samples and 2 regolith samples from the Delta Front, Upper Fan, and Margin Campaigns (27). The Delta Front samples include a variety of sandstones and mudstones that record fluvial, deltaic, and lacustrine settings in Jezero Crater (34). These sedimentary rocks are composed of detrital igneous grains and products of aqueous alteration. These aqueous alteration products include various clay minerals, sulfates, oxides, chloride salts, hydrated silica, and carbonates (27). Furthermore, many of these samples host cements composed of aqueous alteration products. Special consideration of the curation environment will be needed to prevent alteration of the most sensitive phases that could undergo phase changes over time as a function of relative humidity, temperature, and pressure including some clay and sulfate minerals. In fact, there will likely be some time-sensitive measurements that will need to occur in the SRF shortly after opening select sample tubes to avoid loss of science (35).

In addition to considering the physical forms of the samples that will be returned within the sample tubes and the various rock and mineral types they will host, the types of scientific investigations that will be prioritized must also be considered when designing the infrastructure and procedures associated with sample processing. Such considerations will ensure that Earth-based contamination is kept below any threshold values that could compromise the prioritized scientific investigations. Based on the samples that are present within the Perseverance rover and at the Three Forks Depot, the scientific investigations of the samples will span a broad range of topics about Mars and the solar system at large. For example, the igneous rocks collected during the Crater Floor Campaign hold invaluable information about the interior of Mars, and they will enable transformative advances in our understanding of the physicochemical evolution of Mars and the nature of its mantle and crust. Furthermore, these samples will provide key insights into the chemical composition of the building blocks that formed Mars, which will aid in understanding the nature and distribution of materials that formed the terrestrial planets at the nascent stages of solar system evolution, including processes such as the delivery of volatiles like water (36–43). Both the igneous and sedimentary samples from Jezero Crater will be targeted for detailed organic studies as both exhibit luminescent properties that offer tantalizing evidence of potential organics in the samples, although inorganic sources could also be responsible for the observed luminescence features (31, 44). Studies of the aqueous alteration products preserved in the Jezero Crater samples will yield key insights into Martian surface processes and elucidate further on the habitable conditions that once existed at the Martian surface (45). The presence of aqueous alteration phases, particularly in fine-grained samples from subaqueous paleoenvironments recorded in the facies 2 rocks of the Shenandoah Formation, has a high potential for biosignature preservation (34). These investigations represent only a minor fraction of the types of studies that will be done on the returned samples (46), but they highlight the need for stringent inorganic, organic, and biological contamination control measures in the curation facilities where the samples will be opened, processed, and allocated (32, 47). In addition to contamination control measures, contamination knowledge strategies will be needed to facilitate quantification of contamination throughout sample processing activities. These strategies will include the deployment of witness materials within the curation environment that will act as procedural blanks that are processed alongside the Martian samples (48) and could also include analysis of hardware coupons or processing tools (49). Additionally, they include active monitoring of the curation environment for inorganic, organic, and biological contamination (16–18).

The Martian samples collected thus far by Perseverance have an abundance of science value, regardless of whether it is the samples on the Perseverance rover or the samples from the Three Forks Depot that are ultimately returned. Returning these samples for study in terrestrial laboratories will enable hypothesis testing and independent validation of important rover observations using laboratory-based instruments with capabilities that cannot be achieved with flight instruments.

With the successful execution of stringent contamination control and contamination knowledge measures during the MSR Campaign, including in the curation facilities, that covers inorganic, organic, and biological contamination, returning either set of samples collected thus far would transform our understanding of the solar system rock record broadly. The Perseverance rover continues to explore the Jezero Crater margin, and it will eventually arrive at the crater rim where additional samples of high scientific value could be collected that will only add to the scientific value of the collection of samples on the Perseverance rover. With a scientifically compelling set of samples collected, the first major challenge to a successful MSR Campaign has already been surpassed.

Sample Retrieval and Return to Earth

The two flight elements for the MSR Program are still in development, but the top-level functional needs for these flight elements have been identified. The first flight element is the Sample Retrieval Lander that will retrieve up to ~30 sealed sample tubes and place them within transport hardware called the Orbiting Sample (OS) for return to Earth. The retrieval of the samples will either occur directly from the Perseverance rover, or they will be collected from the Three Forks Sample Depot. Having both options mitigates the risk of one of the two options not being tenable at the time of retrieval. The Sample Retrieval Lander will also have a launch capability referred to as the Mars Launch System that will launch the OS into Mars orbit. The second flight element consists of an Earth Return Orbiter that is responsible for capturing the OS from Mars orbit and placing it within a secondary containment vessel that will be capable of safely delivering the sample to Earth through an Earth Entry System (EES). A cartoon depicting the functional execution of the MSR Campaign, including the Mars 2020 mission, the two MSR Program flight elements, and the ground element of MSR is depicted in Fig. 1.

One of the biggest challenges to overcome during the two flight elements of the MSR Program architecture is the process referred to as "breaking the chain" and represents the step for which biocontainment of the OS is achieved prior to being sealed into the secondary vessel that is integrated within the EES. Although a specific implementation for breaking the chain has not been selected, the functional requirement for this step will involve sterilization of the outer portion of the OS so that it is not a risk to Earth's biosphere after it lands. This sterilization step is part of the overall planetary protection strategy for the MSR Campaign. Notably, Jezero Crater was chosen, in part, as the sampling target for MSR because it is a place of past aqueous activity on Mars and has the potential to preserve an ancient record of aqueous processes and potential past life. In addition, Jezero Crater is not in a "special region" that is thought to potentially host extant Martian life (50), and life-detection is not one of the scientific objectives of MSR (22, 51). However, life-detection investigations of the MSR samples will be part of the sample safety assessment to meet planetary protection requirements (52).

The United Nations' (UN) Outer Space Treaty of 1967 (53) outlines the basic framework of planetary protection in its article IX, which declares "…States Parties to the Treaty shall pursue studies of outer space, including the moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose…" The United States and ESA's member states are signatories of the Outer Space Treaty, and this treaty motivated NASA Procedural Requirement (NPR) 8715.24 entitled: Planetary Protection Provisions for Robotic Extraterrestrial Missions. This NPR defines planetary protection designations for the return phases of sample return missions as being either Class V Unrestricted or Class V Restricted Earth-return. For samples that are returned from a habitable world, like Mars, the return phase of the flight mission is designated as Class V Restricted Earth-return. Although the likelihood of returned Martian samples from Jezero Crater having a deleterious impact on the terrestrial biosphere is exceptionally low (22, 54), these planetary protection policies represent important safeguards to establish procedures for mitigating the risks associated with returning samples that could harbor life. These policies are motivated by the idea that "preventing harmful biological contamination of Earth's biosphere is the highest priority." The term "break the chain" comes from NPR 8715.24, and it requires a strategy to be implemented that will isolate and robustly contain the return samples prior to delivery to the Earth–Moon system. Several break the chain implementation strategies are under evaluation and include methods such as redundant layering, chemical, heat, or ultraviolet (UV) sterilization (55).

Once the chain is broken, the sample capsule will be permitted to enter the Earth–Moon system. Once the EES is "Go" for Earth Entry, it will enter the Earth's atmosphere and land. At this time, the EES is being designed such that it can withstand a terminal velocity landing without the aid of a parachute given the risks associated with parachute reliance and the challenges associated with mass and volume that come with including a parachute. Although the engineering implementation for the two flight elements of the MSR Program will offer many challenges, there is nothing in the current architecture that is considered to be impossible to overcome.

As the EES is heading through the Earth's atmosphere, recovery operations on the ground will already be underway to 1) assess whether it is a nominal landing, 2) have a team ready to recover the capsule from the landing site, and 3) have a team ready to transport the EES to a temporary staging area, possibly for the first steps of hardware deintegration, before it is transported to the SRF. The ground element of MSR is referred to as the Sample Receiving Project (SRP), and this step begins once the samples land on Earth and are transported to a facility where curation activities, early science activities, and sample safety assessment activities will be conducted (Fig. 1). Other than the additional biocontainment requirements that come with a Restricted Earth-return mission, much of the recovery operations can take advantage of lessons learned from recent sample recovery operations for unrestricted sample return missions like Genesis, Stardust, Hayabusa, Hayabusa2, and OSIRIS-REx.

The most significant departure from an unrestricted return is to develop a baseline biocontainment plan that, at least in part, considers the possibility that the EES partially breaches upon landing because it may not be possible to confirm whether the EES remained intact until a detailed engineering inspection occurs within the SRF. The additional risk mitigation steps include but may not be limited to: moving the EES into a biocontainment box at the landing site, sterilizing the outside of the biocontainment box before it is transported to the temporary staging area, and remediating the landing site utilizing best practices dictated by the Center for Disease Control and/or Department of Agriculture.

Even the biocontainment portions of the initial ground operations can borrow heritage from mobile biocontainment labs that have been used in field settings by the medical profession for over a decade (56). These mobile biocontainment labs can be designed to meet necessary contamination control requirements (57). The availability of a "clean" biocontainment laboratory would enable some initial flight hardware disassembly to occur at the temporary staging area to limit the time the Sample Containment Vessel (SCV) is outside of an inert environment and in proximity to the highly contaminating Earth entry vehicle. This clean biocontainment lab could also be utilized as a robust sample triage area in the event of a major breach of the EES.

The transportation of Restricted Earth-return samples to the SRF also requires major considerations since the transportation container, simultaneously, needs to minimize the risk to the samples and minimize the risk to the terrestrial biosphere. Traditionally, unrestricted samples are packaged to mitigate contamination risks to the samples and are transported by a United States Military aircraft to the receiving/curation facility. It is anticipated that if the EES lands within the United States, this paradigm would also be deemed the safest route for MSR samples.

Role of a Sample Receiving Facility

The SRF is a specialized facility in which the samples will be initially curated and assessed for their safety. As with a traditional curation facility, the SRF must have capabilities to accept and disassemble the flight hardware, preserve the scientific integrity of the Martian samples, perform initial characterization of the samples to inform the collection catalog, and allocate samples to scientists within and outside (for sterilized samples or samples deemed safe for release) the SRF. While there are any number of potential implementation strategies that depend on the desired facility scope, there are two fundamental differences between a traditional curation facility and an SRF. The first, and most apparent, is the capability of an SRF to maintain the samples under high-containment. The second is the enhanced analytical capability that is necessary to complete a sample safety assessment, conduct sample sterilization, and, in some cases, perform select time- or sterilization-sensitive analyses.

The National Institute of Health defines a high-containment biological laboratory at Biosafety Level (BSL)-3 and -4. To meet these requirements, the facility must meet both infrastructural and procedural parameters necessary to ensure the personnel working within the laboratory and public are protected (58, 59). Although the probability is extremely low (22, 50, 54), it is not known if the returned Mars samples contain a pathogen transmissible by air for which there is no known treatment. Therefore, due to the nonzero potential for an unknown, NASA's Planetary Protection Office recommends the utilization of containment at "the highest level based on current technology" to safeguard the terrestrial biosphere. This stance is in line with Article IX of the UN Outer Space Treaty (53).

While UN and NASA Planetary Protection recommendations give clear guidance that an SRF for MSR should provide containment equivalent to a BSL-4 facility, there is currently no requirement to formally commission a high-containment facility that does not house a select agent or known infectious pathogen. This nuance may be especially important since formal classification as a BSL-4 facility may levy certain requirements on the facility that are not conducive to long-term sample integrity. One of these requirements could be to sterilize all samples removed from the facility, even if the sample safety assessment deems the samples safe for release (i.e., the samples are devoid of Martian life). The "unnecessary" sterilization of all extraterrestrial samples could be catastrophic to the scientific value of the MSR collection, especially if standard high-containment sterilization procedures were required, such as wet heat in the form of an autoclave. Therefore, the current assumption is that the SRF should be structurally equivalent to a BSL-4 facility and maintain a laboratory that is negative pressure relative to the surrounding area, but not be formally classified as BSL-4.

There are two ways in which to achieve the infrastructural requirements necessary to meet BSL-4 equivalence. The most common method is to operate a negative pressure laboratory with full body, air-supplied, positive pressure suits, known as a BSL-4 suit laboratory. Traditionally these facilities are constructed with outer walls of thick single-poured concrete. However, new stainless-steel technology is coming on the market (57) and will be evaluated for its potential use in the SRF. The second method for meeting BSL-4 equivalence is to utilize negative pressure glove boxes called Class III Biosafety cabinets (BSC-III), known as a cabinet laboratory. In the United States, there is a strong preference for operating a suit laboratory due to some ergonomic limitations of working in the BSC-III, as well as the greater flexibility of the working space. Given the wide range of processes to occur within the SRF, it is likely that both implementation strategies would be utilized. The implementation of either option will depend on an array of factors, including sample integrity, SRF footprint, and schedule. For example, for operations required to be performed in ultraclean, inert environments, the utilization of a custom BSC-III may enable both high-containment and contamination control compliance.

In addition to containing the samples and enabling the sample safety assessment, a major priority of the SRF is to maintain sample integrity by protecting the samples from terrestrial contamination. It is anticipated that, given the scientific objectives associated with MSR, the contamination control requirements levied on the SRF will be stringent for select operations, specifically for activities involving pristine sample handling. Unlike previous sample return missions that emphasized inorganic and organic contamination control measures, protecting the samples from biological contamination will be vital for not only achieving science goals but also for minimizing the potential risk of false positives during the sample safety assessment. A false positive during the sample safety assessment would not only delay the unsterilized release of the remaining MSR collection from the SRF, but it would also likely require more samples to be utilized/consumed for the sample safety assessment (52).

There are four fundamental considerations when developing contamination-controlled environments within curation infrastructure: 1) materials restrictions, 2) needed rates of air-exchanges to meet particle counts and flush organic outgassing, 3) sample sensitivity to the terrestrial atmosphere or atmosphere of the curated environment, and 4) the cleaning processes necessary to achieve cleanliness with respect to organic, inorganic, and microbial contamination. Each of these considerations is customized for each collection and for specific operations within the curatorial process. While the implementation of technology that provides an inert environment utilizing stringent material restrictions is standard practice within curation, the integration of negative pressure environments with the positive pressure barrier(s) necessary to minimize terrestrial contamination is novel. However, this concept has been under consideration for over two decades (60) and ESA has made significant investments into developing the necessary technology, in the form of the Double Walled Isolator (DWI) (61), to achieve clean handling of pristine samples in containment. Fig. 2 updates the Draft Test Protocol pressure paradigm (60) and represents potential implementation strategies for integrating positive and negative pressure environments.

Fundamentally the DWI would be a custom, material-compliant BSC-III with positive pressure interstitial regions that create an inert, positive pressure barrier between the laboratory and the samples. It is conceivable that DWI technology could be implemented within the SRF to not only meet high-containment requirements but also to ensure that the samples remain pristine during handling and processing. The core functionality of the DWI is based on the use of remote manipulation instead of gloves, to minimize human-related contamination, glove-related contamination, and to add a more solid biobarrier between the pristine samples and the environment. However, while remote manipulation is preferred to meet contamination control requirements, it is not required for planetary protection, and the utilization of gloves could be considered for certain processes such as flight hardware disassembly.

In addition to curatorial isolation technology, the SRF must also accommodate an array of analytical instruments necessary for initial characterization of the samples [i.e., pre-basic characterization, basic characterization, preliminary examination] (32) and the sample safety assessment. Depending on the type of analysis, it may be feasible to integrate these instruments with DWIs or custom isolation cabinets. However, initial reports from MSR science working groups have recommended an array of instruments where integration with or within a DWI would be challenging or necessitate costly custom development (e.g., mass spectrometers) (23, 32, 62). For all instruments not able to be integrated with isolators, either within them or measurements made through windows or viewports, suit laboratories would be required. Additional suited laboratory space may also be needed for sample preparation, tool and cabinet cleaning, cold storage, and/or sample sterilization.

The cleaning and sterilization steps implemented during hardware disassembly are another major consideration for the SRF design. The degree to which cleaning and sterilization steps are integrated will depend on the final mission architecture and acceptable risks. For example, if the hardware is hermetically sealed, then more aggressive measures such as vapor phase hydrogen peroxide could be utilized for sterilization of the outside container. However, the risk of false positives should be weighed against the potential degradation of the samples if there is an undetected breach in the outer container. Therefore, it may be advisable to simply

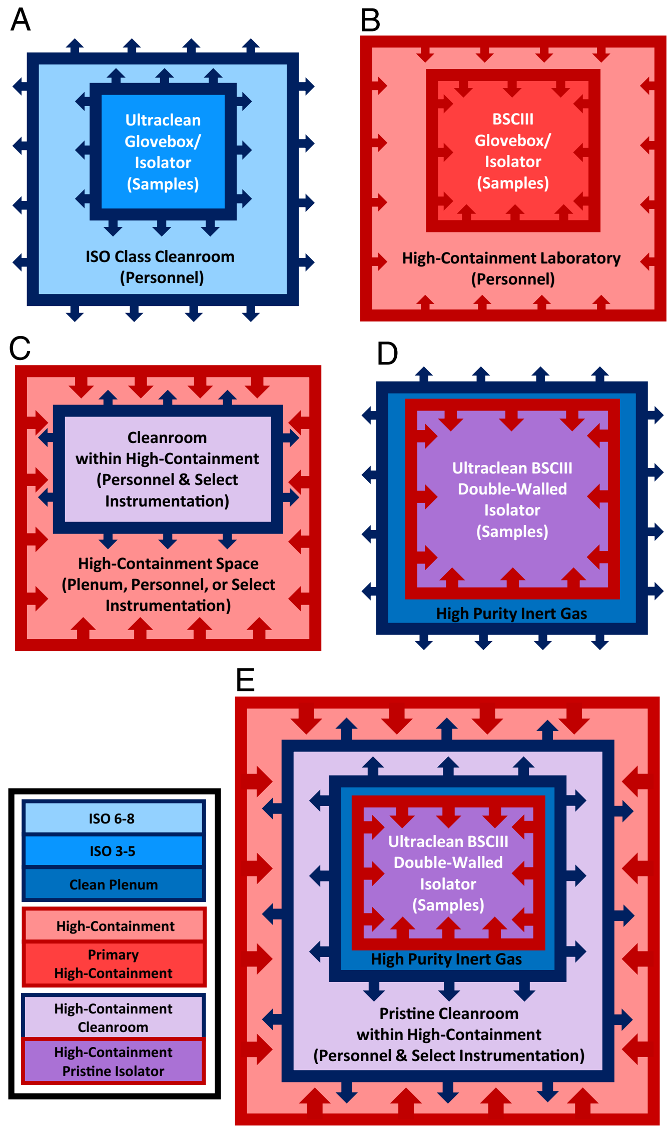

Fig. 2. Airflow direction in various clean (positive pressure) and biosafety (negative pressure) laboratory settings. The legend refers to a plenum, which is a part of a building that facilitates air circulation through various pathways for airflow. Panels (*A* and *B*) include traditional airflow in cleanrooms and biosafety labs, respectively. Panels (*C*–*E*) illustrate various strategies for achieving clean high-containment environments that could be utilized for MSR in the SRF. The implementation choice for meeting clean and contained environmental requirements will be dictated by the level of high containment, the cleanliness requirements, and the necessary operations. (*A*) Typical cleanroom positive-pressure technology; (*B*) typical high-containment negative-pressure technology; (*C*) cleanroom within high-containment lab, operated by personnel in positive pressure suits (for activities with less stringent contamination control requirements and larger equipment); (*D*) specialized ultraclean isolator (for activities with more stringent contamination control requirements and for activities with inert gas requirement); (*E*) specialized isolator installed within a cleanroom in an overall contained space operated by personnel in cleanroom attire for nominal operations (for isolators, the negative versus positive pressure configuration is reversed to ensure planetary protection requirements are met).

wipe the hardware down and trace contamination by preserving those wipes as contamination knowledge samples for early hardware disassembly. Another trade-off when planning hardware disassembly is the number of isolators utilized for each process. Balancing the desire to isolate each of the disassembly steps into individual isolators and providing isolation chambers for cleaning and/or sterilization steps will have to be weighed against other priorities within the facility. Therefore, combining processes within a given isolator must be strategic.

Sample and Science Management in the SRF

A close working relationship between the project science and curation teams is integral to the success of any sample return mission. The relationship becomes even more critical and intertwined for Restricted Earth-return missions due to the additional planetary protection considerations and the resulting complexity of designing, constructing, and operating an SRF. For MSR, the necessity to develop a strong working relationship is further mandated by the mission's design (e.g., the flight hardware and the return of 10 to 30 individual sample tubes), the additional sample safety assessment considerations, and the diversity of the sample collection ranging from igneous to sedimentary rock cores, samples of atmosphere, unconsolidated regolith, and witness tube assemblies.

Traditionally, curation takes a minimalistic approach to initial characterization (18). For example, the OSIRIS-REx collection predominantly relied on high-resolution imaging supplemented with some XCT and structured light scanning to develop the initial sample catalog and to inform sample requests. Due to timing, the initial sample catalog for MSR will likely be predominantly composed of the Perseverance sample dossiers, bulk magnetic properties, XCT measurements, and high-resolution photographs of the samples and any subsamples once extracted from their tubes. However, project science and sample safety assessment teams may request the inclusion of additional measurements during any of the three phases of initial characterization. For example, given the prioritization of the sample safety assessment and life detection (i.e., origins, extinct, extant) within the SRF, it is conceivable that systematic high-resolution, high detection sensitivity organic mapping of sample cores may help identify high-priority regions of interest within the samples. This information could focus the sample requests from the sample safety assessment and project science teams and optimize the resulting sample processing and allocation by curation.

It is important to note that while curation staff may be collecting the enhanced scans recommended by project science and sample safety assessment teams, given the restrictive nature of a high-containment facility, these data are likely to be scientifically compelling and suitable for inclusion in peer-reviewed publications. From the curation perspective, all information collected initially to characterize the samples should be incorporated into the sample catalog. However, publication of the data from pre-basic characterization, basic characterization, and preliminary examination would be at the discretion of the project science and sample safety assessment teams, similar to the ground element of other sample return missions like OSIRIS-REx.

The concept of operations for the SRF (*SI Appendix* and Fig. 3) relies on the idea that project science and sample safety assessment teams work with the curation team to prioritize sample processing order and activities. While the development of the sample catalog and the completion of the sample safety assessment will take precedence within the SRF, considerations may be made for select investigations on samples that could degrade rapidly once the sample tubes are punctured for gas extraction (e.g., hydrated clays, sulfates, and salts). Those investigations are referred to as time-sensitive sample science investigations, and information from the Perseverance Sample Dossiers and other data collected during initial characterization will help to identify samples for which time-sensitive studies are necessary (35). To further identify potential time-sensitive samples, we can also rely on results from Hayabusa2 and OSIRIS-REx, which returned aqueous alteration products similar to those collected in samples from Jezero Crater (19). The OSIRIS-REx samples are curated in gaseous N_2, which is also the baseline plan for MSR samples (32). The OSIRIS-REx samples will enable a critical assessment of the use of N_2 with volatile-rich phases within the curation environment to better determine what phases are most susceptible to change. In general, significant advanced planning for each tube, sample type, and potential physical sample state (e.g., solid core, semifractured core, highly fragmented core, regolith) is necessary to limit sample degradation and mitigate work stoppages due to unforeseen issues.

Practically, this means that the project science and sample safety assessment teams should study the Perseverance Sample Dossiers extensively before the samples arrive to prioritize the order in which the samples will be processed. Once the pre-basic characterization is initiated, the curation team, in collaboration with the project science and sample safety assessment teams, should then examine the data to determine how best to execute sample extraction and processing, as well as identify areas of high interest for potential additional XCT or organic mapping scans during preliminary examination. If additional XCT or organic mapping scans are requested by the project science or sample safety assessment teams, it is anticipated that these teams will need to evaluate the data before further subsampling can occur. Therefore, it may be prudent to store the sample after mapping and begin processing and/or scanning the next sample instead of waiting for the decision of the project science and sample safety assessment teams. Given that not all potentialities can be identified in advance, the curation, project science, and sample safety assessment teams will have to be flexible to respond to unknowns. Communication and understanding that issues will occur is vital to make forward progress.

Despite the many challenges and the development of novel concepts to implement the ground element of MSR, the concept of operations at the landing site and within the SRF is mature and many options are available for the successful execution of all the activities required to occur within the SRF (*SI Appendix*). The SRF is not intended to be a long-term curation facility for MSR. Although Mars is a habitable planet, Jezero Crater and the surrounding area are unlikely to harbor extant life (22, 50, 54), and the baseline plan is that

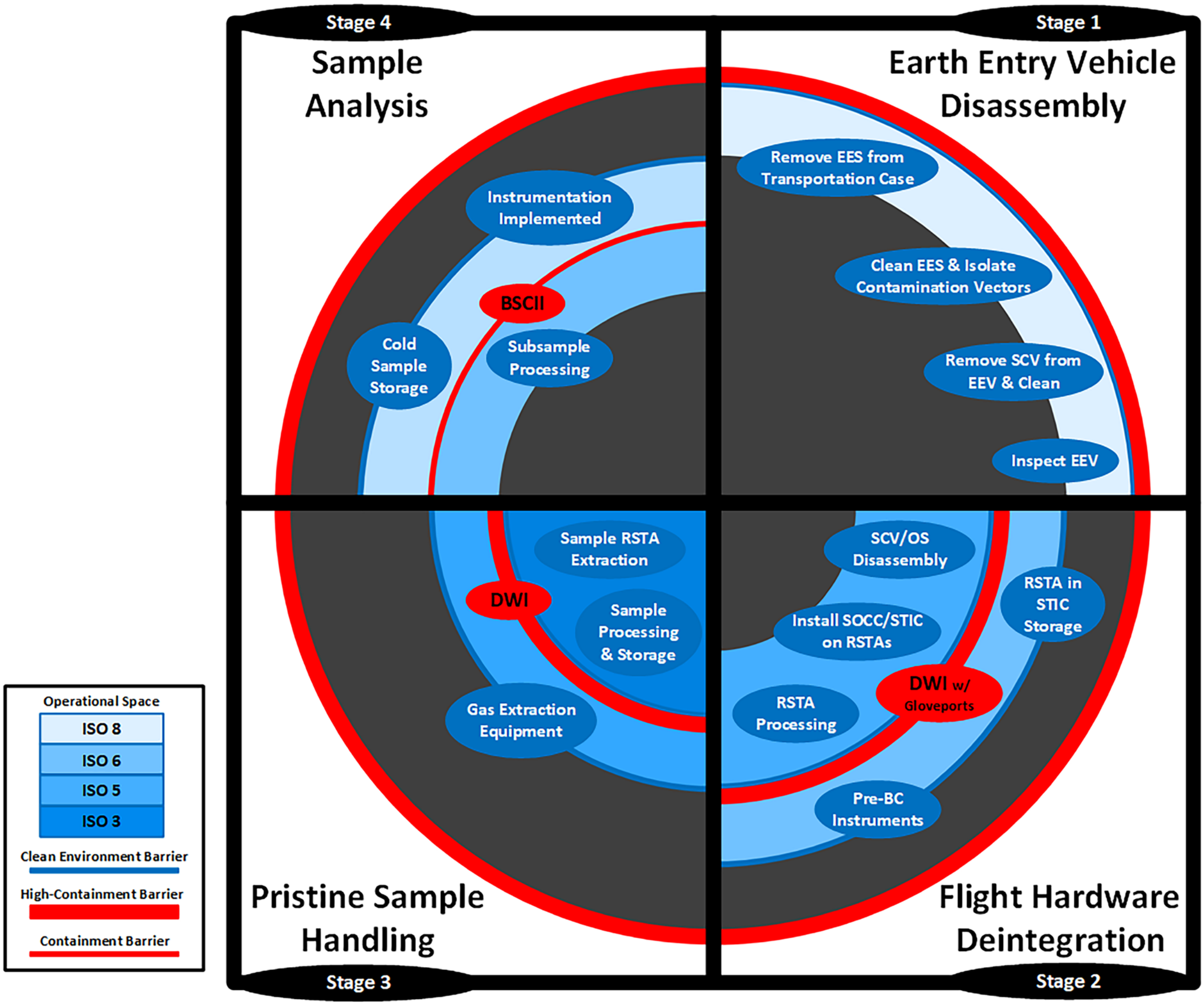

Fig. 3. The anticipated high-level concept of operations within the SRF is demonstrated in Stages 1 to 4. Infrastructural requirements within the high-containment portion of the SRF will be determined by the operational functions and the cleanliness requirements. The center of the circle represents the environment with the most stringent contamination control requirements, where the pristine samples are processed (Stage 3). Less stringent contamination control requirements are anticipated during hardware disassembly (Stage 1 and 2) and within analytical suites (Stage 4), therefore, this work is positioned closer to the border of the circle. The stages and activities highlighted represent notional examples and are not an exhaustive list of the potential activities or types of spaces that may be implemented within the SRF. Previously undefined acronyms in the figure include: STIC, sample tube isolation container; SOCC, secondary outer containment caps; SCV, secondary containment vessel; RSTA, returnable sample tube assemblies; Pre-BC, Pre-basic characterization; EEV, Earth entry vehicle.

samples will be deemed safe for release at the conclusion of the sample safety assessment. How the SRF will be utilized after MSR is uncertain but, even if it is not used for other Restricted Earth-return missions, the lessons learned during MSR will be critical for the potential return of more complex or high-risk samples from other habitable worlds in the outer solar system like Enceladus and Europa.

Long-Term Curation

The curation of the MSR samples begins in the SRF. The infrastructural requirements and contamination control measures implemented in the SRF to maintain the scientific integrity of the samples are the same requirements and measures that will be needed in any long-term curation facility for the MSR collection. Keeping the sample processing and sample curation infrastructure between the SRF and long-term curation facilities the same will minimize the types of materials that come into contact with the pristine samples over the lifetime of the collection, which will help to maintain the long-term scientific integrity of the MSR sample collection. Unlike the SRF, a long-term or "uncontained" curation facility does not have to provide high containment or support the extensive array of analytical equipment that is needed for the sample safety assessment. However, as with the SRF, an uncontained facility must provide a contamination-controlled environment to preserve sample integrity and must support sample processing and allocation of samples to scientists worldwide.

It is anticipated that a long-term curation facility will need to be operational when the samples arrive on Earth, since a portion of the collection may be sterilized soon after return to enable research outside of the SRF before the sample safety assessment is complete (23, 63, 64). Sterilized samples will be housed in a long-term curation facility, and once the samples are deemed safe for release, one or more long-term curation facilities will become the only MSR curation facilities for the collection. A long-term curation facility will operate at relative positive pressures, will provide an area for pristine sample handling and storage, as well as space to store and process returned samples and perform "dirty" sample preparation (e.g., making thin sections). The pristine sample handling and storage area is notionally planned to meet equivalent contamination control requirements as the SRF and adopt the same thresholds for inorganic, organic, and biological contamination. It will also implement similar contamination knowledge strategies such as the deployment of witness materials and contamination monitoring procedures that verify the levels of inorganic, organic, and biological contamination within the curation environment. The equipment and laboratory materials will be restricted to the same degree as in the SRF to minimize organic outgassing and particle shedding, specifically operating ISO 3 equivalent isolation chambers within an ISO 5 cleanroom. The isolation cabinets may be operated with remote sample manipulation systems, even though it would be for contamination control purposes only. Similar to the SRF, the cabinets should be developed with windows to allow for high-resolution imaging and geochemical sample mapping through the cabinet window, which has been successfully implemented for Apollo samples, Hayabusa2 samples, and OSIRIS-REx samples (e.g., 19, 65). Traditional gloveboxes could also be utilized in a long-term curation facility, but their implementation should adhere to the same materials restrictions that are implemented in the SRF for processing and handling pristine MSR samples.

Planning for the long-term curation of the samples is critical, and development of a curation strategy that maximizes the science value of the samples from the time they are received in the SRF, through their transfer to a long-term curation facility, and throughout the decades that follow is the key to successful curation of the samples. The development of these facilities is a means to ensure a return on investment for decades by enabling analyses of pristine Mars samples by scientists that are not yet born, to answer questions that are not yet conceived, using instrumentation that has not yet been invented. Humanity has over 50 y of experience with the long-term curation of returned astromaterials outside of containment, and the lessons learned from past endeavors have fed forward into the long-term curation strategy of MSR samples. Although MSR will mark the first sample return from a habitable world, the overarching strategies for maintaining the scientific integrity of the collection over decadal timescales is largely the same as those developed through earlier sample-return missions from the Moon and asteroids.

Summary

There are some important challenges to overcome for the successful implementation of the MSR Campaign, but paths to overcome all those challenges are tenable. Furthermore, the samples that have already been collected by Perseverance are scientifically compelling and represent key gaps in our solar system rock record. The scientific value of the MSR sample collection is immeasurable and will contribute to questions ranging from the origin of our solar system to the origin of life. The scientific potential of these samples to answer fundamental questions will not only draw planetary scientists with interests that span across the solar system, but it will bring in scientists outside of planetary science from the fields of terrestrial geology, physics, chemistry, biology, and medicine to take part in the discoveries that lie within the returned Martian samples. As the first samples returned from a habitable world, the processes established will provide critical insights into sample return missions from other habitable worlds like Enceladus and Europa. Through the careful curation and conservation of the samples, MSR will enable generations of scientific discoveries about Mars and about the solar system at large for decades to come.

Data, Materials, and Software Availability. There are no data underlying this work.

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