Final Report of the Mars Sample Return Science Planning Group 2 (MSPG2)

Citation: Summons, Roger. 2022. "Final Report of the Mars Sample Return Science Planning Group 2 (MSPG2)." Astrobiology, 22 (S1).

Published Version: 10.1089/AST.2021.0121

Publisher: Mary Ann Liebert Inc

Permanent Link: https://hdl.handle.net/1721.1/148255

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

ASTROBIOLOGY
Volume 22, Supplement 1, 2022
Mary Ann Liebert, Inc.
DOI: 10.1089/ast.2021.0121

Final Report of the Mars Sample Return Science Planning Group 2 (MSPG2)

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This paper was written by the MSR Science Planning Group 2 (MSPG2) working under a Terms of Reference from NASA and ESA.

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Abstract

The Mars Sample Return (MSR) Campaign must meet a series of scientific and technical achievements to be successful. While the respective engineering responsibilities to retrieve the samples have been formalized through a Memorandum of Understanding between ESA and NASA, the roles and responsibilities of the scientific elements have yet to be fully defined.

In April 2020, ESA and NASA jointly chartered the MSR Science Planning Group 2 (MSPG2) to build upon previous planning efforts in defining 1) an end-to-end MSR Science Program and 2) needed functionalities and design requirements for an MSR Sample Receiving Facility (SRF). The challenges for the first samples brought from another planet include not only maintaining and providing samples in pristine condition for study, but also maintaining biological containment until the samples meet sample safety criteria for distribution outside of biocontainment.

The MSPG2 produced six reports outlining 66 findings. Abbreviated versions of the five additional high-level MSPG2 summary findings are:

Summary-1. A long-term NASA/ESA MSR Science Program, along with the necessary funding and human resources, will be required to accomplish the end-to-end scientific objectives of MSR.

Summary-2. MSR curation would need to be done concurrently with Biosafety Level-4 containment. This would lead to complex first-of-a-kind curation implementations and require further technology development.

Summary-3. Most aspects of MSR sample science could, and should, be performed on samples deemed safe in laboratories outside of the SRF. However, other aspects of MSR sample science are both time-sensitive and sterilization-sensitive and would need to be carried out in the SRF.

Summary-4. To meet the unique science, curation, and planetary protection needs of MSR, substantial analytical and sample management capabilities would be required in an SRF.

Summary-5. Because of the long lead-time for SRF design, construction, and certification, it is important that preparations begin immediately, even if there is delay in the return of samples.

1. Introduction

1.1. Context

THE CURRENTLY ENVISIONED Mars Sample Return (MSR) Campaign is one of the most ambitious planetary exploration undertakings ever attempted. Scientifically selected samples collected by NASA's Mars 2020 (M2020) mission would be returned to Earth through the joint efforts of the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). Upon delivery to Earth, the samples would be made available to the international science community to conduct investigations and address some of the most fundamental questions about the formation and evolution of the solar system and potentially the origins of life.

Beginning with M2020 operations, the MSR Campaign must meet a series of scientific and technical achievements to be successful. While the respective engineering responsibilities to retrieve the samples have been formalized through a Memorandum of Understanding (MOU) between ESA and NASA, the roles and responsibilities of the scientific elements have yet to be fully defined.

To aid in the process, ESA and NASA jointly chartered the MSR Science Planning Group 2 (MSPG2). The group's overarching aims were to build upon previous planning efforts in defining (1) an end-to-end MSR Science Program, highlighting a number of important issues that would influence the development and implementation of this Science Program and (2) needed functionalities and design requirements for an MSR Sample Receiving Facility (SRF). The challenges for the first samples brought from another planet include not only maintaining and providing samples in pristine condition for study, but also maintaining biological containment until the samples are demonstrated to meet sample safety criteria for distribution outside of biocontainment. To maximize the scientific output of the samples and minimize the cost and size of an SRF, as many analyses as possible should be conducted in labs outside of biocontainment, either on sterilized samples or after the samples have been determined to be safe for release.

1.2. Abbreviated Statement of Task

The MSPG2 Terms of Reference (Appendix A) includes four main tasks (listed here in abbreviated form):

1. Develop inputs to a comprehensive MSR Science Management Plan;
2. Identify and describe technical issues related to the science of MSR and how the implementation of the SRF impacts the potential scientific usefulness of the samples;
3. Develop approaches and a working list of high-level requirements for the SRF that represent the needs and interests of science, curation, and planetary protection and can be used in cost estimation and budgeting, with the assumption that as many analyses as possible should be done outside of the SRF;
4. Produce a list of key decision points related to the Mars returned samples with inputs from science, curation, and planetary protection.

1.3. Process

Following the ESA and NASA signature of the Terms of Reference, a "Dear Colleague" letter soliciting participation was released April 2, 2020, to the international science community. Applicants to the competitive process were selected through a joint ESA-NASA review, joining two *ex officio* members and a small group of assigned organizers. During the course of MSPG2's work, ESA and NASA each assigned one additional participant. In total, other than the assigned coordination team, MSPG2 had 25 members representing 11 countries summarized as follows: 11 United States, 12 Europe, 1 Canada, 1 Japan. The group was co-chaired by the NASA and ESA MSR Science Leads and organized into a Coordination Team, a Tactical Team, and a Strategic Team.

The group was given approximately one year to produce its deliverables. As the entirety of the MSPG2 effort was carried out during the course of the global COVID-19 pandemic, all of its work was conducted by virtual means; there was no travel and no in-person meetings were held.

A number of Focus Groups and Topical Teams comprising subsets of the MSPG2 membership were formed and assigned specific portions of the statement of task. Overall strategic direction and integration of materials was performed by the Coordination Team. In total, the MSPG2 produced 6 reports outlining 66 findings (Supplement 1), culminating in a briefing to the ESA and NASA sponsors May 27, 2021.

1.4. Summary of high-level MSPG2 findings

The overall conclusions of MSPG2 can be summarized with 5 high-level findings:

Summary-1. A long-term NASA/ESA MSR Science Program, along with the necessary funding and human resources, will be required to accomplish the end-to-end scientific objectives of MSR (Haltigin *et al.,* 2022).

Summary-2. Traditional curation of extraterrestrial samples involves cleanroom operations, but MSR curation would need to be done concurrently with BSL-4-level containment. This would lead to complex first-of-a-kind curation implementations and require further technology development.

Summary-3. Most aspects of MSR sample science could, and should, be effectively performed on samples deemed safe (either by test or by sterilization) in uncontained laboratories outside of the SRF. However, other aspects of MSR sample science would be both time-sensitive and sterilization-sensitive, including the search for life, assessment of habitability, and volatile exchange processes, and would need to be carried out in the SRF.

Summary-4. To meet the unique science, curation, and planetary protection needs of MSR, and even with an

explicit goal of performing as many MSR sample analyses as possible outside of biocontainment, substantial analytical and sample management capabilities would be required in an SRF.

Summary-5. The schedule required to have an SRF designed, constructed, and ready to receive the MSR samples has a longer lead time than perhaps anything previously attempted by NASA/ESA. It is important that preparations begin immediately; a potential delay in the return of the samples does not impact the overall science program planning beyond some shift in the mid-term activities.

The following section represents a synopsis of 7 reports (Haltigin *et al.,* 2022; Tosca *et al.,* 2022; Velbel *et al.,* 2022; Carrier *et al.,* 2022; Tait *et al.,* 2022; Grady *et al.,* 2022; Swindle *et al.,* 2022) that address the four deliverables (tasks) requested of the MSPG2. This information is offered to ESA and NASA management to aid in securing the approval and resources that would allow the MSR effort to be a success.

2. Summary of the MSR Campaign

2.1. Primary campaign elements

The concept of MSR as a campaign of missions has been studied for many years (see, *e.g.,* Beaty *et al.,* 2008; Mattingly and May, 2011, and references therein). However, the specifics of the proposed campaign have evolved over time. The origins of the current version of the MSR campaign can be traced to the 2013-2022 Decadal Survey ''Visions and Voyages for Planetary Science in the Decade 2013-2022'' (NRC, 2011). The technical inputs from the Mars Program Office of NASA's Mars Exploration Program (MEP) to the decadal survey described an architecture that they referred to as ''3 + 1'', alluding to three flight mission elements and one ''ground segment'' element to receive and investigate the samples on Earth. A key principle of the 3 + 1 architecture was that, in the intervals between the major elements, the samples would be placed in one of several possible safe and stable states to minimize timing risk associated with the sequential nature of the campaign. The NASA MEP (NRC, 2011) subsequently assigned its highest priority in the Flagship mission class to the MSR sample-collecting rover (referred to at the time as MAX-C) that subsequently evolved to be implemented as the sample-caching M2020 mission and the Perseverance rover.

Utilizing the concept of safe sample states, it was deemed possible to set the 1st element of the ''3 + 1'' campaign architecture in motion with the M2020 mission without knowing the full details of the other campaign elements. Work on M2020 began with extensive early advance development planning, capitalizing on heritage from the Curiosity rover, which launched in 2011, and a Science Definition Team (Mars 2020 SDT, 2013). This was followed by a full development cycle that consisted of requirements definition, hardware design, delivery, test, and integration, resulting in a system superbly designed to meet the needs of MSR (see Farley *et al.,* 2020). This mission was launched on July 30, 2020, and the Perseverance rover successfully landed in Jezero Crater, Mars on February 18, 2021. As of this writing, mission operations are in progress (see Farley, 2021).

The current version of the 2nd and 3rd elements of the ''3 + 1'' campaign architecture began to take shape with joint work between NASA and ESA engineers beginning in 2017. Early architectural work was presented at the 2nd International Mars Sample Return Conference (see especially Edwards and Vijendran, 2018; Muirhead, 2018; Duvet *et al.,* 2018; Vijendran *et al.,* 2018; and Parrish *et al.,* 2018). This cooperation led to the formalization of an MSR partnership between NASA and ESA (beginning with a statement of intent in 2018, and a MOU for the flight elements of the MSR Program in October 2020). The current plan is for two flight missions, each of which has several key subsystems that would collectively carry out the work of transporting the samples from Mars to Earth, while protecting their scientific integrity. The two missions consist of:

- **(i) NASA Sample Retrieval Lander (SRL) Mission:** includes the Mars Ascent System (MAS), the Orbiting Sample container (OS), and the ESA Sample Fetch Rover (SFR)
- **(ii) ESA Earth Return Orbiter (ERO) Mission:** includes the NASA Capture, Containment, and Return System (CCRS) that includes the Earth Entry System (EES) that would notionally land in the United States.

Work over the last four years on these missions has consisted of understanding the requirements and the resource constraints (including mass, volume, energy, cost, and schedule), how to optimize the architecture, the constraints on the design of the different elements, and the interfaces between elements. Recent summary descriptions may be found in Lock *et al.* (2019), Nicholas (2020), and Muirhead *et al.* (2020).

The most recent planning for the ''+1'' ground segment campaign element was the work of the MSR Science Planning Group (see MSPG, 2019a,b,c), its extension into MSPG2 (this work and associated papers) and parallel systems engineering work (see *e.g.,* Mattingly *et al.,* 2020). The MSPG and MSPG2 work builds upon several major prior studies, including the International Mars Architecture for Return of Samples (iMARS; Beaty *et al.,* 2008), Phase 2 Architecture and Management Plan for Return of Samples (iMARS-2; Haltigin *et al.,* 2018), and the International MSR Objectives and Samples Team (iMOST; Beaty *et al.,* 2019). Much of this prior planning has used the term Mars Returned Sample Handling (MRSH) to describe the overall set of ground-based activities. After landing on Earth, MRSH has been deemed to encompass: 1) transportation of the returned flight hardware (with included samples) from the Earth landing site to a Biosafety Level-4 grade SRF; 2) an SRF where the samples would be extracted from the tubes in which they had been stored since acquisition and tested for safety; 3) one or more uncontained sample curation facilities; and 4) a set of processes and systems that would allow the world's research scientists and laboratory infrastructure to carry out scientific investigations on the Mars samples.

Recent summaries of the MSR Campaign are provided by Gramling *et al.* (2021) and Gramling and Meyer (2021). Brief descriptions of the primary functional steps from the point of view of the samples are provided below (note that some aspects of planning are still in progress and are subject to modification).

2.2. The planned history of the samples

2.2.1. Sample integrity. A key consideration that stretches across all aspects of the MSR campaign is the need to preserve the scientific integrity of the sample collection in order to maximize its scientific value. Planning related to the expected state of the samples as received on Earth began early in the development process for the M2020 mission. Key goals for maintaining the integrity of important sample attributes include limiting fracturing, maintaining seals on the sample tubes, limiting organic and inorganic contamination, limiting maximum temperature, and limiting exposure to magnetic fields. Early contributors to this planning included Liu *et al.* (2014), Beaty *et al.* (2008; 2014; 2016) and Summons *et al.* (2014). Sample integrity related requirements for the M2020 and MSR Program flight missions have been derived from this work. Planning for protecting the scientific integrity of the samples after they arrive on Earth is currently underway, and the first set of proposed requirements in this domain for an SRF have been outlined by MSPG2 (Carrier *et al.,* 2022).

2.2.2. Sample acquisition. The science team of the Perseverance rover plans to identify and collect a set of Scientifically Return-Worthy (SRW) martian samples. The Perseverance rover has a prime mission lifetime of one Mars year (about two Earth years) with a qualified lifetime of 1.5 Mars years (about three Earth years). In total, the rover has 38 sample tubes that can be filled with samples (one of which could be a drillable blank), and five single-use witness tubes used to document any terrestrial contamination during sample collection. The rover has the capability to acquire at least 20 samples within its prime mission lifetime. If the rover survives in a functional state into one or more extended missions, it could continue sampling until either the sample tube supply is used up, or the rover reaches the end of the lifetime of either the sampling subsystem or the rover itself. Samples would be chosen by the M2020 science team to represent the geologic diversity of the area that Perseverance explores and may include regolith/dust and breccias, sediments, carbonates and hydrated minerals, crater floor material, igneous rocks, and martian atmosphere. Relevant sample information including geological context, drill performance, the surface wind, temperature, pressure, and relative humidity during and after sampling are planned to be documented in a Sample Dossier for each sample.

2.2.3. Sample caching and sample depot(s). The samples collected by Perseverance would be sealed inside sample tubes and stored, at least temporarily, in a rack inside the Perseverance rover. To make the samples available for retrieval by the SFR, the samples would need to be moved from Perseverance to the ground in one or more groups that are referred to as cache depots. If Perseverance continues to function, some samples could be retained onboard and delivered directly to the MAS. The number and placement of the depots is a critical planning question (see CSSC, 2021) that needs to be coupled with planning for the landing site of the SRL and the relative positioning of the Perseverance rover and its ability to function, as well as the design of the SFR traverses. All systems need to work together to result in the convergence at the OS of an SRW cache, currently defined as: (i) distinct sample suites or individual samples selected to represent the diversity of the exploration area and address the science objectives of MSR described by iMOST, in general, and the astrobiological potential, geologic history, and evolution of Mars as reflected in the Jezero Crater region, in particular; (ii) availability of *in situ* data and other information to understand the geological and environmental context of the returned samples, and; (iii) inclusion of one and preferably two, witness samples (CSSC, 2021).

2.2.4. Sample retrieval. The NASA-led SRL mission, including an ESA-led SFR, is currently proposed for launch in 2026 (with a primary backup date of 2028). Some (or potentially all) of the samples collected by Perseverance and left at a depot on the martian surface could be acquired by the SFR. The SFR is designed with the capability to pick up as many as 30 tubes from a single depot and place them in a tube storage rack on the SFR for transport to the SRL platform. Once there, some or all tubes would be transferred to the OS inside the MAS. It is planned that the option would also exist for the Perseverance rover to drop sample tubes in a sample tray in the front of SRL that could be accessed by the SRL robotic arm and, from there, loaded into the OS. The OS, as currently envisioned, is planned to have a capacity of up to 30 sample tubes.

2.2.5. Earth return. Current planning shows MAS launch from Mars's surface in 2029 (with 2031 as the backup date) and release of the sample-containing OS into low Mars orbit. The ERO would then capture the OS in orbit. The CCRS payload inside ERO would orient the OS (so that the samples would land in a preferred orientation). The OS and its encapsulated samples would then be sealed inside both a Primary Containment Vessel (PCV) and a Secondary Containment Vessel (SCV) to safely contain martian samples and dust and sterilize any uncontained martian dust to prevent any unsterilized martian material from being exposed to Earth's biosphere. This containment and sterilization process is referred to as ''Breaking the Chain'' and is required for Planetary Protection Category V Restricted Earth Return missions (COSPAR, 2021). The primary purpose of the PCV and SCV seals is for planetary protection. ERO would then jettison part of the Capture and Containment Module (CCM), leave Mars orbit, and return to Earth with an arrival in 2031 (backup date of 2033). Once at Earth, the ERO would release the EES for a ballistic entry through Earth's atmosphere.

2.2.6. Ground retrieval and processing. Upon successful landing and recovery in the United States, the EES would be placed in a biosafety container and transferred to an SRF. Activities conducted within an SRF would include (but not be limited to) the following: hardware de-integration; archiving and analyses of the flight hardware; collection, analyses, and curation of dust from the OS interior and the tube exteriors; sample tube headspace gas extraction and analyses; extraction of samples from the tubes; processing of witness materials; initial sample characterization; completion of sample safety assessment (Kminek *et al.,* 2021); scientific investigations that are time-sensitive and sterilization-sensitive; and preparation of samples for investigations to be conducted in the SRF and in external laboratories.

2.2.7. Scientific investigation. After delivery of the samples to an SRF, scientific investigations would commence concurrently with the initial characterization of the samples. Teams of investigators competitively selected years in advance would conduct a variety of studies addressing the MSR objectives (“objective-driven investigations”). During this period, there would be considerable overlap with curation activities and sample safety assessment, which would require appropriate coordination to optimize the use of sample material and maximize the scientific return.

Two types of investigations would be conducted within the SRF itself as follows: (i) those that require time-sensitive measurements (*i.e.,* characterizing physical or chemical properties that may change rapidly after sample tube opening) (MSPG, 2019a; Tosca *et al.,* 2022) and (ii) those that require measurements that are sensitive to sample sterilization processes and have an element of time-criticality (Velbel *et al.,* 2022). These two categories also encompass scientific investigations necessary to complete the sample safety assessment. However, most of the scientific study of the martian samples is expected to take place in uncontained laboratories outside the SRF, using sample material that has either been determined to be safe by test or rendered safe by sterilization. As with other sample return missions, it is envisioned that scientific investigations would continue for decades into the future.

3. Summary of MSPG2 Results

3.1. Science Management Plan (Deliverable #1)

A fundamental premise of the MSR Campaign is that the scientific benefit and discoveries are meant to be shared between the MSR Science MOU Partners and the world’s scientific community. Because there are so many scientific elements that must be executed to achieve Campaign success, significant coordination is required. It is thus critical to ensure that the appropriate planning, resources, management, and oversight are available.

MSPG2 Deliverable #1 involves developing inputs for the MSR Campaign Science Management Plan (SMP). The scope covers the interface to the M2020 mission, science elements in the MSR flight program, ground-based science infrastructure, MSR science opportunities, and the MSR sample and science data management. Some of the required bodies and activities already exist; the remainder require definition and action. In our report on this topic, we propose a science management structure comprising specific bodies and/or activities that could be implemented to address the science functionalities throughout the MSR Campaign (Figure 1). Although some coordinating activities have already been instituted, and the timing of certain elements may be flexible depending on the anticipated date of samples arriving on Earth, it is crucial that others are implemented as soon as is feasible. Recommended first steps are to formalize the Science Program’s management structure and overall MSR science agreement between the MSR partners by the end of 2021 (*i.e.,* MSR Science MOU) and establish an MSR Campaign Science Group (MCSG) to support the NASA and ESA MSR Science Leads to implement the program.

MSPG2 Summary Finding #1
A long-term NASA/ESA MSR Science Program, along with the necessary funding and human resources, will be required to accomplish the end-to-end scientific objectives of MSR.

3.2. Sample curation (Deliverable #2)

All material that is collected from Mars (*e.g.,* gases, dust, rock, regolith) would need to be carefully handled, stored, and analyzed following Earth return to minimize the alteration or change that could occur on Earth and to maximize the scientific measurements that can be done on the samples, now and into the future. There are four curation goals that encompass all activities within the SRF:

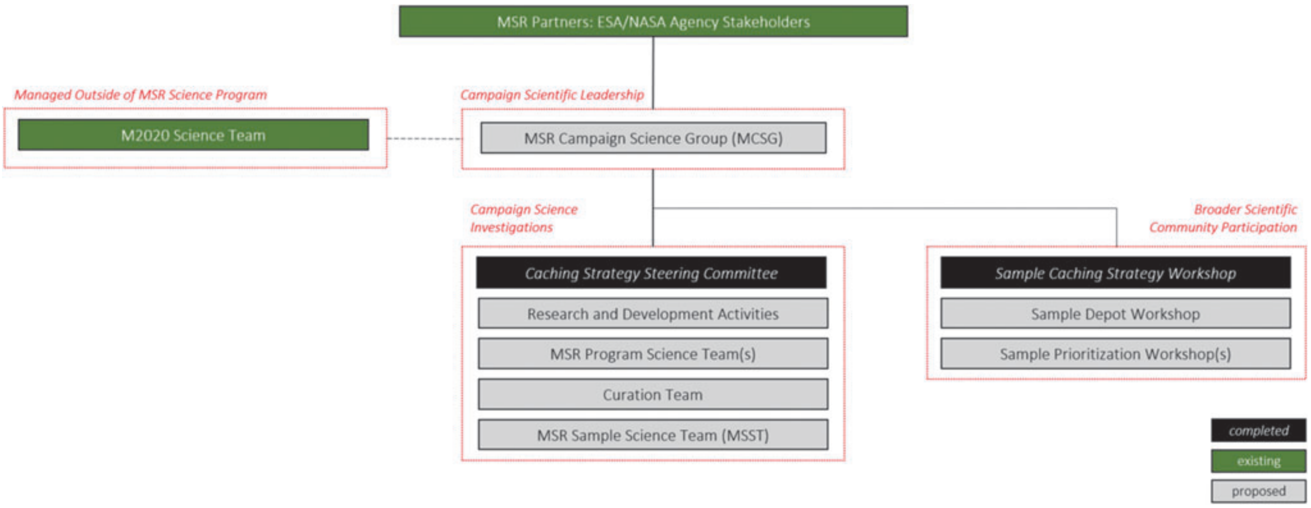

FIG. 1. Hierarchical structure of the proposed MSR Science Program, representing relationships amongst the bodies and representative activities required to execute the MSR Campaign’s scientific elements. Note that this is not meant to be a comprehensive list of necessary activities. Modified after Haltigin *et al.,* 2022.

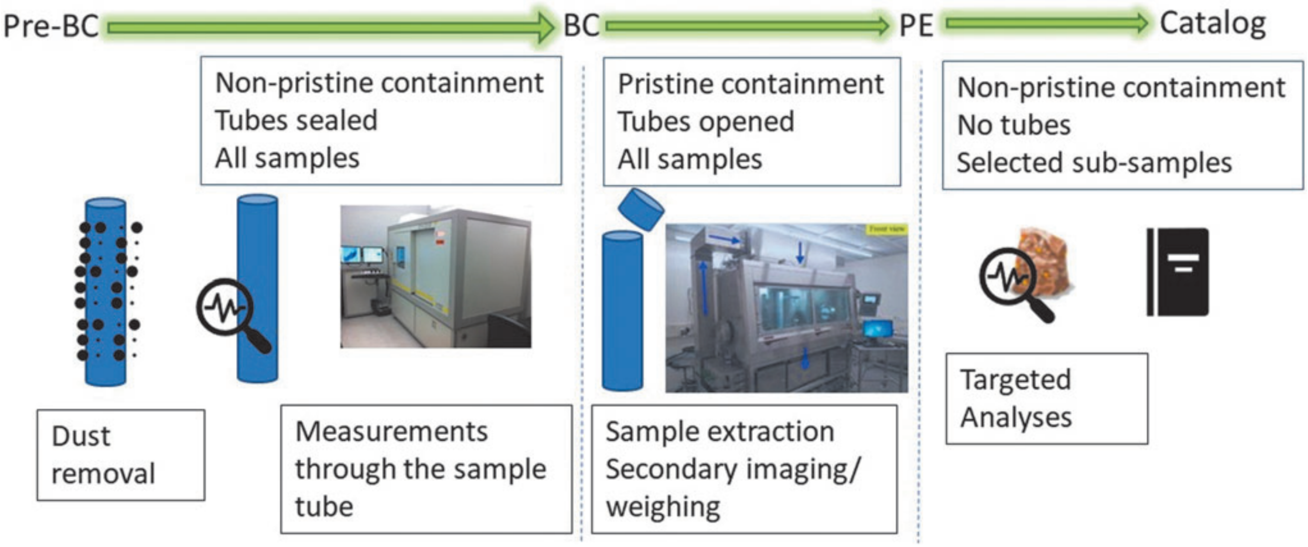

FIG. 2. Proposed sequence of activities within the Pre-Basic Characterization (Pre-BC), Basic Characterization (BC), and Preliminary Examination (PE). Modified after Tait *et al.,* 2022.

1. Carefully manage the sample workflows, from entry into the SRF until exit from the SRF;
2. Monitor sample environments, handling, and storage to maximize preservation of sample scientific value;
3. Conduct initial sample characterization to enable preparation of a sample catalog and the sample allocation process;
4. Work together with scientific investigators at all stages to maximize the scientific value and utility of the samples.

To make these samples accessible, a series of observations and analytical measurements would need to be completed to produce a sample catalog for the scientific community. The sample catalog would be populated with data and information generated during all phases of activity, including data derived from the M2020 mission and produced during sample collection and transport to Earth and reception within the SRF. Data on specific samples and subsamples would also be generated during curation activities carried out within the SRF, including a series of initial sample characterization steps, which we have called Pre-Basic Characterization (Pre-BC), Basic Characterization (BC), and Preliminary Examination (PE) (Figure 2). The sample catalog would also be augmented by data collected during science investigations within the SRF.

There is need for substantial future work to refine sample workflows, cleanliness and contamination control requirements, and further technology development related to the extraction from the sample tubes and subsequent sample handling.

MSPG2 Summary Finding #2

Traditional curation of extraterrestrial samples involves cleanroom operations, but MSR curation would need to be done concurrently with BSL-4-level containment. This would lead to complex first-of-a-kind curation implementations and require further technology development.

3.3. Time-sensitive science (Deliverable #2)

Samples returned from Mars would be placed in biocontainment until it can be determined that they are safe to be released from biocontainment. The process of determining whether samples are safe for release, which may involve detailed analysis and/or sterilization, is expected to take several months per sample and up to two years or more (depending how many samples there are) for the full collection, but there is a substantial amount of uncertainty related to the timeline for release of samples from the SRF. However, it is certain that the process of breaking the sample tube seal and extracting the headspace gas would perturb local equilibrium conditions between gas and solid sample material and set in motion irreversible processes that proceed as a function of time.

Consideration of both the timescales and the degree to which these processes would jeopardize scientific investigations as a function of time supports the conclusion that the SRF must permit characterization of:

1. Organic material, possibly biosignatures
2. Sample headspace gas
3. Volatiles bound to solid samples
4. Solid-phase volatile hosts.

These investigations must be completed inside the SRF and on timescales that minimize the irrecoverable loss of scientific information (*i.e.,* several months or less) (Figure 3). It is also important to note that all of the investigations identified as time-sensitive are related to sample attributes that can be altered by sterilization (see Section 2.4) and therefore cannot be done on samples that have been sterilized by heat or gamma irradiation. To allow these investigations to be carried out successfully, a number of specific recommendations for sample preparation and instrumentation within the SRF have been prepared (Carrier *et al.,* 2022; Tosca *et al.,* 2022).

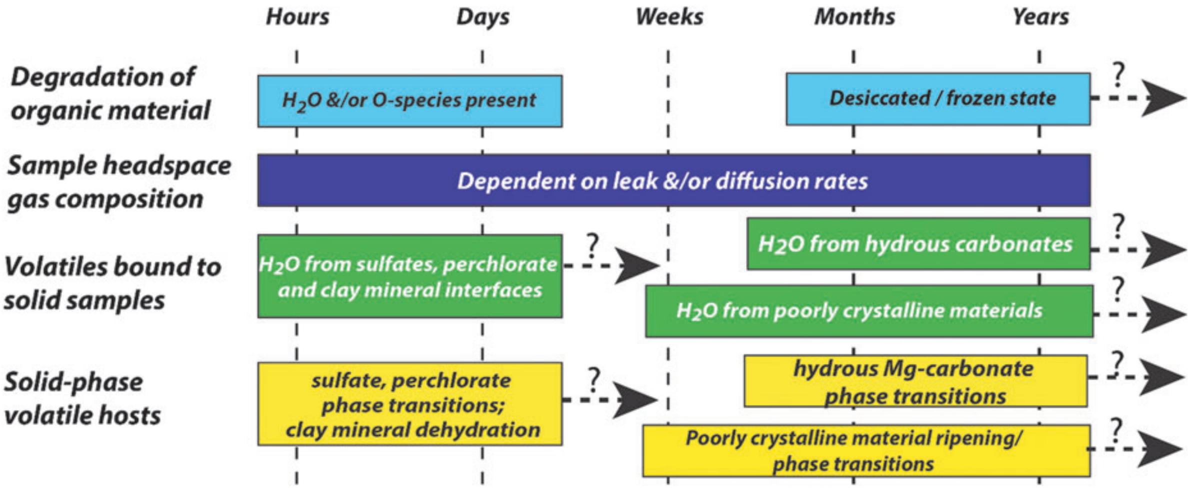

FIG. 3. Characteristic timescales of processes that underpin the time-sensitivity of MSR measurements. Some processes (such as the degradation of organic material and mineral-volatile exchange) are associated with different timescales depending on other factors such as environmental conditions and mineralogy. Modified after Tosca *et al.,* 2022.

3.4. Sterilization-sensitive science (Deliverable #2)

A high priority of the MSR Campaign is to establish whether life on Mars exists or existed where and when environmental conditions allowed. To answer these questions through analyses of the returned samples requires measurements of many different properties and characteristics by multiple and diverse instruments. While it is preferable to plan for as many scientific investigations as possible outside the SRF in specialized laboratories, it is scientifically necessary to anticipate the negative effects that sterilization might have on sample integrity, specifically the fidelity of the subsample properties that are to be measured. By understanding potential sterilization effects, a balance may be achieved by allowing science that is minimally compromised by a sterilization method to be sterilized early in the process and to be analyzed by the world's best instruments outside biocontainment.

To determine what sample properties are sterilization-sensitive or sterilization-tolerant, the sterilization effects of two techniques were considered: (a) the application of dry heat under two temperature–time regimes (180°C for 3 hours; 250°C for 30 min) and (b) γ-irradiation (1 MGy). Four categories of science were considered:

1. Extant or recent martian life
2. Biosignatures of past martian life
3. Geological materials
4. Gas samples.

Several types of scientifically important measurements, especially those involving easily volatilized elements and molecules, cannot be made on sterilized samples:

1. No sterilization process could destroy the viability of cells whilst still retaining molecular structures completely intact. This applies not only to the organic molecules of living organisms, but also to most organic molecular biosignatures of former life (molecular fossils). As a matter of biological principle, any sterilization process would result in the loss of biological and paleobiological information, because destroying organic molecules is what sterilization is supposed to do.
2. Sterilization by dry heat at the proposed temperatures would lead to changes in many of the minerals and amorphous solids that are most significant for the study of paleoenvironments, habitability, preservation of potential biosignatures, and the geologic context of life-science observations.
3. Water and the effects of the products of its radiolysis for redox-sensitive chemical species are all adversely affected by γ-irradiation at even sub-MGy doses.

Sample properties that do not survive sterilization intact should be measured on unsterilized samples. If the investigations in question are also time-sensitive, then the SRF would need to provide the capabilities needed to perform these scientific investigations. If the measurements are not time-sensitive then they should be planned for outside of the SRF (Figure 4), if at all possible (Velbel *et al.,* 2022).

MSPG2 Summary Finding #3
Most aspects of MSR sample science could, and should, be effectively performed on samples deemed safe (either by test or by sterilization) in uncontained laboratories outside of the SRF. However, other aspects of MSR sample science would be both time-sensitive and sterilization-sensitive, including the search for life, assessment of habitability, and volatile exchange processes, and would need to be carried out in the SRF.

3.5. The analysis of martian dust (Deliverable #2)

Dust that is lifted into the martian atmosphere is a material of high interest to martian atmospheric scientists, as well as planners for future human missions and some geologists and astrobiologists. The MSR Campaign, as it is presently designed, presents an important opportunity to return dust that has fallen out of the atmosphere by means of airfall sedimentation. The M2020 sample-collecting rover is planning to begin placing sample tubes in cache depots on the martian surface perhaps as early as 2023-24, and they are expected to be recovered by a subsequent mission not

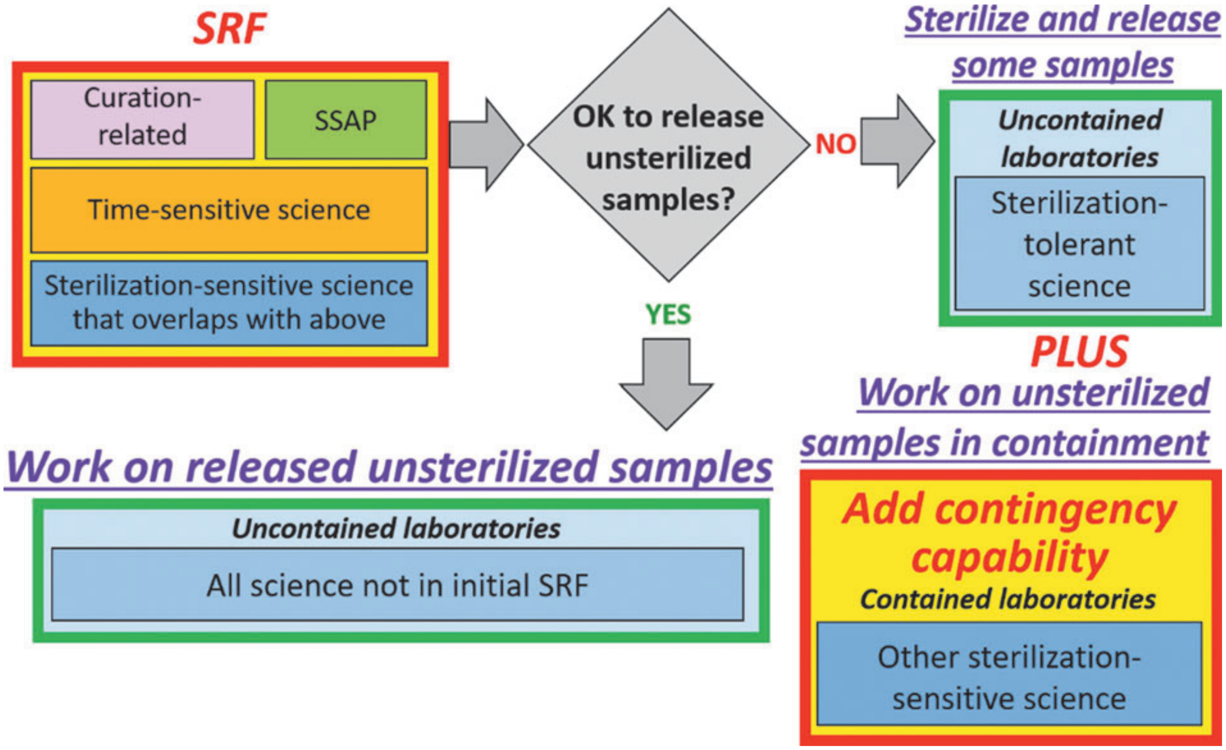

FIG. 4. A key SRF strategy in which the SRF is designed to initially accommodate only the measurements and analyses that cannot reasonably or safely be made outside of biocontainment, including those required for initial sample characterization, the Sample Safety Assessment Protocol (SSAP), and time-sensitive science. Once it is determined whether the samples are free of biohazards, two possible scenarios exist. If it is possible to release unsterilized samples (''YES'' path in diagram), then all other measurements can be made outside the SRF in uncontained laboratories. If it is not possible to release unsterilized samples (''NO'' path in diagram), then most of the remaining measurements can be done on sterilized samples outside of biocontainment, but some capability would be needed for additional sterilization-sensitive science to be done inside biocontained laboratories (modified after Carrier *et al.,* 2022).

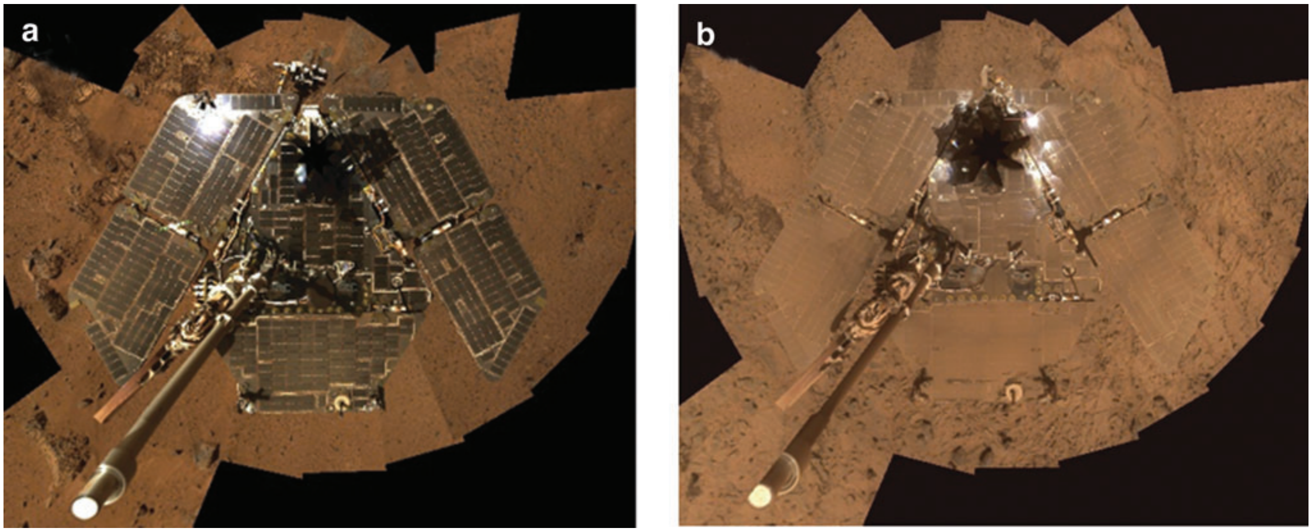

FIG. 5. Two images of the Spirit Exploration Rover taken by its Panoramic Camera **(a)** Sol 586; August 2005 (PIA 03272) (left)(https://photojournal.jpl.nasa.gov/catalog/PIA03272); **(b)** Sol 1355 -1358; October 2007 (PIA 10128) (right) (https://photojournal.jpl.nasa.gov/catalog/PIA10128). Note the accumulation of dust on the rover during the elapsed 2+ years on the martian surface. If the same thing happens to the cached sample tubes, the dust on the outside of the tubes would be of significant scientific interest. (Image Credits: NASA/JPL-Caltech/Cornell).

earlier than 2028-29, and it could be as late as 2030-31. Thus, the sample tube surfaces could passively collect dust for multiple years as demonstrated by the rover Spirit shown in Figure 5. This dust is deemed to be quite valuable scientifically. This dust would inform our knowledge and understanding of Mars's global mineralogy, its surface processes, surface-atmosphere interactions, and atmospheric circulation. Initial calculations indicate that the total mass of such dust on a full set of tubes could be as much as 100 mg, which would be sufficient for many types of laboratory analyses. Two planning steps would optimize our ability to take advantage of this opportunity: 1) The dust-covered sample tubes should be loaded into the OS with as little cleaning as possible and 2) The capability to recover the dust early in the workflow within the SRF needs to be established. A further opportunity to advance dust/atmospheric science using MSR, depending on the design of the MSR Campaign elements, may lie in the area of directly sampling and returning airborne dust (Grady *et al.,* 2022).

3.6. The analysis of martian atmospheric gas (Deliverable #2)

There are several high-priority science questions that can be answered with a sample of martian atmosphere. Furthermore, the composition of the ambient atmosphere provides an important control for the headspace gas over solid samples collected by M2020, which itself would be of significant scientific interest. The headspace gas itself is of limited usefulness for atmospheric geochemistry investigations because the quantity of gas is insufficient for many investigations, and there would be exchange between solid samples and headspace gas (a topic of interest in itself) as well as tube walls. Furthermore, the sample tube materials and their preparation were not designed for optimal collection and storage of atmospheric gas (most importantly, they were not sent to Mars in an evacuated state, so they would have been exposed to both Earth's and Mars' atmospheres before collection), and there is a risk of seal leakage that would allow fractionation of the sample (for a leak out) and contamination (for a leak in).

The overall MSR science return can be significantly improved (and in some cases dramatically so) by adding one or more of several strategies:

1. Have M2020 collect a gas sample in one of its empty sample tubes (volume ∼13 cc)
2. Collect gas in a newly designed, valved, sample-tube sized vessel that is flown on either SFR or SRL
3. Add a larger (50-100 cc) dedicated gas sampling volume to the OS
4. Add a larger (50-100 cc) dedicated gas sampling volume to the OS, fill it with compressed martian atmosphere.

For all the above options, useful science is possible as long as the samples are managed correctly. Importantly, making proper use of headspace gas requires the presence of one of the dedicated gas sample types as an experimental control (*i.e.,* a gas sample that is not in contact with a solid sample). Options for collecting a dedicated gas sample by SRF or SRL should be investigated. If this implementation is not possible, then M2020 should be directed to use one or more sample tubes for collection of an atmospheric gas sample, and a program should be undertaken to investigate the interactions of a similarly processed tube with a simulated martian atmosphere.

3.7. Implications for the SRF (Deliverable #3)

The most important single element of the ground portion of the MSR Campaign is the SRF. The SRF would need to be designed and equipped to enable the following: the ability to receive and house the returned spacecraft; extraction and opening of the sealed sample container; extracting the samples from the sample tubes and; a set of evaluations and analyses of the samples—all under strict protocols of biocontainment, cleanliness, and contamination control (Figure 6). One key open question for planning the SRF relates to the minimum size and cost needed to achieve its performance requirements. This, in turn, naturally leads to the question—what are those requirements?

The SRF needs to be designed to carry out certain curatorial functions associated with maintaining the scientific value of the samples. Protecting the samples from alteration and contamination is a very high priority. The SRF must also be designed to accommodate the range of analytical activities that cannot be done in outside laboratories because they are time-sensitive, sterilization-sensitive, necessary for the Sample Safety Assessment Protocol (SSAP), or are necessary components of the initial sample characterization process (Sections 2.2-2.4). Although one of the guiding principles of our analysis has been that as many scientific investigations as possible should be conducted outside the SRF, we have determined that SRF's laboratory functionality would need to include ∼20-30 scientific instruments, most of which are benchtop size instruments. Some of these would also have associated sample preparation steps. This results in a significant amount of floor space being required for analyses inside biocontainment; however, having the capabilities needed to analyze and allocate the samples correctly is crucial to achieving the scientific objectives of MSR. The final determination of what analytical capabilities are needed may be impacted by which sterilization methods are approved, and could potentially be reduced somewhat if alternative sterilization techniques, such as solvent extraction or gas filtration, are deemed to be acceptable with regards to both planetary protection and science quality concerns.

MSPG2 Summary Finding #4
To meet the unique science, curation, and planetary protection needs of MSR—even with an explicit goal of performing as many MSR sample analyses as possible outside biocontainment—substantial analytical and sample management capabilities would be required in an SRF.

3.8. Key decisions timeline (Deliverable #4)

The notional timelines for key management and interagency level decision points, events, activities, and approvals for the flight elements (M2020, ERO, SRL/SFR), the SRF, the National Environmental Policy Act (NEPA) process, and for science-related items are shown in Figure 7.

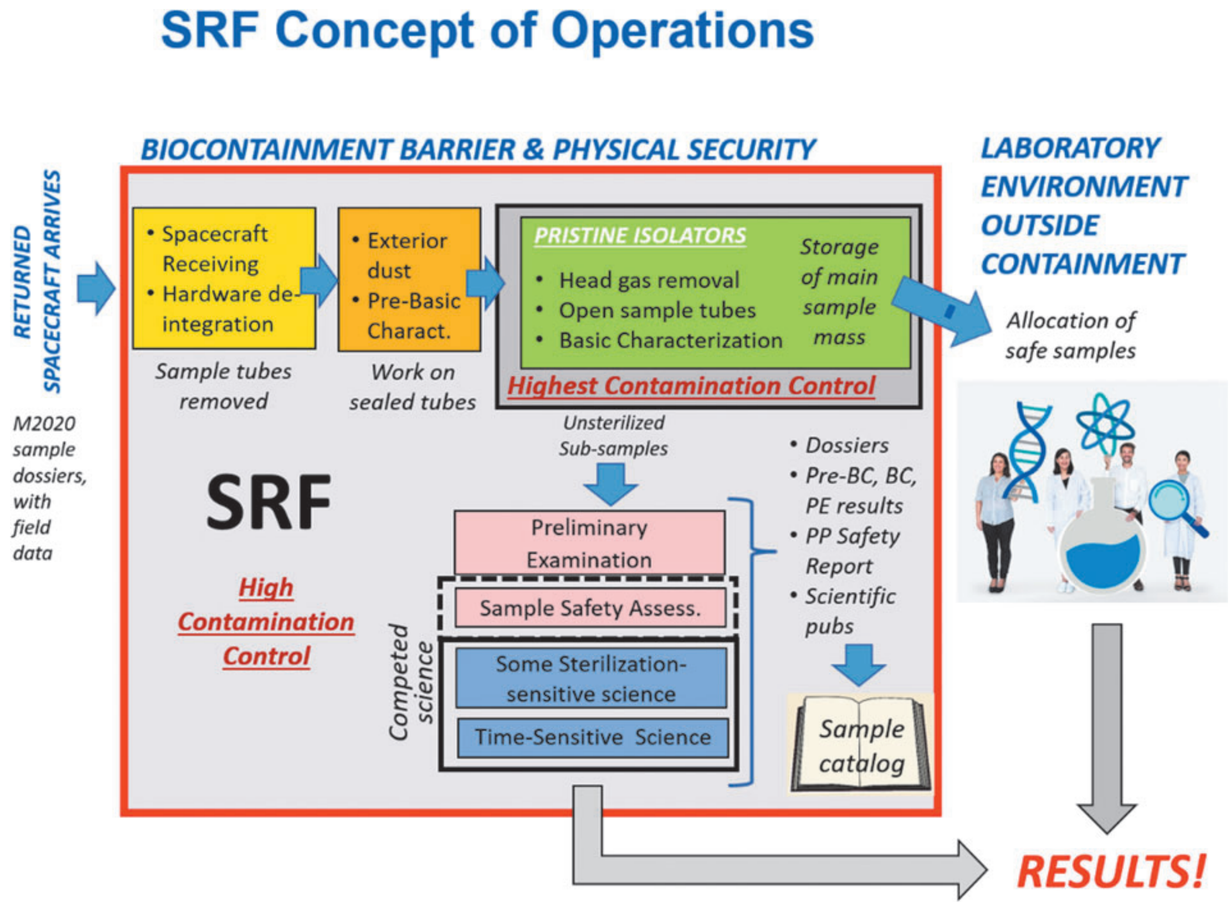

FIG. 6. Schematic diagram showing the key concepts for SRF science-related activities that would need to be done inside biocontainment (Carrier *et al.,* 2022).

Two different scenarios are presented, dependent upon the launch years and years that Mars samples will be returned to Earth. A list summarizing the key decision points is provided below and a longer discussion of the purpose of the timelines and dependencies between different items is provided in Appendix C. The timelines contain a subset of the items that could have been included (*e.g.,* EES recovery was not included) so as to focus on those items that were most relevant to MSPG2 considerations.

A comparison of the two notional timeline scenarios illustrates that a potential two-year delay in the return of the samples does not impact the overall science program planning beyond some shift in the mid-term activities. This is because some MSR Campaign science planning elements are linked to M2020, some are linked to the MSR Program flight elements, and some are linked to the arrival date of the samples on Earth. Note that the timeline with sample arrival at Earth in 2031 has no margin in the current best-estimate SRF development schedule.

The list below includes the management and interagency level items shown in Figure 7 grouped by interagency MOUs, followed by items relevant to the flight elements, and continuing down through items relevant to the science community. Such a list groups related items together even though they may be separated by several years chronologically.

1. Flight Elements MOU (October 2020)—agreement on NASA and ESA respective roles and responsibilities for the flight elements under the Program
2. MSR Science MOU (expected 2021/2022)—agreement on NASA and ESA roles and responsibilities for the MSR science element of the MSR Campaign
3. NEPA Environmental Impact Statement (EIS) process for flight elements (mid-2021 thru mid-2024)—completed for the flight elements (ERO and SRL/SFR), with the resulting NASA Record of Decision determining the path forward, if any, on subsequent timeline milestones
4. MSR SMP (expected 2021/2022)—describes how NASA and ESA develop and manage the MSR Science Program
5. MSR Campaign Science Group 1 (late-2021)—selection of the science team to support the NASA and ESA MSR science leads to implement the SMP
6. Objective-driven Investigation Announcement of Opportunity (AO)—selection of teams that would conduct the objective-driven science analyses (mid-2024 OR mid-2026)—based on an international competitive AO; PIs of the selected science teams would form the MSR Sample Science Team and, together with the NASA and ESA science leads, form the MSR Campaign Science Group 2

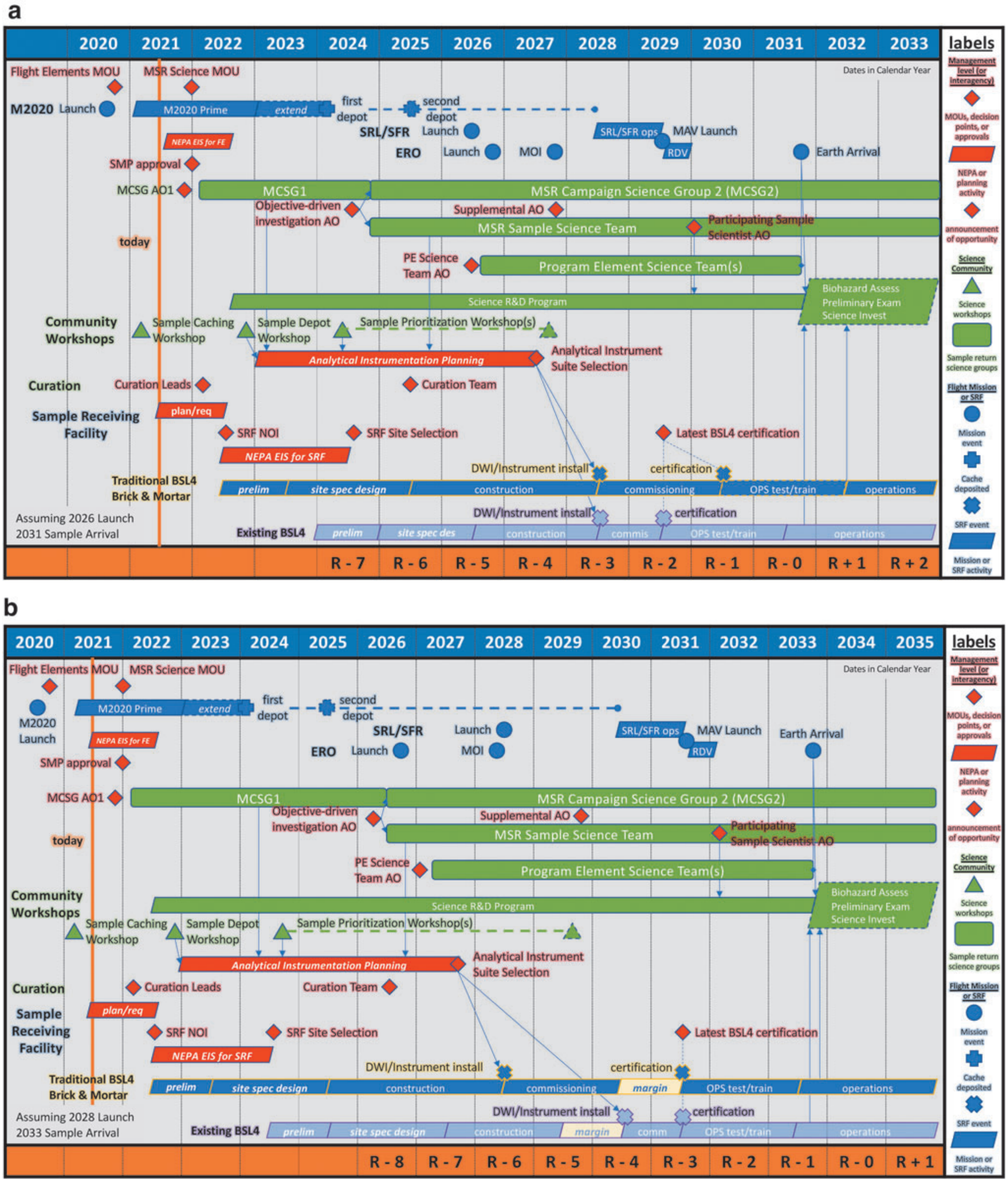

FIG. 7. The notional timeline for major mission milestones and key decision points. The top timeline reflects a 2026 launch for SRL/SFR and a 2031 sample return; the bottom timeline assumes a 2028 launch for SRL/SFR and a 2033 sample return. Dates along the top are calendar year, not fiscal year; dates along the bottom are listed relative to the year of sample return. The same events are included on both timelines, and all events marked in red are described in section 4.8 Key Decisions Timeline. AO, Announcement of Opportunity; BSL, Biosafety Level; CSG, Campaign Science Group; EIS, Environmental Impact Statement; ERO, Earth Return Orbiter; MOI, Mars Orbit Insertion; MOU, Memorandum of Understanding; MSST, MSR Sample Science Team; NEPA, National Environmental Policy Act; NOI, Notice of Intent; OPS, Operations; RDV, Rendezvous; SFR, Sample Fetch Rover; SMP, Science Management Plan; SRF, Sample Receiving Facility; SRL, Sample Retrieval Lander.

7. Supplemental AO (late 2027 OR late 2029)—a second international competitive AO for additional expertise for ‘‘objective-driven science’’ that may be identified after further sampling activities
8. Participating Sample Scientists AO (early 2030 OR early 2032)—selection based on an international competitive AO; individuals proposing novel research investigations unique from those being performed by PI-led teams, but that contribute to overall MSR science objectives
9. Program Element Science Team(s) AO (late 2026 OR early 2027)—selection based on an international competitive AO; select the science teams of the SRL/SFR and ERO missions
10. Analytical suite instrument plan (early-2023 to mid-2027)—determination of instrumentation that would need to be accommodated in the SRF; inputs expected from the MCSG/MSST, Curation leads, and possibly from the Sample Prioritization Workshop(s)
11. Analytical instrument suite selection (at least 3-4 years prior to Earth Return)—selection of final suite of Analytical Instruments, must happen with enough time for installation, commissioning, certification, and operations testing and training for the given SRF design
12. Curation leads in place (TBD; early 2022)—selected as part of MCSG1; the NASA and ESA curation leads support SRF-related planning
13. Curation team in place (TBD; mid-2025 OR mid-2026)—selected as a joint NASA/ESA curation team that supports SRF detailed design and construction
14. SRF Planning and Requirements Definition (mid-2021 to mid-2022)—study of the types and requirements of the SRF in preparation for the Notice of Intent (NOI); key to deciding which type of SRF(s) would be considered
15. SRF NOI (mid-2022)—posting of public NOI in advance of solicitation for proposals to build or design the SRF
16. NEPA process for SRF (mid-2022 to mid-2024)—completion of the NEPA EIS for the SRF
17. SRF Site Selection (mid-2024)—decision of the specific site and architecture option for the SRF
18. SRF commissioning (at least 2 years prior to Earth Return) –the design and construction of the SRF as a biocontainment facility ends with Biosafety Level 4 (BSL-4) certification; start of test and training phase for the SRF functionalities not related to the biocontainment function.

MSPG2 Summary Finding #5

The schedule required to have an SRF designed, constructed, and ready to receive the MSR samples has a longer lead time than perhaps anything previously attempted by NASA/ESA. It is important that preparations begin immediately; a potential delay in the return of the samples does not impact the overall science program planning beyond some shift in the mid-term activities.

4. Conclusions

4.1. *Implications of the MSPG2 findings*

Two significant implications arise from the findings and conclusions of MSPG2:

First, the establishment of a NASA/ESA MSR Science Program, along with the necessary funding and human resources, would enable proper interface management with both M2020 and the design of the sample transportation missions of the MSR Program. Both are currently in a high pace of activity and likely will be for several years. Science considerations must be adequately accounted for in the MSR Campaign, and the interfaces involving the samples must be managed correctly for the potential value of the samples to be maximized. Perhaps just as important, the community needs to be confident that NASA and ESA have a vested interest in the science of MSR.

Second, the merging of high-performance cleanroom operations and BSL-4 containment in a single facility has never been attempted by NASA or ESA before. This would necessarily lead to complex first-of-a-kind curation implementations. The planning lead time for such a facility has some uncertainty, and it may be a significant management challenge in the coming years to avoid underestimating it. Delaying SRF planning could compromise the ability to carry out MSR science in a timely and effective manner. Thus, it is important that preparations begin immediately. Finally, for the SRF to effectively enable high-level MSR science objectives to be achieved, even with the goal of conducting as few analyses as possible inside the SRF, it needs to have substantial laboratory analysis capability to accomplish analyses needed for curation, planetary protection, and time-sensitive science.

4.2. *Key requests of management*

Stemming from the MSPG2 findings and implications, a of the short-term priorities listed below have been identified for NASA and ESA decision makers to act on as soon as is feasible to achieve the scientific objectives of MSR.

1. **Initiate the MSR Science Program**
    - Generate the documented agreements between NASA and ESA to define the end-to-end MSR Science Program (*i.e.,* Science MOU and SMP) and seek the necessary funding and authority to implement them.
2. **Establish the MSR Campaign Science Group**
    - Develop a Terms of Reference, hold a competitive call, perform the selection of the MCSG membership, and provide them with an appropriate budget to carry out their duties.
3. **Fund Research & Development for MSR Preparatory Activities**
    - Utilize and/or augment existing funding mechanisms or develop new mechanisms to support short- and medium-term technical studies required to carry out the MSR Science Program.
4. **Advance SRF Requirements**
    - Near-term action to refine the draft SRF science-related requirements, especially regarding environmental conditions, cleanliness, contamination control,

and priorities; and translate them into an overall curation plan, facility concept, budget and schedule as input into SRF implementation planning.

4.3. Highest-priority recommendations for future work

A listing of all recommendations for future work recognized by MSPG2 is presented in Appendix B. The following five recommendations are deemed to be of highest priority and require a dedicated funding profile through existing or new R&D programs supported by NASA and ESA.

1. Two critical sample-related science-engineering developments are needed that include the methodology to extract the gas samples and the solid samples from the sample tubes without compromising the scientific integrity of the samples. A related development should be the design of a secondary container (*i.e.,* a sample tube isolation chamber) for samples tubes once removed from the OS.
2. Constrain the initial sample storage conditions to fit time-sensitive investigations within a functional sample workflow in the SRF.
3. Define the sterilization methods and parameters that could be approved for use on martian samples, which would include the sterilization-chamber atmosphere and potential non-traditional sterilization methods (*e.g.,* filtration of gas samples, acid hydrolysis of solvent extracts).
4. Refine the draft SRF science-related requirements, especially with regard to environmental conditions and cleanliness contamination controls and priorities, and to translate them into an overall curation plan, facility concept, budget, and schedule, as input into SRF implementation planning.
5. Ensure that the end-to-end environmental conditions of the samples (from before collection on Mars to after receipt in the SRF) are well characterized, whether through direct measurements, numerical modeling, or some combination thereof.

4.4. Final thoughts

Achieving MSR would represent one of humankind's greatest technical accomplishments, with a two-part measure of success—one engineering and one scientific. In addition to the remarkable engineering accomplishments that are required to deliver samples safely from Mars to Earth, the world's scientific community stands to make historic discoveries. With the NASA-ESA partnership now confirmed, and the development of the flight program funded and well underway, it is crucial that the corresponding scientific elements are accorded similar careful and sustained attention that are required to achieve campaign success.

The reports and deliverables provided by the MSPG2 provide a framework to do just that, outlining a comprehensive MSR Science Program and highlighting important considerations for the eventual SRF. With appropriate action taken now, ESA and NASA could enable the safe and appropriate reception and handling of the samples and would ensure their role in providing invaluable scientific opportunities for laboratories around the world and for generations to come.

Acknowledgments

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

Disclosure Statement

No competing interests.

Funding Information

A portion of this work was funded by the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the Canadian Space Agency (CSA).

A portion of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

This work has partly (H. B.) been carried out within the framework of the NCCR PlanetS supported by the Swiss National Science Foundation. M.A.V's participation in MSPG2 was supported in part by a sabbatical leave-of-absence from Michigan State University. M.-P.Z. was supported by projects PID2019-104205GB-C21 of Ministry of Science and Innovation and MDM-2017-0737 Unidad de Excelencia 'Maria de Maeztu'- Centro de Astrobiología (CSIC-INTA) (Spain).

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Acronyms Used

AO = Announcement of Opportunity
BC = Basic Characterization
BSL-4 = Biosafety Level 4
CCM = Capture and Containment Module
CCRS = Capture, Containment, and Return System; a subsystem of the Earth Return Orbiter spacecraft
EES = Earth Entry System; a subsystem of the Earth Return Orbiter spacecraft
EIS = Environmental Impact Statement
ERO = Earth Return Orbiter; a spacecraft managed by ESA that is part of the MSR Program.
ESA = European Space Agency
iMars = International Mars Architecture for Return of Samples
iMars-2 = Phase 2 Architecture and Management Plan for Return of Samples
iMOST = International MSR Objectives and Samples Team
M2020 = Mars 2020; A NASA mission launched in July, 2020 and landed on Mars in Feb. 2021. The primary system is a sample-collecting rover named Perseverance.
MAS = Mars Ascent System
MCSG = MSR Campaign Science Group
MOI = Mars Orbit Insertion
MOU = Memorandum of Understanding
MSPG = MSR Science Planning Group
MSPG2 = MSR Science Planning Group 2
MSR = Mars Sample Return
MSST = MSR Sample Science Team
NASA = National Aeronautics and Space Administration
NEPA = National Environmental Policy Act
NOI = Notice of Intent
OS = Orbiting Sample Container
PCV = Primary Containment Vessel; a subsystem of the Containment and Return System
PE = Preliminary Examination
Pre-BC = Pre-Basic Characterization
SCV = Secondary Containment Vessel; a subsystem of the Containment and Return System
SFR = Sample Fetch Rover
SMP = Science Management Plan
SRF = Sample Receiving Facility
SRL = Sample Retrieval Lander; a spacecraft managed by NASA that is part of the MSR Program.
SRW = Scientifically Return-Worthy
SSAP = Sample Safety Assessment Protocol

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Appendix A MSPG2 Terms of Reference

Terms of Reference

Mars Sample Return Science Planning Group-2 (MSPG-2)

Introduction. Following several years of discussions, in April 2018 NASA and ESA signed a Joint Statement of Intent regarding Mars Sample Return (MSR), documenting their wish to pursue joint planning for a partnership to transport some or all of the samples to be acquired by the Mars 2020 sample- collecting rover to Earth. A fundamental premise of the partnership is that competed and selected d scientists would equitably share access to the samples for collective scientific benefits and discoveries, as outlined in the NASA-ESA Joint Statement of Intent on MSR science benefits signed in July 2019. As one component of that planning, the MSR Science Planning Group (MSPG) was jointly chartered by NASA and ESA in late 2018 to develop 1) several key technical inputs to MSR science planning, by means of two workshops, and 2) a *Framework for Mars Returned Sample Science Management* (MSPG2, 2019c). This planning material was delivered in October 2019 (https://mepag.jpl.nasa.gov/reports.cfm?expand=mspg), and supported the decision process at ESA with the 2019 November Council meeting at ministerial level (Space19+) and the NASA annual budgeting process (President's Budget FY2021). Both ESA and NASA have allocated substantial budgets to support further development of an MSR partnership.

Given the extensive work done by the MSPG, under the leadership of NASA and ESA representatives, and the feedback associated with the budgetary processes described above, it is now time to follow up and 1) develop the MSR Science Management Plan, using the guidelines in the ''Framework'' document, 2) address the highest priority open technical planning questions identified in the 2019 MSPG workshop reports, and 3) delineate the options and decision points for managing samples returned from Mars, from landing on Earth through analyses in the SRF and other potential facilities. The MSPG-2 will recommend requirements intended to maximize the science return of the sample collection. These follow-up planning activities specifically need to incorporate curation and Planetary Protection.

Assumptions

1. The scientific objectives of MSR are comprehensively described by iMOST (Beaty *et al.,* 2019).
2. Facility plans include the following:
   a. A biological containment and curation facility equivalent to a Biosafety Level 4 (BSL-4) Sample Receiving Facility (SRF) in the U.S. This facility would be responsible for the initial receipt of all returned flight hardware, including the samples. Within the SRF the Earth Entry System (EES) would be opened, and the samples extracted. This primary SRF would provide sample containment until such time as the samples are transferred (under containment) to another equivalently rated facility or are deemed safe for use in laboratories without containment. Scenarios involving a second containment facility in Europe may be under consideration by the MSR campaign partners, but it is not necessary to specify an assumption in this area for the purpose of this ToR
   b. In addition to the biological containment and curation in the SRF, curation facility(s) without containment may exist in the U.S. or in Europe for samples determined to be safe. Knowledge of the final locations of curation facilities is not relevant/necessary for the purpose of the activities described in this ToR.
   c. Scientists from around the world will desire access to samples in containment and eventually, if safe, access to samples transferred out of containment for analysis in their own laboratories.
3. The decision on where to locate the U.S. SRF, and as appropriate a potential European facility, will be determined at a later time.
4. Delineating specific laboratory research or instrumentation will not be part of this activity, although the scope of the needed measurements will be.
5. The framework established by MSPG (*A Framework for Mars Returned Sample Science Management*), will serve as the foundation for the Science Management Plan. The Framework document considers and incorporates prior work, specifically including the important antecedent work that was completed by iMARS-2 and iMOST.
6. Personnel who will have worked on MSPG-2 will be eligible to work on later aspects of MSR.

Statement of Task. MSPG-2 will address MSR science and curation planning questions for which the specifics and the schedule will determined by the NASA and ESA leads. These questions may include, but not be limited to, the following topics:

1. Inputs to the ''Science Management Plan*.'' The MSPG-2 is expected either to adopt the MSPG recommendations, or to propose suitable alternatives, regarding science management planning issues. The scope of this task could include, but not necessarily be limited to, the following:
   A. Amplify the planning descriptions of the bodies & processes described in the ''Framework'' document, Section 4.
   B. Define the interfaces, organizational relationships, and communication pathways between science, curation, Mars 2020, facilities planners, and planetary protection.

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2. Technical issues related to the science of MSR and how the implementation of MSR impacts the potential scientific usefulness of the samples. The technical issues considered may include, but are not limited to:
    A. Sample sterilization, including consideration of the effects of sterilization on the science as well as implications for the SRF.
    B. Use of penetrative imaging (synchrotron imaging or CT scanning) on the sample tubes before they are opened.
    C. As needed, propose quantitative sample quality-related requirements for the transport/handling of the samples during the MSR flight campaign.
3. Develop approaches and a working list of high-level requirements for the SRF that can be used in cost estimation and budgeting. The requirements specifically need to represent the needs and interests of each of science, curation, and planetary protection. All proposed requirements need a justification statement.
4. A list of key decision points related to the Mars returned samples with inputs from science, curation, and planetary protection, and represent them on a master timeline.

Operating Procedures

These issues would be addressed by means of convening representatives from the scientific community, conducting workshops, and regular telecom and e-mail discussions. Emphasis is placed on the responsibility of this group to represent the view of the international science community and other stakeholders of Mars Sample Return science output.

It is expected that MSPG-2 will begin its work as soon as possible after May 31, 2020. MSPG- 2's leadership is asked to:

A. Identify and prioritize the specific tasks that need MSPG-2's attention.
B. Propose a realistic schedule for the delivery of interim results as well as the delivery of final products for each task assigned. Assume that interim briefing(s) will be supported by a PPT-formatted presentation file(s), and that the final results will be delivered as one or more text-formatted reports with accompanying PPT presentation file(s).
C. Formulate strategies to maintain engagement with the science research community during this early planning period.

MSPG-2 is expected to document the results of all of the topics that it takes up in the form of written reports.

Logistics

- Co-chairs will consist of NASA and ESA representatives.
- The implementation support will be provided by the ''MSR Office'' at JPL, and sponsorship by NASA and ESA.
- For reasons of both cost and time, it is expected that most of the MSPG-2's work will be carried out using e-mail and teleconferences. However, it is hoped that two face-to-face meetings will be scheduled in 2020. If circumstances permit, the team will be encouraged to take advantage of opportunities to meet when most/all of the team will be in the same place at the same time (e.g. at major conferences).
- As needed, task groups can be commissioned to address specific issues within the scope of the MSPG-2
- MSPG-2 is expected to complete its work by a draft date of April 30, 2021.

Lori S Glaze

1 April 2020

Lori S. Glaze, Ph.D. Date

Director

Planetary Science Division NASA Headquarters

Francois Spoto 2020.04.02 11:09:15 +02'00'

Mr. Francois Spoto Date

Martian Programme Group Leader (acting)

Directorate of Human and Robotic Exploration (D-HRE) European Space Agency

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*The Science Management Plan is an MSR Campaign document that encompasses the science requirements and management for handling, containment, and distribution of the returned samples.

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Appendix B Recommendations for Future Work

Research and Development Needs

Engineering

Determine the best way to extract headspace gas from sample tubes, taking relevant sample quality considerations into account.

Develop systems for extracting solid samples from the sample tubes while minimizing contamination and retaining stratigraphic information and fine-scale features.

Design a sample tube isolation chamber (*i.e.,* secondary container for sample tube storage prior to opening the OS).

Initiate technology and work-process development work to support capture and characterization of the volatile byproducts generated during the sterilization process.

Develop deep ultraviolet fluorescence spectroscopy instrument as currently available commercial instruments are not optimized for MSR needs.

Develop methods to check the integrity of the seals, including the sample tubes as well as the PCV and SCV of the returned spacecraft.

Science Planning

Define the optimal sample workflow to be able to conduct time-sensitive scientific investigations within the SRF.

Constrain the timescales over which analogous samples (*e.g.,* cores of lithified sedimentary rocks) exchange volatiles with ambient surroundings. This should involve, for example, monitoring chemical/mineralogical changes over time.

Ensure that the end-to-end environmental conditions of the samples (from before collection on Mars to after receipt in the SRF) are well characterized, whether through direct measurements and images, numerical modeling, or some combination thereof.

Investigate the effects of high resolution X-ray tomography (HR-XCT) on organic/microbial specimens.

Sample Sterilization

Define the sterilization methods and parameters that will be approved for use, including the sterilization-chamber atmosphere and evaluate the use of potential non-traditional sterilization methods such as filtration of gas samples and acid hydrolysis of solvent extracts.

Investigate the effects of sterilization on the macromolecular biological components of geological materials.

Investigate the effects of sterilization on amorphous solids, poorly crystalline glasses, and oxides.

Investigate the effects of perchlorates and other oxidants on the behavior and destruction rates of key biological macromolecules during sterilization.

Evaluate the attenuation of gamma-rays through gas sample vessel walls for both confirmation of sterilization efficacy and concurrent modification of gaseous molecules' properties and isotope systems.

Evaluate methods to safely isolate and contain unsterilized sample aliquots for analysis outside the SRF (*e.g.,* biocontainment within X-ray transparent materials).

Establish a testbed in an uncontained laboratory environment to experiment with final/approved sterilization methods to better understand the anticipated effects of sterilization on the MSR samples.

Refinement of SRF Requirements

Define environmental, cleanliness, contamination control requirements for the SRF.

Further develop approaches, requirements, and techniques related to the extraction, storage, sterilization, and analysis of martian headspace gas samples.

Develop technical requirements for instruments needed in the SRF, sufficient to form the basis for a competitive procurement.

Define further necessary sample preparation capabilities in the SRF.

Evaluate the need/priority for redundant instruments in the SRF.

Define expectations for the timescale at which samples will be evaluated for safety and put through the initial sample characterization process and made available for allocation, which will have an impact on SRF footprint, design, and staffing.

Expand the work of the MSPG2 in the area of SRF design requirements into SRF operations requirements.

Sample Handling and Workflow Optimization

Develop a contamination control and knowledge plan, including contamination control measurement and verification protocols for tools, containers, and other equipment.

Evaluate the possibility of using robotics and remote manipulation systems both inside and outside atmosphere and gas isolators. Determine whether micromanipulators could be constructed of materials compliant with Contamination Control requirements inside isolators.

Determine how much material will be reserved for the future (previous assumption has been 40%), and how this retained material will be selected.

Determine the best way to remove the dust from the outer surfaces of the sample tubes and OS interior hardware surfaces, without disturbing the samples within the tubes.

Determine the best curation gas for isolators.

Define the controlled list of materials allowed in the pristine isolators.

Conduct a risk assessment for the risks related to keeping all the samples in one location.

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Appendix C: Notes Regarding the Timeline

C-1 Purpose of the timelines

In response to the statement of task for this activity, a timeline of key decision points was developed that reflects the timelines of the flight elements (M2020, ERO, SRL/SFR), the SRF, the NEPA process, and the science management. Two versions were created—both containing the same items and represented with the same symbols—to reflect how some of these would shift for a 2026 launch of SRL/SFR and a 2031 sample arrival to Earth versus a 2028 launch and a 2033 arrival.

Both timelines include key mission milestones that help to establish the relative timepoints for the associated activities and decisions that reflect the needs of returned sample science. These should serve as a reference for NASA and ESA management to identify key decision points and the likely timing and duration of required funding, as well as for the science community to identify opportunities in the coming years for participation in this endeavor. At the highest level, international or interagency partnerships or agreements that need to be established are listed. Also included are the establishment of Announcements of Opportunity (AO) and decisions relating to those or decisions regarding sample selection or infrastructure that need to be made. Finally, points where funding needs to be in place to support individual roles or multiple modalities for building infrastructure construction and operations are also included. Note that, while some of these milestones are set external to the MSPG2 group (*e.g.,* those associated with the various missions), others are based on the recommendations in this report (*e.g.,* the MSR Campaign Science Groups outlined as part of the SMP). However, these timelines contain only a subset of the items that could be included, and some items (*e.g.,* Earth Entry Vehicle recovery training and operations) are not included in order to focus primarily on those that were part of the MSPG2 activity. Note that the timeline with a sample arrival on Earth in 2031 has no margin in the current best-estimate SRF development schedule.

C-2 Description of the timelines

Memoranda of understanding. At the top of the timelines, in red diamonds, are two memoranda of understanding between NASA and ESA. The first, Flight Elements MOU (signed October 2020), is an agreement on the respective roles and responsibilities of NASA and ESA for the flight elements under the program. The second, the MSR Science MOU, is expected to be signed in late 2021 or early 2022 and will serve as an agreement on NASA and ESA roles and responsibilities for the MSR science element of the MSR Campaign. These dates are not expected to change with different launch or arrival dates. Further discussion of these MOUs can be found in the SMP section of this report (section 3.1).

Flight elements. Important milestones for the different elements of the campaign, including the Mars 2020 mission, the SFR, the SRL mission, and the ERO mission are shown in blue. Most milestones are shown either as circles (including launches, Mars Orbit Insertion (MOI), and Earth arrival), crosses (cache deposition(s) on the surface of Mars with a range of time for the potential deposition of the second depot indicated by a dashed line), or parallelograms for activities that happen over a range of time (*e.g.,* surface operations for the SRL and SFR, and Mars Ascent Vehicle (MAV) launch and ERO rendezvous (RDV)). Although it is not guaranteed that the Mars 2020 mission will have an extended mission, a cache will be deposited before the end of its qualified lifetime. Also on this level, indicated by a red parallelogram, is the time period for the NEPA Environmental Impact Statement process for the SRL/SFR and ERO elements, with the assumption that both missions could be covered in the single process. Obviously, there are differences between these items in the two timelines.

Science Management Plan. The approval of the Science Management Plan that describes how NASA and ESA will develop and manage the MSR science program is expected to happen around the same time as the MSR Science MOU and, as with other major management level approvals, is shown as a red diamond on both timelines.

Science community: Teams and workshops. The operational periods for three different science teams are shown in green bars with rounded edges on the timeline, along with the respective AOs (as red diamonds) for international scientists to become members of these teams. Beneath this green bar is a green parallelogram that outlines the Science R&D program. The MCSGs 1 and 2, the MSST, and the Program Element Science (PES) Team(s) and the Science R&D program are all described in more detail in the SMP section of this report (Section 4.2 and 4.3). A second green parallelogram represents the earliest science activities on the returned samples, which include sample safety assessment, initial sample characterization, and science investigations. These early activities are discussed in much more detail in sections 4.2-4.4 of this report. Some of these science community groups need to begin soon, as there are long lead-times for their activities, and others are dependent on flight element launch dates or sample arrival dates and would be expected to change between the two timelines.

In the first timeline, with a 2031 sample arrival, the MCSG1—the science team that supports the NASA and ESA MSR science leads implementing the SMP—would be expected to start around the same time as the SMP approval (in early 2022), with the MCSG AO1 coming out just before the SMP approval is expected (in late 2021). The Objective-driven investigation AO—an international competitive AO to select teams that will conduct the objective-driven science investigations—would be expected approximately two years later (in mid 2024). These teams would become the MSR Sample Science Team (MSST), with the PIs joining MCSG2 (both initiated late 2024). If needed, a Supplemental AO to address any different sample analyses needs with regard to samples collected later in the Mars 2020 mission would take place about three years later (in late 2027) around the same time as ERO MOI. The Participating Sample Scientist AO, for individuals proposing novel research investigations that are unique from those of the PI-led teams, would come out approximately 1.5 years before samples would be expected to arrive at Earth, around early 2030. The Program Element Science Team AO (in

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mid 2026), an international call for the science teams of the SRL/SFR and ERO missions, would come out shortly before those launches, and the Program Element Science Team(s) would start in late 2026. The Science R&D program would come from the roadmap generated by the MSCG1 team, in late 2022, and would serve to identify critical open trades to be addressed by science investigations that would then be incorporated into further planning for sample return.

In the second timeline, with a 2033 sample arrival, the MCSG AO1 and the MCSG1 would be expected to have the same schedule as in the earlier timeline, but would run for closer to four years, with the Objective-Driven Investigation AO just before the ERO launch in early 2026, the supplemental AO in late 2029 (at least six months before SRL/SFR landing and operations), and the MCSG2 and MSST both starting in mid-2026. The Participating Sample Scientist AO would still be dependent on the sample arrival date and therefore would be expected to come out in early 2032. The PES Team AO would also be delayed, to early 2027, and the PES Team(s) would be expected to start in mid-2027. Even with a later launch and arrival date, the Science R&D roadmap would not be expected to be delayed and would start in late 2022.

Three science community workshops, which provide opportunities for a wider range of the science community or the public to participate in the MSR campaign, are included as green triangles. The first, the MSR Sample Caching Workshop, was run by the Caching Strategy Steering committee on January 21, 2021 (CSSC, 2021). The Sample Depot Workshop and Sample Prioritization Workshop(s) (listed as a single event but might be either more or fewer than that) would be opportunities for a broader community to provide input into decisions regarding which samples, after they have been collected by the Perseverance rover, would be made available for later collection and return. These workshops are described in more detail in the Science Management Plan section of this report (section 4.4). Since these workshops are more closely tied to the activities of the Perseverance rover, they would be expected to have no difference between the timelines—with the Sample Depot Workshop expected in late 2022, near the end of the Mars 2020 prime mission, and the first Sample Prioritization Workshop(s) in mid-2024, once the first cache was deposited. Since additional Sample Prioritization Workshop(s) may be held, a dashed green line ending in a dashed triangle indicate the range of times and the latest date for these workshops. These latest dates are different on the two timelines and correspond, on each, to just before the Supplemental AO for Objective-Driven investigations, mid-to-late 2027 on the 2031 arrival timeline and mid-to-late 2029 on the 2033 arrival timeline.

Analytical Instrument Planning. The Analytical Instrumentation Planning, represented by a red parallelogram, and the selection of the Analytical Instrumentation Suite, represented by the red diamond, are located on the timeline beneath the science community activities and above the curation and sample receiving facility, which reflects that these activities receive input from a number of science community workshops as well as from a number of the science teams. These activities will provide input on the selection of the instruments that will ultimately be installed in the SRF. The Analytical Instrument Planning activity incorporates multiple aspects related to instrumentation for the SRF, including planning for these in the SRF, the design of the specific instruments to be used, and fabrication and installation into the SRF. In both timelines, this planning would start sometime shortly after the Sample Depot Workshop (in early 2023) and run until instrument selection, which would ideally happen one year prior to the instrument installation (mid-2027).

Curation. The Curation section of the timeline includes major decision points and activities that are expected as part of the Curation Plan recommended by the Curation subgroup of MSPG2, though these are not specifically described in the ‘‘Planning for the curation of MSR samples in a Sample Receiving Facility’’ section of this report. The selection of Curation Leads, who will be part of the MCSG1 group, would happen in early 2022 (shortly after SMP approval) in either timeline, and is a key interagency milestone that precedes many of the downstream planning activities for the SRF instrumentation and design. Later, after the Objective-driven investigation AO, but before the Analytical Instrumentation Plan, the selection of the full Curation team to support detailed design and construction of the SRF will complete the personnel working on the curation of samples. The selection of this team would happen in mid-2025 for the 2031 sample arrival timeline and mid-2026 for the 2033 timeline.

Sample Receiving Facility. For the Sample Receiving Facility section of the timelines, the items on top in red are those that apply to whatever type of facility is selected, and below in blue are two (of the four identified) possible SRF types. The planning and requirements definition for the SRF, indicated by a red parallelogram, is the first stage and should begin immediately, and is expected to be completed in about one year. Once the requirements for the SRF have been defined, a public NOI should be issued, marked with a red diamond in mid-2022, in advance of the solicitation for proposals to build or design the SRF. At the same time, the NEPA Environmental Impact Statement process for the SRF, marked with a red parallelogram, should begin and is expected to last for two years. At the end of this two years, the decision of the specific site and architecture option for the SRF should be finalized, a point marked with a red diamond in mid-2024. The final item at this level is the red diamond, which marks the completion of the SRF commissioning phase, when the SRF can operate as a biocontainment facility and has acquired BSL-4 certification; this is considered the latest date for the BSL-4 certification to allow the recommended two-year test and training phase prior to the sample arrival for the SRF functionalities not related to the biocontainment function. This point would be either in mid-2029 for a 2031 sample arrival or mid-2031 for the 2033 sample arrival.

At the bottom of the timelines are two rows of blue parallelograms of various stages of SRF construction that correspond to a new traditional BSL-4 brick-and-mortar facility or the use of an existing brick-and-mortar BSL-4 facility—the two options with the longest and shortest development timelines. The novel modular BSL-4 approach or a hybrid combination of brick-and-mortar, modular, and existing BSL-4 facilities approach have development timelines in between these two end-members and are therefore not included here. The elements of these two approaches are based on data collected in the NASA Tiger

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Team RAMA report ''Tours of High-Containment and Pristine Facilities in Support of Mars Sample Return (MSR) Sample Receiving Facility (SRF) Definition Studies'' (Mattingly *et al.,* 2020). For both of these potential SRF designs, there are blue parallelograms that represent different phases as follows: the preliminary design, the site specific design, construction, commissioning, operations testing and training, and operations. These range from one to three years, depending on the specific phases and the type of SRF that is selected. In both the 2031 and 2033 sample arrival timelines, the preliminary design phase of the Traditional BSL-4 Brick & Mortar will need to start as soon as the planning and requirements definition identifies that this would be the SRF approach that is best, with the site-specific design phase in tandem with the NEPA EIS process, and subsequent phases following successively. In the 2031 sample arrival timeline, the end of the recommended two-year operations testing and training would overlap the sample arrival. In the 2031 sample arrival timeline, the Existing BSL-4 preliminary design phase could begin a bit later, in early 2024, but would still have to occur in tandem with the end of the NEPA EIS process to complete the two-year operations testing and training by the time that the samples arrive. In the 2033 sample arrival timeline, a year of margin (noted in a yellow parallelogram) has been added to both the Traditional BSL-4 Brick & Mortar and the Existing BSL-4 options, at different phases of their development where this margin is expected to be most likely given the different types of problems that may arise in the development of the different SRF options.

Timeline element dependencies

Most dependencies between related activities are indicated by proximity or directly sequential items along a horizontal axis. Dependencies between items in different horizontal rows are indicated by diagonal arrows that cross the timelines. All the dependencies discussed below are the same on both the 2031 and 2033 Earth arrival timelines. A potential delay in the return of the samples does not impact the overall science program planning beyond some shift in the mid-term activities; this is because some MSR Campaign science planning elements are linked to M2020, some are linked to the MSR Program flight elements, and some are linked to the arrival date of the samples on Earth.

The Analytical Instrument planning is key to several dependencies in both timelines, both as an activity that is dependent on other items in the timeline, and as one that other items depend upon. For example, this planning will be dependent on a science traceability matrix from the MCSG1, but the planning will also serve as input for the Objective-Driven investigation AO to select the MSR Sample Science Team, which will, in turn, help to finalize the Analytical Instrument planning. Additionally, input from intermediate steps in this planning will be important to different stages in the SRF design and construction, and the output from the Analytical Instrument planning. The selection of the Analytical Instrument Suite must be completed before these instruments can be installed in the SRF, which must happen before commissioning.

Another dependency in the timelines, not explicitly called out with an arrow, regards the number of samples that are collected by the Mars 2020 mission and how many deposits of samples are made. If the Perseverance rover collects fewer samples than can be returned by later missions and deposits all samples in a single location, then there is no need for a sample prioritization workshop. Conversely, if there are more samples collected than can be returned, and if they are deposited in more than one location, then multiple Sample Prioritization Workshops may need to be held. The Sample Prioritization Workshop(s), in addition to the Sample Depot Workshop, will also serve as input into the Analytical Instrument planning, since the type and number of samples will be important for determining the instruments that will be needed for their analyses. Finally, the first Sample Prioritization Workshop will need to take place prior to the Objective-Driven Investigation AO, so that the types of initial sample analyses can be proposed based on the samples to be returned, the latest Sample Prioritization Workshop (if necessary) taking place prior to the Supplemental AO for the same reason.

The arrival of the samples at Earth is also a crucial point with many dependencies and marks a number of endings and beginnings of other items on the timeline. Once the samples have arrived, it will likely mark the end of both the Program Element Science Team(s) as well as the Science R&D program. It will also likely be a transition in the SRF from the operational testing and training period to the operational period when the Biohazard Assessment, the Preliminary Examinations, and Science Investigations will begin.