National Aeronautics and
Space Administration
Headquarters
Washington, DC 20546-0001

November 10, 2020

Reply to Attn of: Science Mission Directorate

Summary of NASA Responses to Mars Sample Return Independent Review Board Recommendations

Mars Sample Return (MSR) is a highly complex and ambitious program of national importance. As noted by the MSR Independent Review Board (IRB), it is one of the most technically difficult and operationally demanding robotic space missions ever undertaken. The MSR IRB's non-consensus report highlights this complexity and importance in laying out their observations, findings, and recommendations. The IRB recommends that NASA proceed with this important program and their detailed recommendations will inform the decisions we make moving forward to maximize MSR's success.

The IRB fully met the scope of its review as laid out in the Terms of Reference, identifying a variety of critical cross-cutting factors across MSR's organization and management, science priorities and integrated operations, technical approach, and schedule and cost. NASA accepts the intent of all the IRB's recommendations. These are included in full below (in italics), and are followed by NASA's response (in bold) to each recommendation.

Our responses indicate the steps SMD has already begun taking to coordinate with our internal and external stakeholders, including our partners at the European Space Agency, to implement the IRB's recommendations.

I want to thank the IRB Chair, Mr. Dave Thompson, and the experienced board he pulled together for their work to produce this comprehensive and rigorous review while meeting the constraints of a challenging eight-week timeframe. The IRB's independent analysis provides us with valuable, thought-provoking insights as we take the necessary steps to realize this ambitious mission, the hallmark of the groundbreaking work we do at NASA.

Thomas
Zurbuchen

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Zurbuchen
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Thomas H. Zurbuchen, Ph.D.
Associate Administrator,
Science Mission Directorate

NASA's Responses to the MSR IRB Recommendations

The IRB recommends that the MSR program proceed.

NASA Response: NASA concurs with this recommendation. NASA wishes to thank the IRB for the significant amount of time and energy that the Board Chair and members put into this independent investigation. Doing this review much earlier than past practice has made this Program stronger.

A. Organization and Management

A-1: NASA and the European Space Agency (ESA) should scrutinize their normal business practices to identify adjustments needed to maximize program success, including using common management information and integrated schedule tracking and risk management tools.

NASA Response: NASA concurs with this recommendation. The Program Office will work with supporting NASA Centers and our ESA partners to ensure there is an ability to assimilate data necessary to understand program status and to facilitate a common understanding of risk.

A-2: ESA should establish a small office at the Jet Propulsion Laboratory (JPL) and NASA should establish a similar office at the European Space Research and Technology Centre (ESTEC) to enhance MSR communications and problem resolution.

NASA Response: NASA concurs with this recommendation. Discussions to co-locate personnel from ESA and NASA are in progress.

A-3: The Program should conduct an independent assessment by NASA and ESA experts of the Sample Transfer Arm (STA) end-to-end design, development and programmatics in order to determine the lowest risk/highest reliability path forward.

NASA Response: NASA concurs with this recommendation. During Phase A NASA and ESA will conduct a review to ensure a low-risk, high-reliability implementation approach for the STA.

A-4: NASA should conduct an independent assessment of all available Center resources at the Goddard Space Flight Center (GSFC) and JPL, including in the analysis the option of industrial contracting of other MSR elements, such as the SRL, if necessary to achieve the best balance of technical capabilities and institutional capacity.

NASA Response: NASA concurs with this recommendation to conduct an independent assessment of resource availability and the possibility of contracting other MSR elements.

A-5: Simplify and clarify NASA Center organizational roles to the maximum extent possible, including the following steps:

- **Unify full Capture Containment Model (CCM) subsystem responsibility where possible and maintain tightly integrated plans for interface control and on-time delivery of flight hardware**

- **Contract the Earth Return Module (ERM) and Mars Ascent Vehicle (MAV) to companies with strong related experience**
- **Limit Ames Research Center (ARC), Langley Research Center (LaRC), and Glenn Research Center (GRC) to technical advisory roles without flight hardware delivery responsibilities.**

NASA Response: NASA partially concurs with this recommendation. NASA will review Center roles, responsibilities, and procurement approaches to streamline and clarify interfaces and ensure MSR implementation benefits from established capabilities across the Agency and industry.

A-6: Involved NASA Centers must recognize the customer/supplier relationships they have to JPL and GSFC and manage, report and resolve problems within this framework.

NASA Response: NASA concurs with this recommendation. Agency management has vested program and project responsibility in JPL and GSFC. All participants understand this and have committed to resolve challenges within this structure.

A-7: Consolidate MSR and Mars 2020 (M2020 or Perseverance) under the NASA HQ MSR Program Director.

NASA Response: NASA partially concurs with this recommendation. During Phase A NASA will conduct a review of the organizational structure to ensure that M2020 operations are executed in alignment with the Mars Sample Return mission with sampling as the highest priority for M2020.

A-8: The IRB strongly recommends that Class A/Category 1 standards be applied to all aspects on the MSR program.

NASA Response: NASA concurs with this recommendation. The Program will be planned as a Class A implementation consistent with recent planetary science large strategic missions and will be focusing effort early in Phase A on an NASA Procedural Requirement (NPR) 8705.4 compliance philosophy.

B. Science Priorities and Integrated Operations

B-1: A scientific advisory team (or dedicated subgroup) for both M2020 and MSR should be formed immediately and integrated into operations planning. The membership of this team should include leading sample analysis and mission operations experts.

NASA Response: NASA partially concurs with this recommendation. The selection of Return Sample Science (RSS) Participating Scientists as part of the Perseverance science team will fulfil the role of an integrated scientific advisory team. This group, which includes representation from both NASA and ESA, is part of the science team that will determine the course of the Perseverance science investigation and which samples to collect. The steering group of the science team (the Project Science Group) is composed of the Principal Investigators from each instrument and two representatives from the RSS group. They are led by the Project and Program scientists. Furthermore, a Memorandum of Understanding is in development that will coordinate and inform M2020 operations and MSR design. A science community workshop is planned in January 2021, engaging leading sample analysis and mission operations experts *from M2020 and MSR, to deliberate on the strategy for caching samples, including factors such as whether and when to take duplicate samples, where to place the depot(s), and which samples to leave on the surface or keep on Perseverance. The workshop results will inform the MOU and serve as a guide for the Return Sample Scientists.*

B-2: Science operational decisions for M2020 after its landing should reflect sample acquisition as the dominant science priority.

NASA Response: NASA concurs with this recommendation. In September 2020, NASA Headquarters (HQ) gave the M2020 Project direction specifying that collection and documentation of a diverse sample cache is the top priority of Perseverance surface operations. The Project is proceeding in accordance with this direction.

B-3: In all sample acquisition and transport phases, careful attention should continue to be focused on backward planetary protection requirements and sample handling for scientific validity.

NASA Response: NASA concurs with this recommendation. The MSR Program is proceeding in this manner and has focused significant attention on backward planetary protection and sample integrity over the past several years.

B-4: Campaign-level baseline and threshold success criteria for sample return (including number of sample tubes and diversity of sample types) should be documented.

NASA Response: NASA concurs with this recommendation. MSR Baseline and Threshold success criteria will be specified in the Program Level Requirements Appendix (PLRA) before the Key Decision Point-B (KDP-B) milestone.

B-5: Reference scenarios should be developed for M2020's sample caching strategy (when, where, and how many samples to deposit) in order to inform MSR's Sample Fetch Rover (SFR) mobility, sample retrieval, and surface lifetime requirements.

NASA Response: NASA concurs with this recommendation. A large number of reference scenarios have been developed that characterize potential Mars 2020 surface operations and sample caching strategies. These scenarios will be discussed with the science community in January 2021 and documented in an MOU between M2020 and MSR.

B-6: Selective sample collection and caching redundancy should be included in scenario planning, especially for early M2020 surface operations.

NASA Response: NASA concurs with this recommendation. Duplicate samples and caching redundancy will be incorporated into the sample caching scenario planning.

B-7: A campaign-level definition of what constitutes a M2020 contingency sample should be established and documented.

NASA Response: NASA concurs with this recommendation. This definition will be developed as part of the sample caching strategy activities.

B-8: Mars Reconnaissance Orbiter (MRO) orbit should be adjusted to increase the efficiency of M2020 science operations so that the number of samples acquired by M2020 is maximized.

NASA Response: NASA partially concurs with this recommendation. During Phase A NASA will study the robustness of the communications strategy supporting M2020 surface operations necessary to facilitate the success of the Mars Sample Return mission.

B-9: Planning and design of the Orbiting Sample (OS) need to be robust enough to ensure the sustained integrity of surface and atmospheric samples for an extended duration that should be defined by the MSR program.

NASA Response: NASA concurs with this recommendation. Mission requirements ensure the integrity of samples on the surface and in orbit for at least a decade.

C. Technical Approach

C-1: Complete Pre-Phase A and Phase A studies on the present schedule with an emphasis on architectural trades.

NASA Response: NASA concurs with this recommendation.

C-2: The single-lander vs two-lander study currently being conducted should use as comprehensive a set of variations as possible and score the results with as quantitative a methodology as possible.

NASA Response: NASA concurs with this recommendation.

C-3: This study should be augmented to include a strong focus on potential Radioisotope Thermoelectric Generator (RTG) incorporation on either a single-lander or two-lander approach, to achieve the following benefits:

- **Type 1 launch option in 2028**
- **Possible longer surface timeline**
- **RTG-sourced heating of the MAV.**

NASA Response: NASA concurs with this recommendation.

C-4: Review requirements on the SFR to determine if some might be modified to enhance utilization of ExoMars mobility, Radioisotope Heater Unit (RHUs) and qualification inheritance and evaluate the ramifications of those modifications on the campaign.

NASA Response: NASA concurs with this recommendation. The current SFR design enhances utilization of ExoMars inheritance. NASA will investigate the potential addition of RHUs during integration and test phase, subject to agreement with ESA and U.S. international policy.

C-5: For the single vs dual-lander trade, include a focus on improving SFR ExoMars inheritance and increased traverse flexibility.

NASA Response: NASA concurs with this recommendation.

C-6: Increase the MAV mass allowance.

NASA Response: NASA partially concurs with this recommendation. The MAV is subject of trade studies in Phase A.

C-7: Increase the thermal conditioning power allocated to the MAV.

NASA Response: NASA partially concurs with this recommendation. The MAV is subject of trade studies in Phase A.

C-8: Evaluate modulating the MAV's Ultra-high Frequency (UHF) beacon signal with sufficient low-band telemetry to allow useful reconstruction of a fault during second stage flight.

NASA Response: NASA partially concurs with this recommendation. The MAV is subject of trade studies in Phase A.

C-9: Accelerate the definitization of the Capture/Containment and Return System (CCRS) specifications that the Earth Return Orbiter (ERO) program requires.

NASA Response: NASA concurs with this recommendation. NASA and ESA are working to a joint requirements document. NASA is accelerating definitization of CCRS specifications as rapidly as possible.

C-10: Synchronize, as much as possible, CCRS development, test, qualification, and validation milestones, and required delivery dates with the ERO development schedule.

NASA Response: NASA concurs with this recommendation. This is already in work.

C-11: Maintain the CCRS pre-Preliminary Design Review (PDR) schedule as much as possible.

NASA Response: NASA concurs with this recommendation. NASA will work to maintain the current CCRS pre-PDR schedule, including requirements definition, maturation of all required technology and engineering developments, and all conceptual and preliminary design work.

C-12: Assign enhanced technical margins to areas in the CCRS that could affect the ERO interface.

NASA Response: NASA concurs with this recommendation. MSR flight systems presently exceed institutional margin guidelines. NASA will continue to enhance technical margins, particularly those across interfaces.

C-13: Bring to bear relevant expertise from similar Earth-return missions (e.g., Stardust, Genesis, OSIRIS-REx) to Earth Entry Vehicle (EEV) design, development, and test.

NASA Response: NASA concurs with this recommendation. The Program recently held a workshop with experts from past sample return missions, is reviewing lessons–learned from these programs, and will continue to engage relevant experts.

C-14: Examine the possibility of EEV integrity sensors being incorporated in the design.

NASA Response: NASA concurs with this recommendation. NASA will study the ability to incorporate a range of such sensors in Phase A.

C-15: Develop a set of abort "safe havens" for sample preservation if things go awry at critical phases of the mission. Examples include the following:

- **Selectively redundant backup sample depot to remain on surface**
- **OS release capability by ERO/CCRS after capture or containment for entry in Mars orbit**
- **Survivable and trackable OS under various MAV and ERO failure scenarios.**

NASA Response: NASA concurs with this recommendation. NASA has incorporated this philosophy into the current conceptual design which builds in safe havens on the Mars surface and in Mars orbit. During Phase A, NASA will continue to look for opportunities for additional safe havens.

C-16: In order to maximize the probability of mission success, "Test As You Fly" must be rigorously adhered to, including careful scrutiny of waivers.

NASA Response: NASA concurs with this recommendation. NASA intends to follow a "Test as You Fly" approach and will present any proposed exceptions to the SRB at lifecycle reviews (LCRs).

C-17: Additional testing and Verification and Validation (V&V) activities should be undertaken to enhance mission success confidence, including the following specific ones:

- **Flight test the MAV including at least ejection, ignition, and initial (high thrust) flight segment**
- **Zero-g test of OS/CCRS capture and release mechanisms**
- **End-to-end IV&V of ERO/OS rendezvous and capture con ops.**

NASA Response: NASA concurs with this recommendation. NASA agrees with the need for a significant test program to enhance design and operations confidence. The MSR Program is examining a wide range of robustness testing options and planning a rigorous V&V program.

D. Schedule and Cost

D-1: NASA and ESA should replan the baseline MSR program for SRL and ERO launches in 2028, with the potential of a 2027 ERO launch continuing to be studied for feasibility and potential benefits.

NASA Response: NASA partially concurs with this recommendation. The MSR team will continue to examine the 2026, 2027 and 2028 launch opportunities during Phase A, while working to maintain current schedules to mature the design and retire risk as quickly as possible during Phase A, while also working to minimize program impacts due to COVID. NASA, in consultation with ESA, will set the Program baseline and finalize the launch date at Confirmation (KDP-C).

D-2: Consistent with the absence of viable post-2028 launch opportunities, the PDR milestone should be maintained.

NASA Response: NASA concurs with this recommendation. Consistent with recommendations C-1 and C-11, the Program will work to complete the current Formulation plan and maintain the present timeline to PDR and Confirmation.

D-3: The MSR Program should establish a joint working group with ESA to fully explore and assess the potential impacts of ERO/CCRS schedule disconnects, and identify possible mitigations.

NASA Response: NASA concurs with this recommendation. Schedule disconnects that cannot be resolved between the ERO and CCRS projects will be brought to the MSR Joint Steering Board (composed of ESA and NASA representation).

D-4: The most-probable Phase A-D cost is \$3.8-\$4.4B, consistent with proposed schedule revisions and current baseline technical design and mission architecture. However, this estimate is based on preliminary information. Consequently, NASA should budget to the higher end of this range, which the IRB believes constitutes an 80/20 most probable cost.

NASA Response: NASA partially concurs with this recommendation. Consistent with Agency practice, prior to Confirmation (KDP-C) NASA will plan to a cost range that bounds program risk. For MSR, the Agency has commissioned independent cost and schedule risk assessments much earlier than past practice to inform KDP-A cost and schedule range projections.

D-5: Consistent with the IRB's belief in the importance of early work, the FY22-23 budgets should be significantly augmented to assure 2028 launch dates are feasible.

NASA Response: NASA is continuing to refine budget estimates. Future funding will be addressed through the annual budget process.

D-6: MSR should apply relevant best practices as recommended by the current Large Mission Study Team in schedule management and cost estimation methods.

NASA Response: NASA concurs with this recommendation.

D-7: MSR should engage SRB in between any LCRs that are more than 12 months apart, given proposed schedule replan.

NASA Response: NASA concurs with this recommendation.

D-8: MSR should manage risks cooperatively across all organizations, including establishing a process for escalating unresolved issues before they become major challenges, e.g., NASA/ESA interfaces.

NASA Response: NASA concurs with this recommendation.

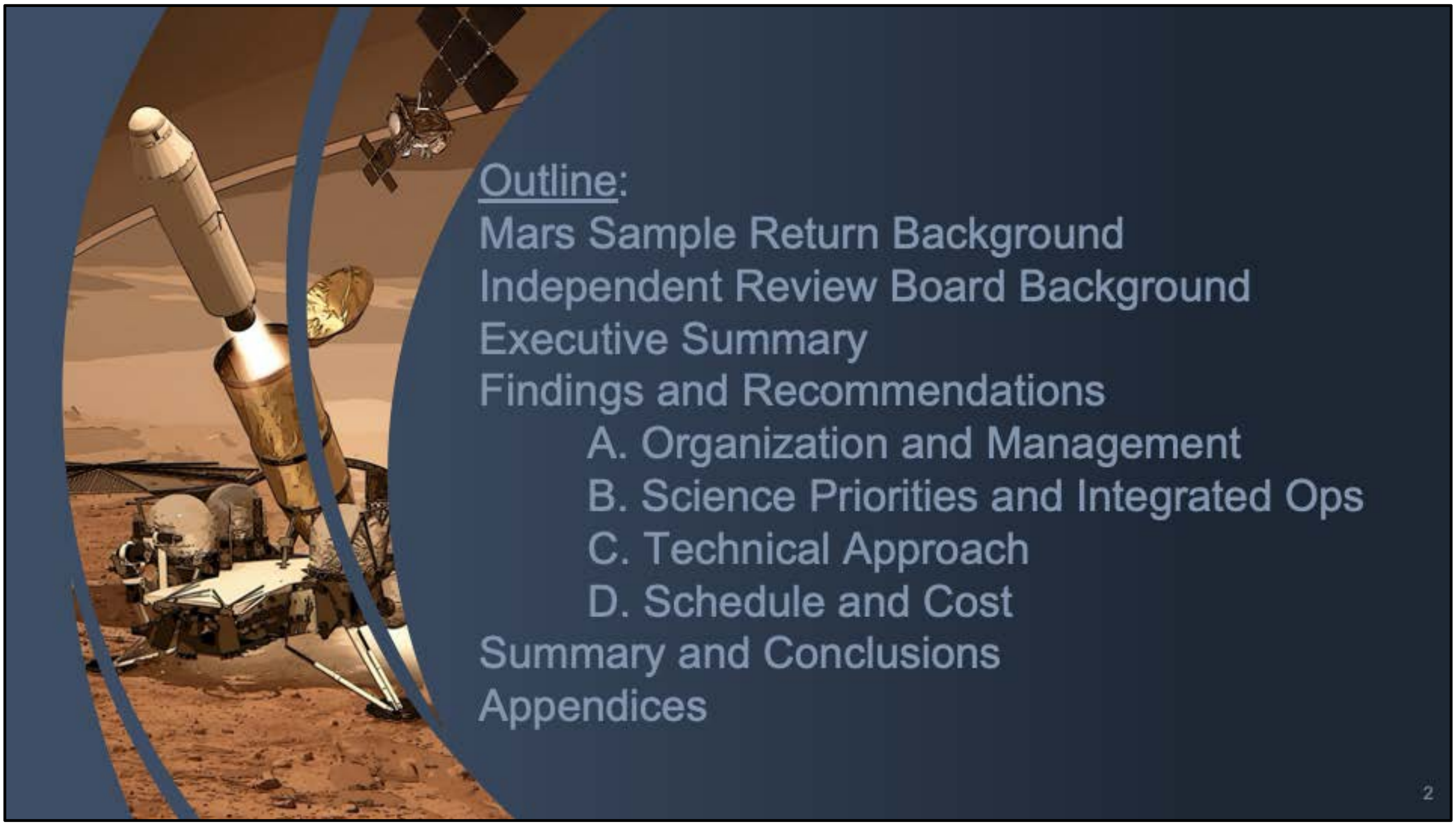
D-9: MSR should establish, document, and communicate HQ PP&C (Program, Planning and Control) Integration philosophy and processes early with emphasis on risk-informed cost and schedule estimates occurring on a routine cadence.

NASA Response: NASA concurs with this recommendation. The Program began planning the PP&C implementation in Pre-Phase A.

Mars Sample Return (MSR) Program

Final Report of the Independent Review Board (IRB)

October 29, 2020



Outline:

Mars Sample Return Background

Independent Review Board Background

Executive Summary

Findings and Recommendations

- A. Organization and Management
- B. Science Priorities and Integrated Ops
- C. Technical Approach
- D. Schedule and Cost

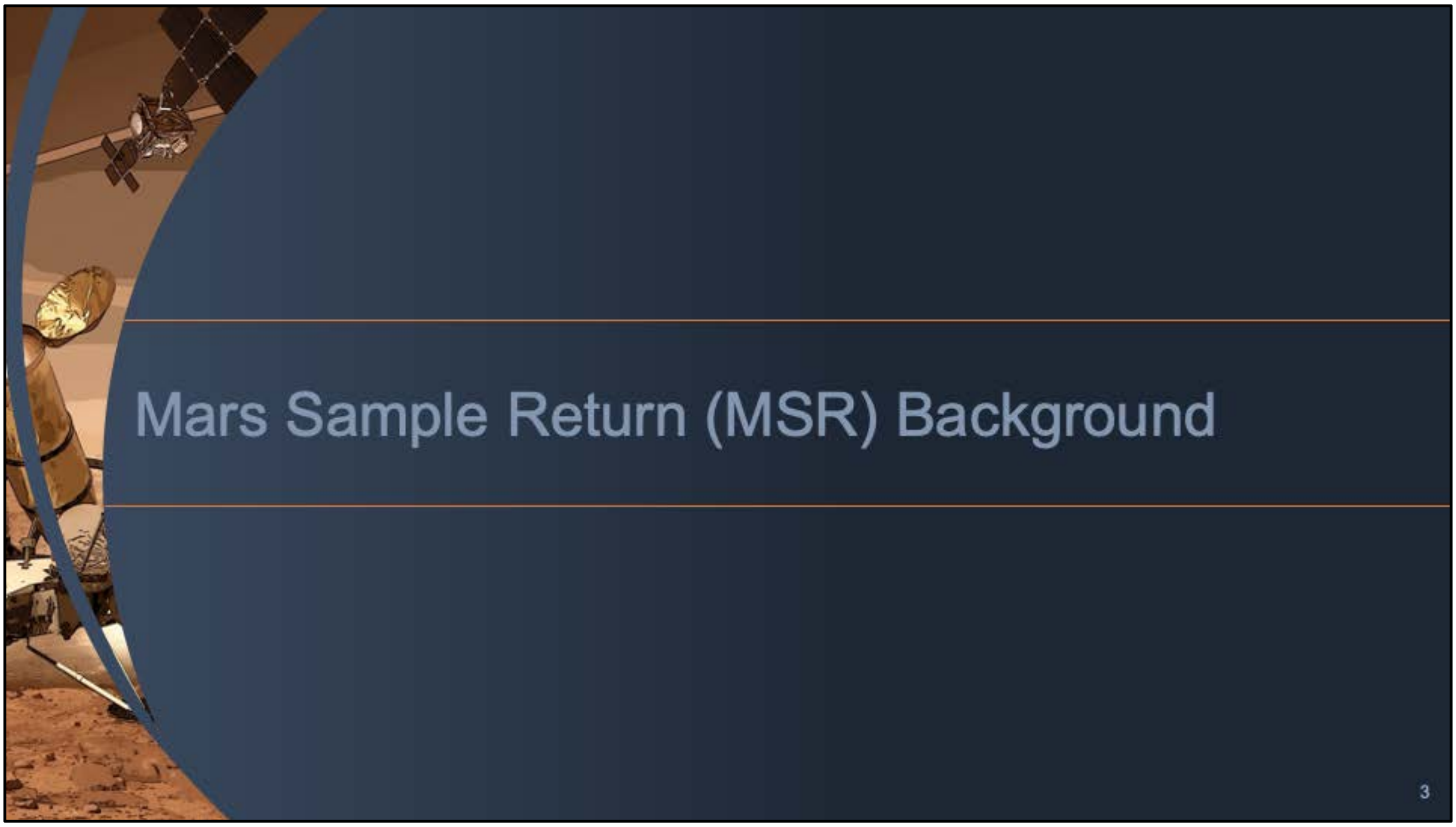
Summary and Conclusions

Appendices

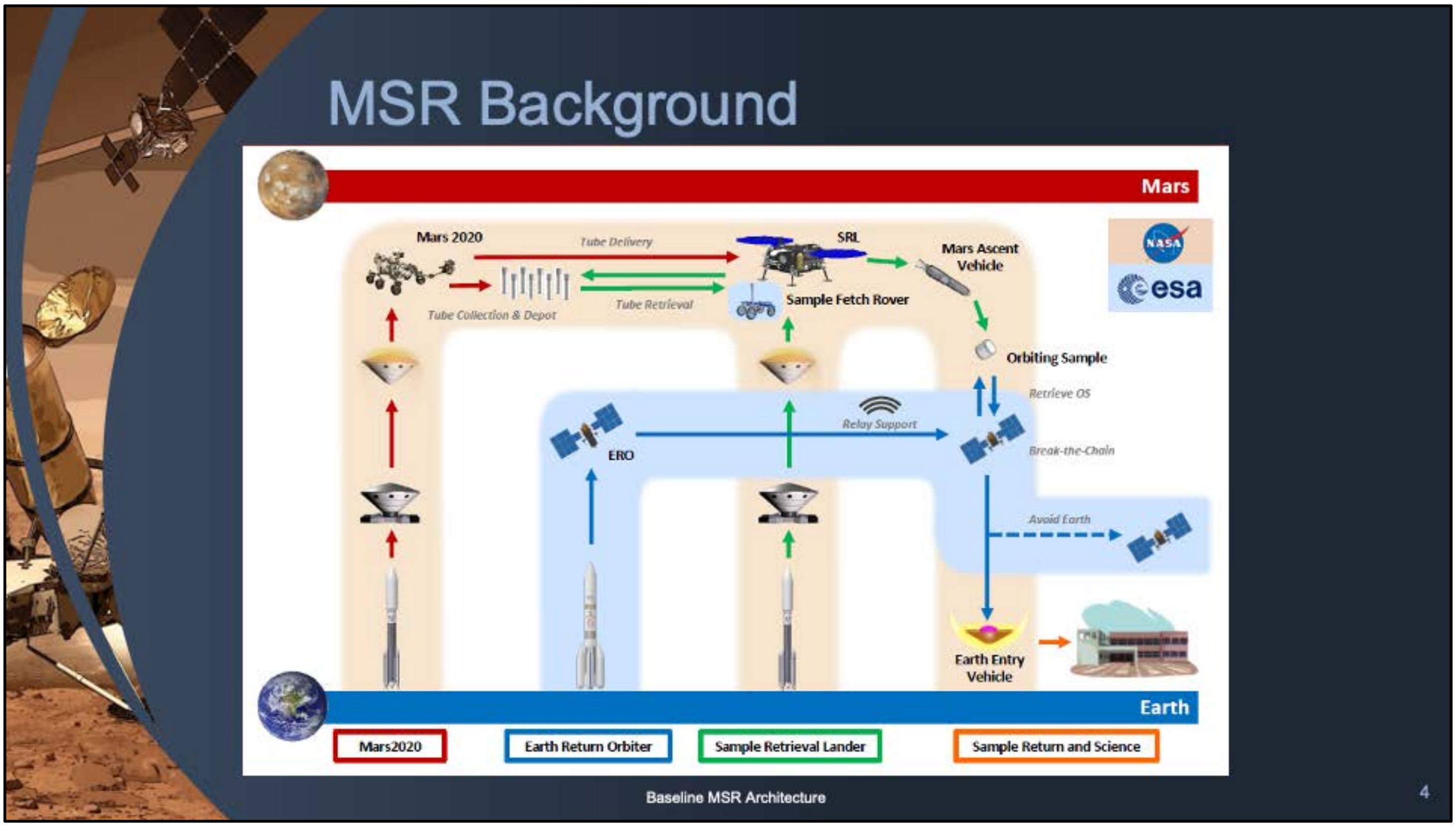
The IRB is pleased to present our report and offer our special thanks to Thomas Zurbuchen and Jeff Gramling at NASA HQ and Bobby Braun at JPL for their support for our work.

We also want to commend the NASA/ESA MSR team for their hard work and excellent progress over the last several years, including the difficult pandemic period this year. The team has formulated a comprehensive plan for carrying out what arguably will be the most challenging, and, in all likelihood, one of the most historic deep-space robotic programs.

Building on the foundation they have created, the IRB submits the results of our work in the form of 44 findings and 44 recommendations, all with the overriding goal of maximizing the probability of MSR mission success.



Mars Sample Return (MSR) Background



MSR Background

Baseline MSR Architecture

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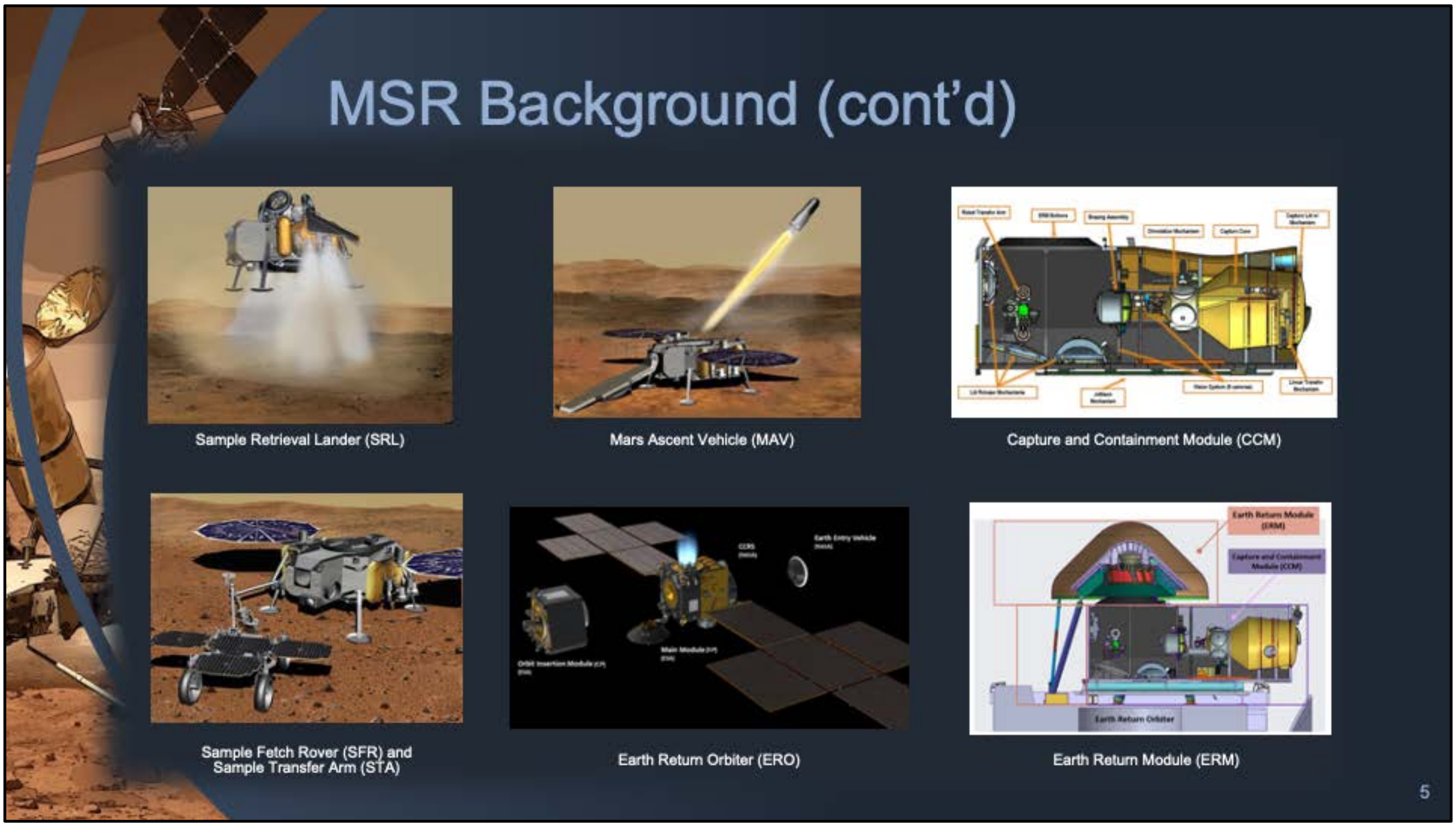
The MSR campaign is a highly ambitious and demanding planetary exploration program involving three advanced space vehicles — the Mars 2020 lander/rover, now on its way to Mars, and two additional vehicles in early development, the Earth Return Orbiter and the Sample Retrieval Lander, to be launched later in the decade. The campaign also includes a new ground-based sample handling and scientific analysis facility, which the IRB did not study.



MSR Background (cont'd)

Sample Retrieval Lander (SRL)

Mars Ascent Vehicle (MAV)

Capture and Containment Module (CCM)

Sample Fetch Rover (SFR) and Sample Transfer Arm (STA)

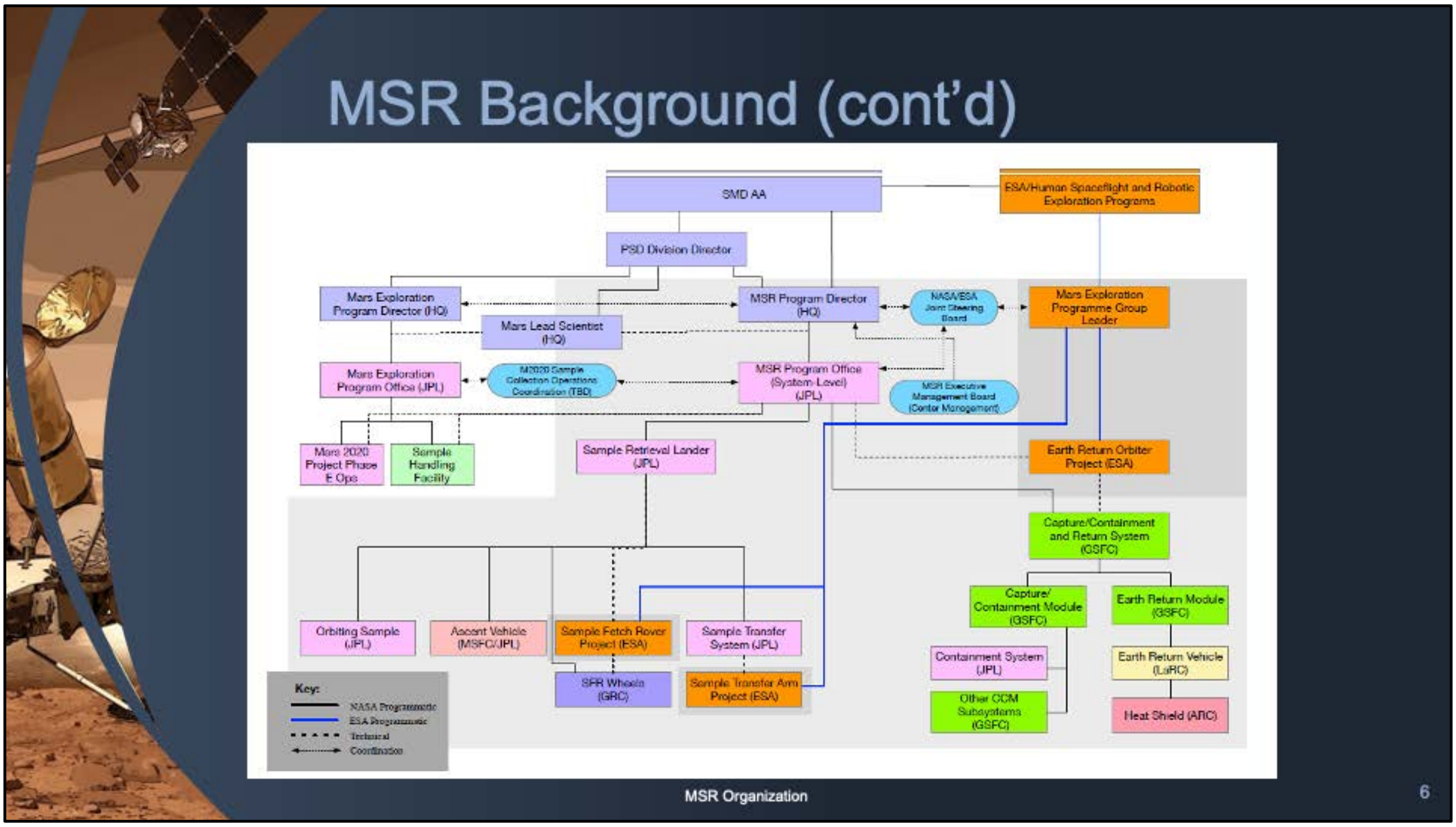
Earth Return Orbiter (ERO)

Earth Return Module (ERM)

The major elements of the two MSR vehicles that are the topics of this report are as follows:

- The Sample Retrieval Lander (SRL), built by NASA and launched on a U.S. rocket. The SRL's payloads include the Sample Fetch Rover (SFR) and Sample Transfer Arm (STA), both provided by ESA, and the Mars Ascent Vehicle (MAV), developed and provided by NASA.

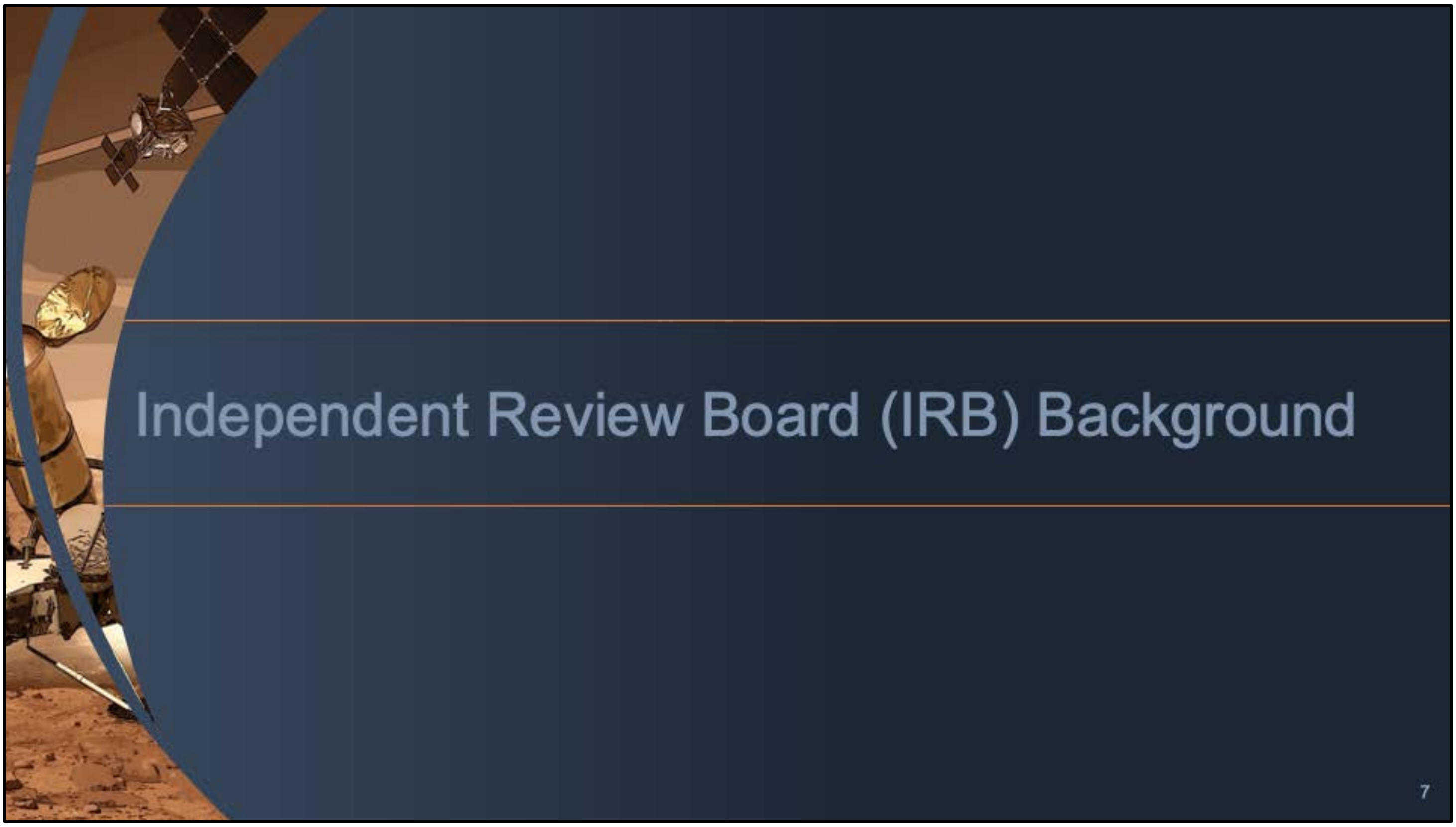
- The Earth Return Orbiter (ERO), developed and launched by ESA, carrying the Capture, Containment and Return System (CCRS), provided by NASA. The CCRS consists of two major elements, the Capture and Containment Module (CCM) and Earth Return Module (ERM).



MSR Background (cont'd)

MSR Organization

MSR's proposed organizational structure and work assignments, shown here, involve six NASA Centers (JPL, GSFC, MSFC, LaRC, ARC and GRC) and three prime ESA-member countries (France, U.K. and Italy). This chart is indicative of the complexity and challenges of the MSR program.



Independent Review Board (IRB) Background

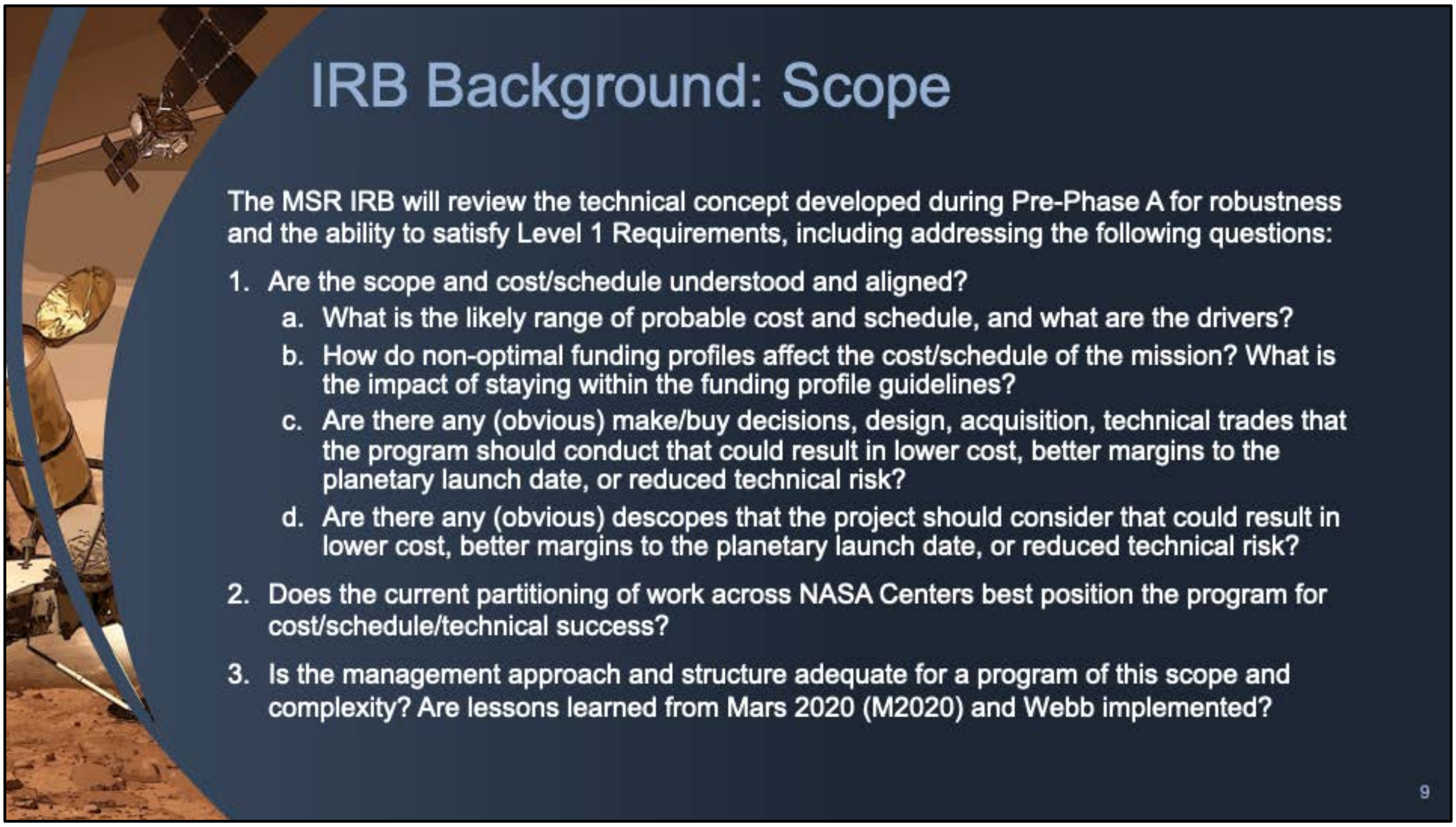
IRB Background: Membership

David Thompson, Orbital ATK, retired (MSR IRB Chair)
Anders Elfving, European Space Agency
Dr. Antonio Elias, Orbital ATK, retired
Michele King, NASA/HQ
Gentry Lee, NASA/JPL
Joe Pellicciotti, NASA/HQ
Peter Theisinger, NASA/JPL
Dr. Meenakshi (Mini) Wadhwa, Arizona State University
A. Thomas Young, Lockheed Martin, retired
Dr. Maria Zuber, MIT (Standing Review Board Chair)

Ex Officio
Dr. T. Jens Feeley, NASA/HQ (Review Manager)
Laura Delgado López, NASA/HQ (Deputy Review Manager)
Josh Handal, NASA/HQ (Public Affairs Officer)

The 10 members of the IRB spent a combined total of approximately 1,000 person-hours on the review, which was conducted between late August and late October 2020. All members of the board participated fully, engaging in discussions that were thorough and spirited.

The support provided by Jens Feeley, Laura Delgado Lopez, and Josh Handal from NASA HQ was terrific...we could not have produced our report without their experience, energy and diligence.

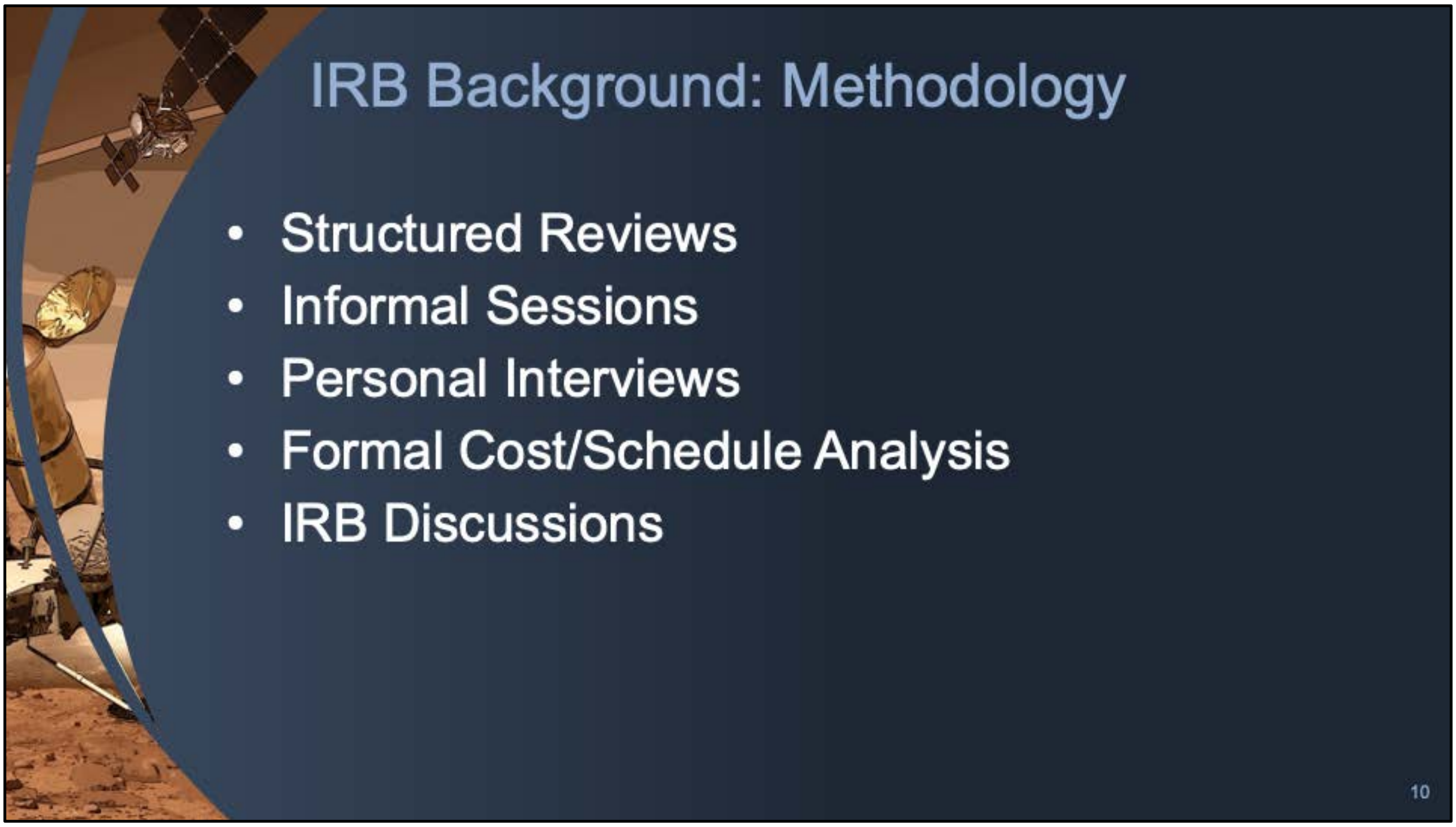


IRB Background: Scope

The MSR IRB will review the technical concept developed during Pre-Phase A for robustness and the ability to satisfy Level 1 Requirements, including addressing the following questions:

1. Are the scope and cost/schedule understood and aligned?
   a. What is the likely range of probable cost and schedule, and what are the drivers?
   b. How do non-optimal funding profiles affect the cost/schedule of the mission? What is the impact of staying within the funding profile guidelines?
   c. Are there any (obvious) make/buy decisions, design, acquisition, technical trades that the program should conduct that could result in lower cost, better margins to the planetary launch date, or reduced technical risk?
   d. Are there any (obvious) descopes that the project should consider that could result in lower cost, better margins to the planetary launch date, or reduced technical risk?
2. Does the current partitioning of work across NASA Centers best position the program for cost/schedule/technical success?
3. Is the management approach and structure adequate for a program of this scope and complexity? Are lessons learned from Mars 2020 (M2020) and Webb implemented?

The IRB's charter, as specified by Thomas Zurbuchen and summarized here, was comprehensive in scope. The formal Terms of Reference for our work is reproduced in the Appendix to this report.



IRB Background: Methodology

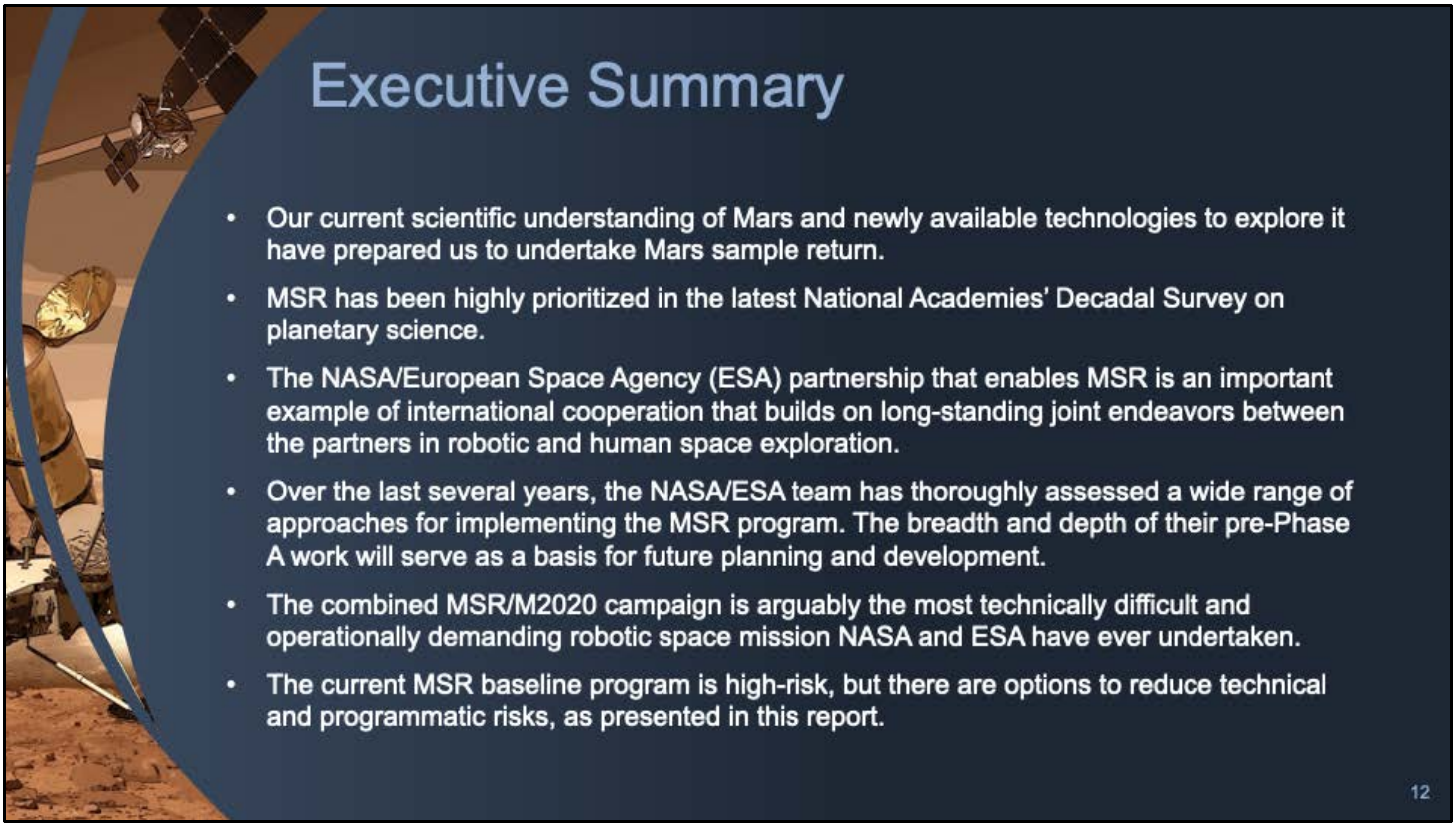
- Structured Reviews
- Informal Sessions
- Personal Interviews
- Formal Cost/Schedule Analysis
- IRB Discussions

The IRB met in virtual plenary sessions on 25 occasions over a nine-week period. Our meetings included six formal presentations by MSR personnel of over 450 pages of technical and programmatic data. In addition, we conducted approximately 30 informal “splinter” sessions and expert interviews. We also reviewed four sets of internal and external schedule and cost analyses that informed our findings and recommendations.

Many of our detailed observations, findings and recommendations were drafted by members of four three-to-five person working groups, which were then discussed and finalized by the entire board. The topical outline of the main body of this report generally follows the working group organization, which consisted of these teams:

- Organization and Management
- Science Priorities and Integrated Operations
- Technical Approach
- Schedule and Cost

Executive Summary



Executive Summary

- Our current scientific understanding of Mars and newly available technologies to explore it have prepared us to undertake Mars sample return.
- MSR has been highly prioritized in the latest National Academies' Decadal Survey on planetary science.
- The NASA/European Space Agency (ESA) partnership that enables MSR is an important example of international cooperation that builds on long-standing joint endeavors between the partners in robotic and human space exploration.
- Over the last several years, the NASA/ESA team has thoroughly assessed a wide range of approaches for implementing the MSR program. The breadth and depth of their pre-Phase A work will serve as a basis for future planning and development.
- The combined MSR/M2020 campaign is arguably the most technically difficult and operationally demanding robotic space mission NASA and ESA have ever undertaken.
- The current MSR baseline program is high-risk, but there are options to reduce technical and programmatic risks, as presented in this report.

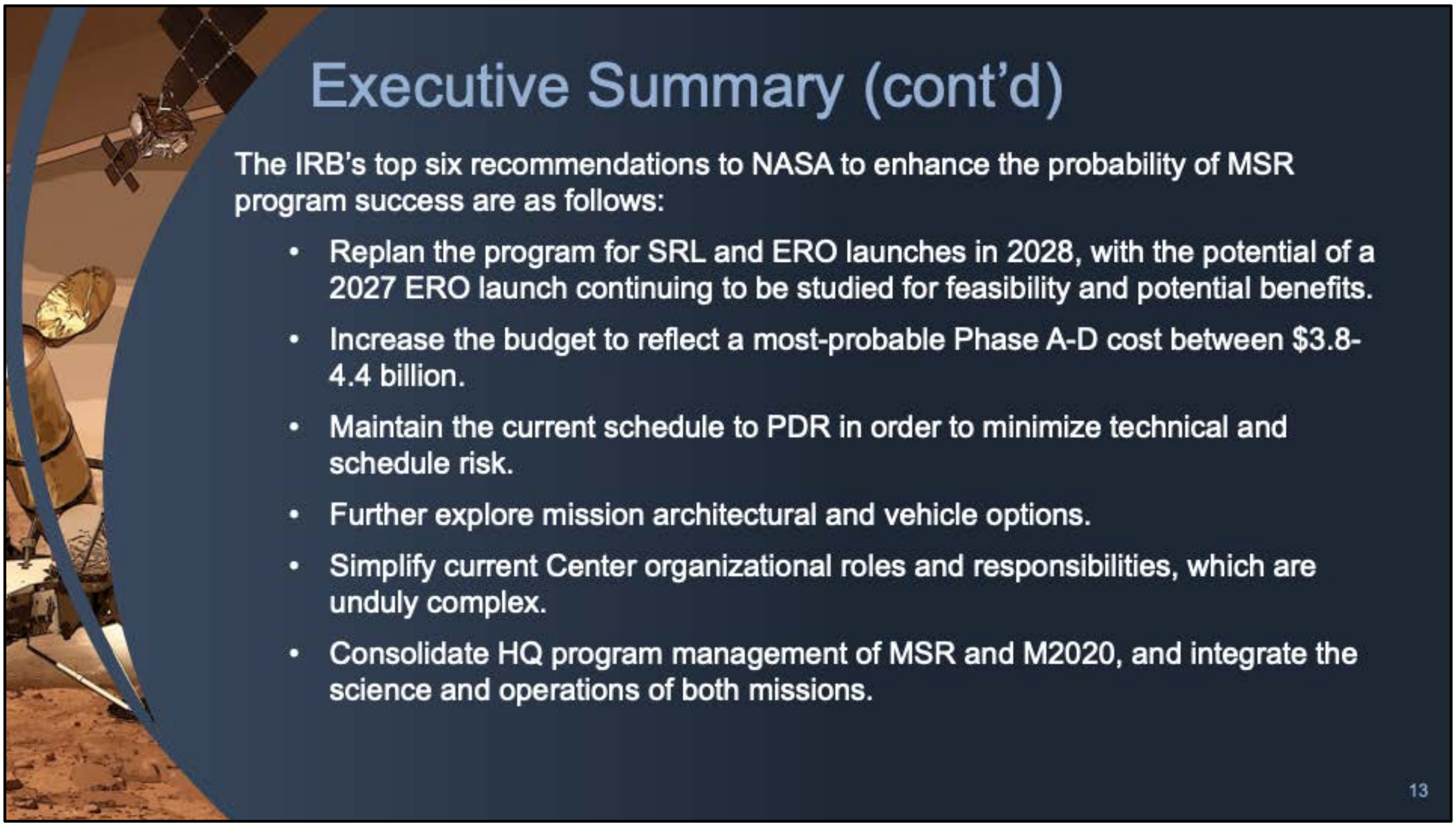
12

The IRB believes that NASA is now ready to undertake the MSR campaign, building on the past several decades of scientific advances and technological progress in Mars exploration.

We observe that the National Academies' 2011 Planetary Science Decadal Survey pointed out the high priority of MSR. Since then, NASA and ESA have formed a major new partnership to carry out this mission, building on and extending over 50 years of highly-productive trans-Atlantic cooperation in space science.

During the pre-Phase A work over the last several years, the MSR team's technical work has covered a broad span of architectural and system design options and has developed a deep engineering baseline for the mission. Their work provides a basis for finalizing the technical approach to the mission during the upcoming Phase A period.

In noting the substantial technical and operational demands of successfully implementing MSR, we underscore the high-risk/high-return nature of the program. As a result, the IRB has focused our primary efforts on identifying options to reduce the various types of controllable risks as much as possible.



Executive Summary (cont'd)

The IRB's top six recommendations to NASA to enhance the probability of MSR program success are as follows:

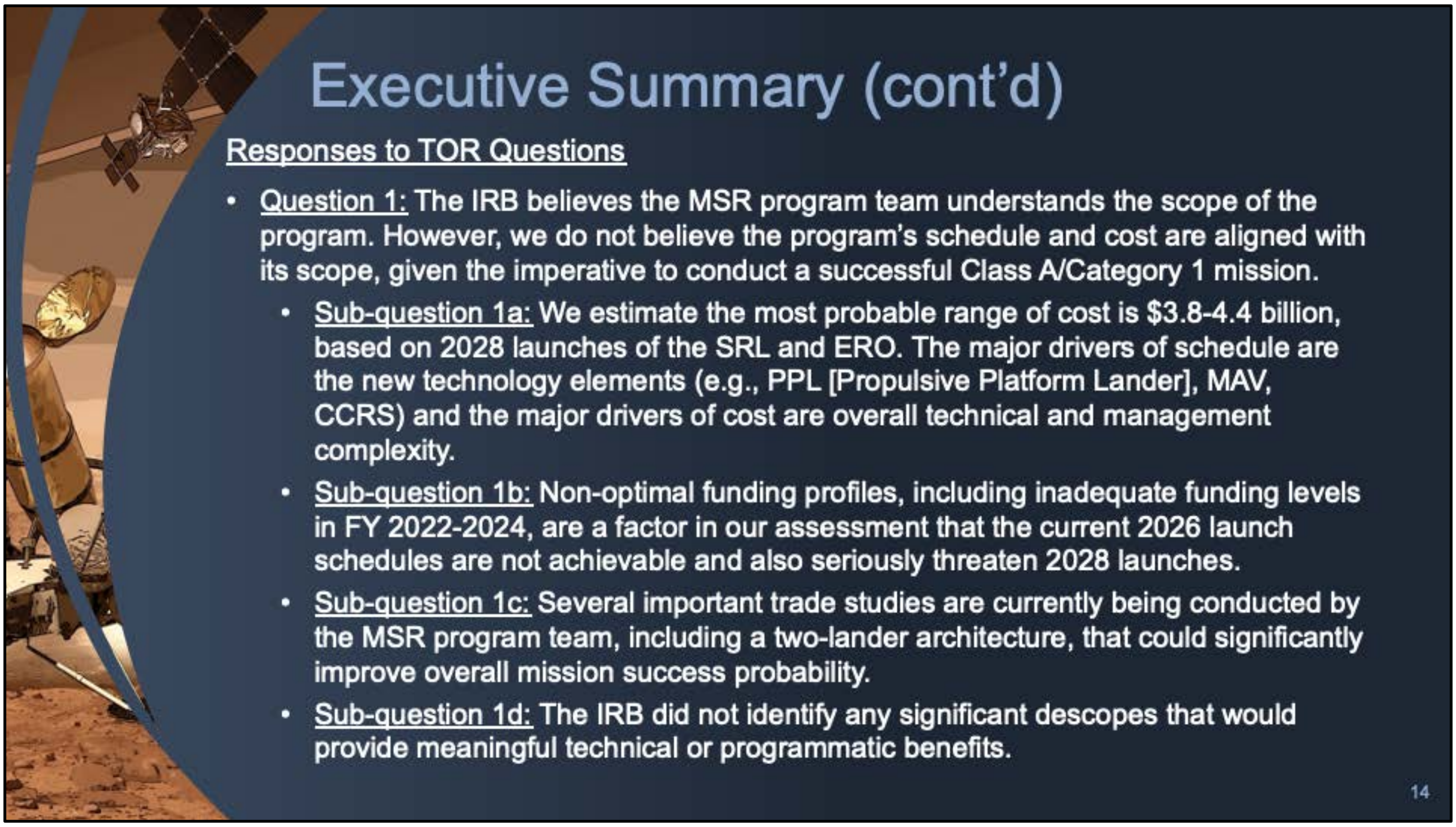
- Replan the program for SRL and ERO launches in 2028, with the potential of a 2027 ERO launch continuing to be studied for feasibility and potential benefits.
- Increase the budget to reflect a most-probable Phase A-D cost between $3.8-4.4 billion.
- Maintain the current schedule to PDR in order to minimize technical and schedule risk.
- Further explore mission architectural and vehicle options.
- Simplify current Center organizational roles and responsibilities, which are unduly complex.
- Consolidate HQ program management of MSR and M2020, and integrate the science and operations of both missions.

13

This chart lists the IRB's most important recommendations, which are addressed in greater detail in later pages of our presentation. The common theme in these recommendations is our belief that their implementation will substantially enhance the probability of MSR program success.

The rationale for our recommendations include these major findings:
- Currently planned 2026 MSR launch schedules are not compatible with NASA's Class A/Category 1 mission risk levels.
- Planned Phase A studies should be enhanced, with an emphasis on the one-lander/two lander trade; additional trades which reduce MAV, SFR, CCRS and OS technical and schedule risk; and other trades which enhance the Validation and Verification program.

The IRB also believes it is very important that NASA take the following steps:
- The Preliminary Design Review (PDR) milestone should be maintained.
- Increase the 2022-2024 Fiscal Year (FY) budget profile by a total of approximately $500 million.

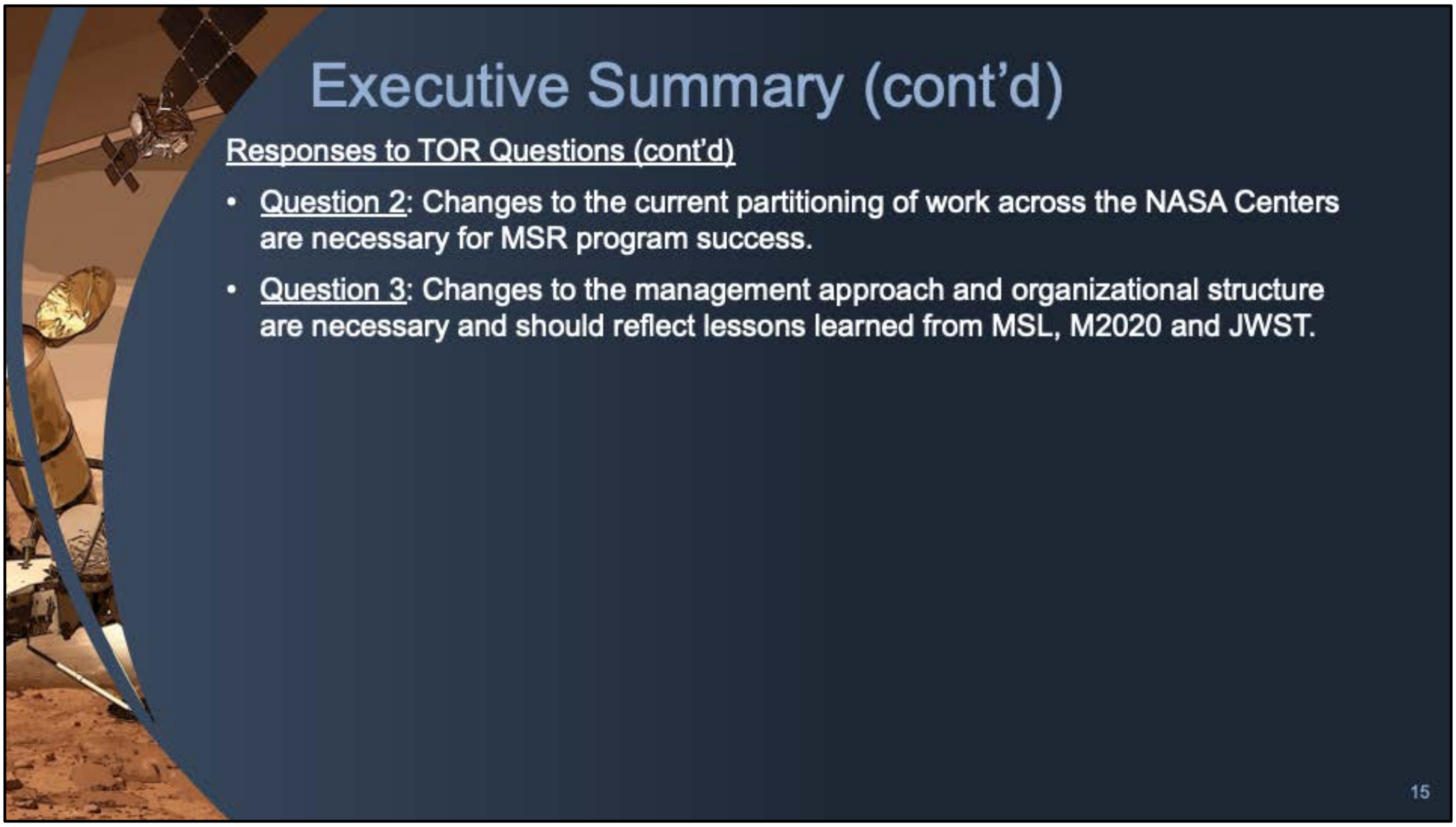


Executive Summary (cont'd)

Responses to TOR Questions

- Question 1: The IRB believes the MSR program team understands the scope of the program. However, we do not believe the program's schedule and cost are aligned with its scope, given the imperative to conduct a successful Class A/Category 1 mission.
  - Sub-question 1a: We estimate the most probable range of cost is $3.8-4.4 billion, based on 2028 launches of the SRL and ERO. The major drivers of schedule are the new technology elements (e.g., PPL [Propulsive Platform Lander], MAV, CCRS) and the major drivers of cost are overall technical and management complexity.
  - Sub-question 1b: Non-optimal funding profiles, including inadequate funding levels in FY 2022-2024, are a factor in our assessment that the current 2026 launch schedules are not achievable and also seriously threaten 2028 launches.
  - Sub-question 1c: Several important trade studies are currently being conducted by the MSR program team, including a two-lander architecture, that could significantly improve overall mission success probability.
  - Sub-question 1d: The IRB did not identify any significant descopes that would provide meaningful technical or programmatic benefits.

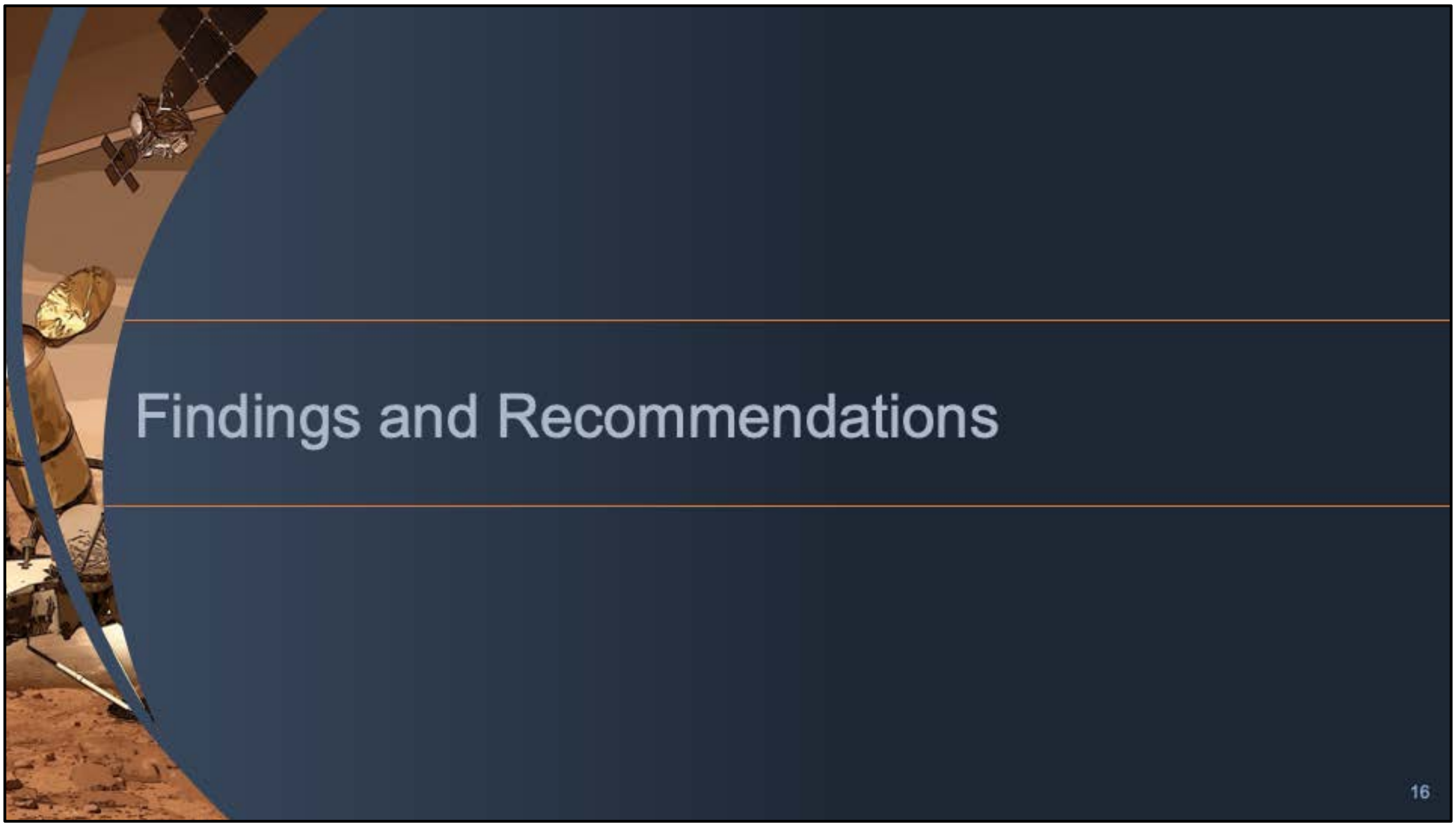
The IRB also provided responses to three specific questions and five sub-questions posed in the study's Terms of Reference (see chart 9 and the first item in the Appendix). Those responses are shown here, with supporting rationale provided in later parts of this report.



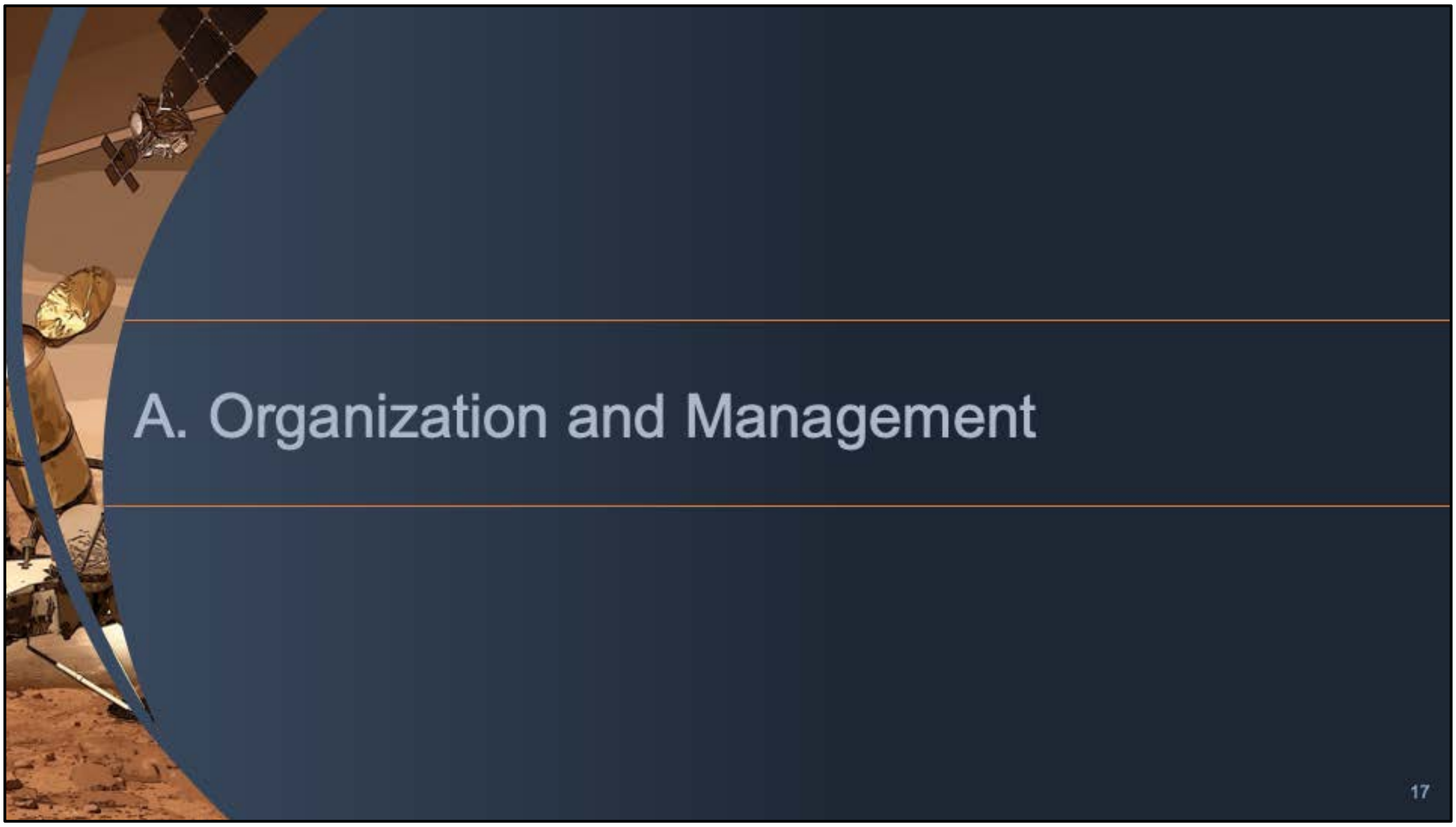
Executive Summary (cont'd)

Responses to TOR Questions (cont'd)

- Question 2: Changes to the current partitioning of work across the NASA Centers are necessary for MSR program success.
- Question 3: Changes to the management approach and organizational structure are necessary and should reflect lessons learned from MSL, M2020 and JWST.



Findings and Recommendations



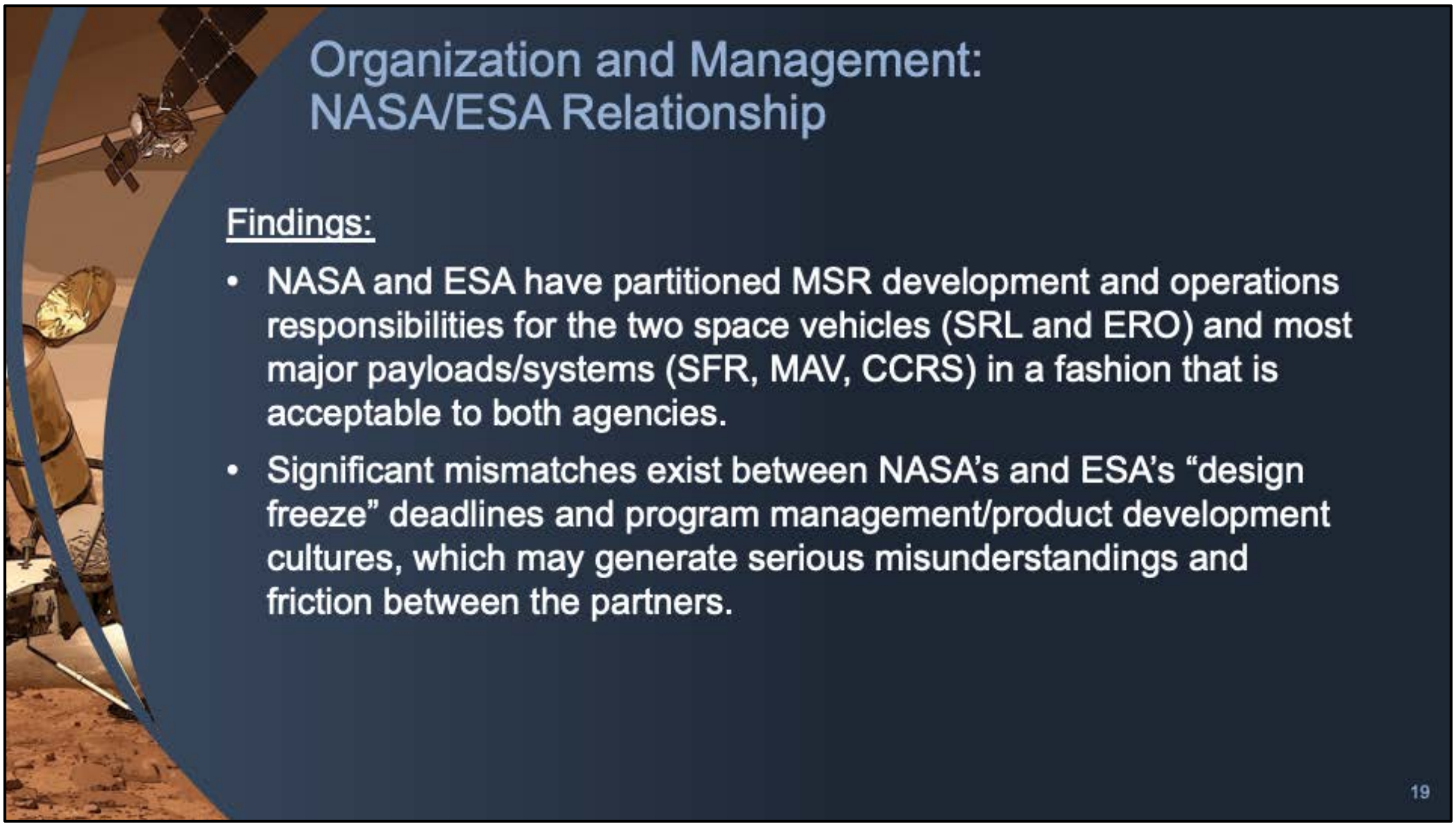
A. Organization and Management

The IRB offers 12 findings and eight recommendations in this category. In essence, we advise NASA to establish mechanisms to enhance interactions with ESA, simplify the organization structure, engage the strongest possible expertise in government and industry in each aspect of the program, and ensure all participating teams and organizations fully embrace their responsibilities for technical and programmatic performance. The IRB also stresses the importance of maintaining an MSR management approach appropriate to a Class A/Category 1 mission.

Organization and Management: Summary

- Establish NASA and ESA offices at the European Space Research and Technology Centre (ESTEC) and JPL, respectively, in order to enhance international partner collaboration.
- Conduct an independent assessment of all available Center resources at GSFC and JPL to achieve the best balance of technical capabilities with institutional capacity for CCRS project management.
  - Maintain organizational continuity within CCRS subsystems.
  - Consider system contracting of SRL to industry.
- Contract the ERM and MAV to companies with strong related experience.
- Limit ARC, LaRC, and GRC to technical advisory roles.
- Conduct an independent assessment of the STA to address its design, development and programmatics.
- Consolidate MSR and M2020 under the NASA HQ MSR Program Director.

Here is a summary of our major recommendations relating to MSR organization and management. Two of these relate to NASA/ESA interactions, three concern NASA Center responsibilities and make/buy decisions, and one addresses NASA HQ program management consolidation.

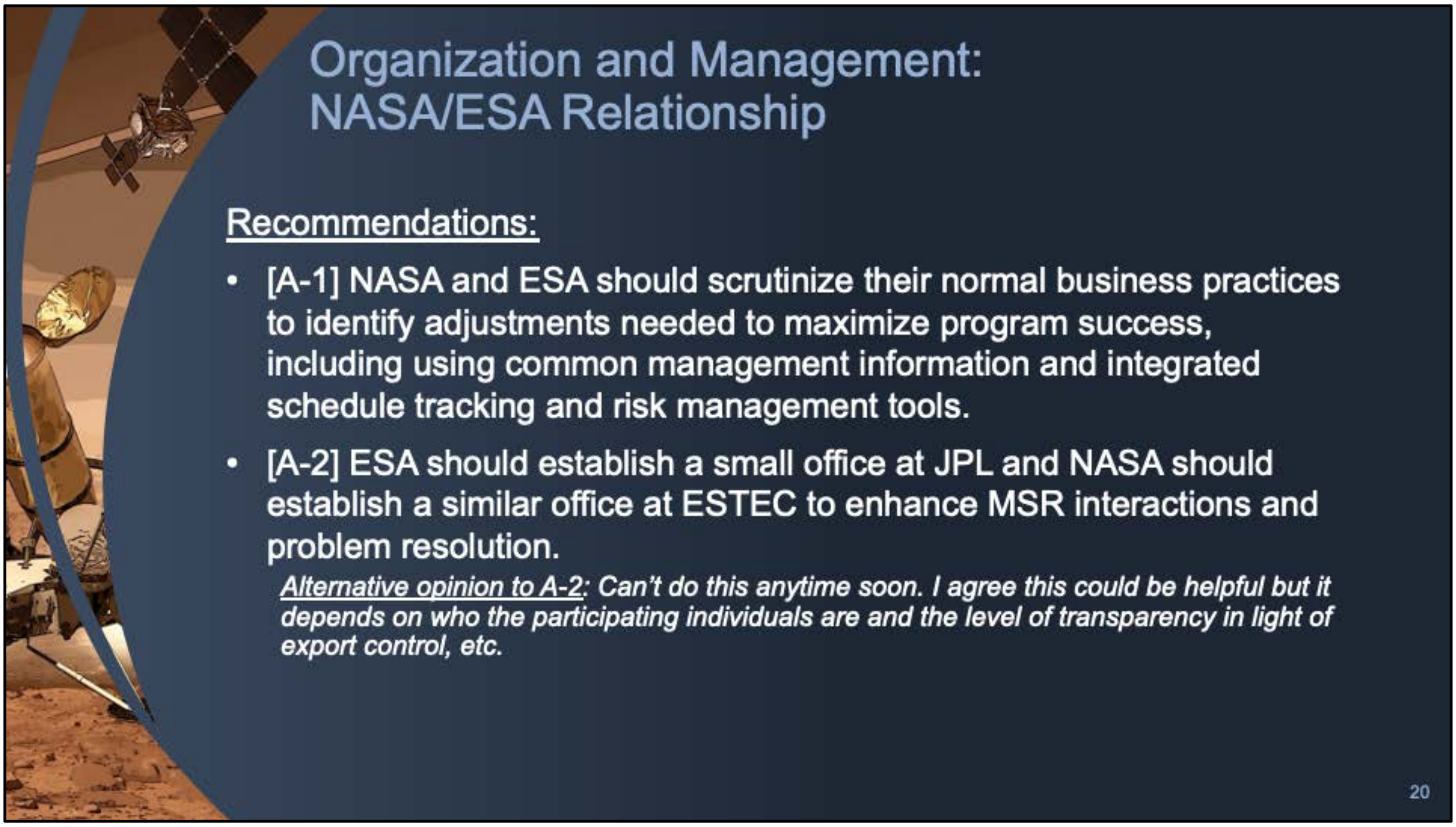


Organization and Management: NASA/ESA Relationship

Findings:

- NASA and ESA have partitioned MSR development and operations responsibilities for the two space vehicles (SRL and ERO) and most major payloads/systems (SFR, MAV, CCRS) in a fashion that is acceptable to both agencies.
- Significant mismatches exist between NASA's and ESA's "design freeze" deadlines and program management/product development cultures, which may generate serious misunderstandings and friction between the partners.

Our main point here is that both NASA and ESA should bridge their differing management approaches and development cultures to avoid future friction between their project teams.



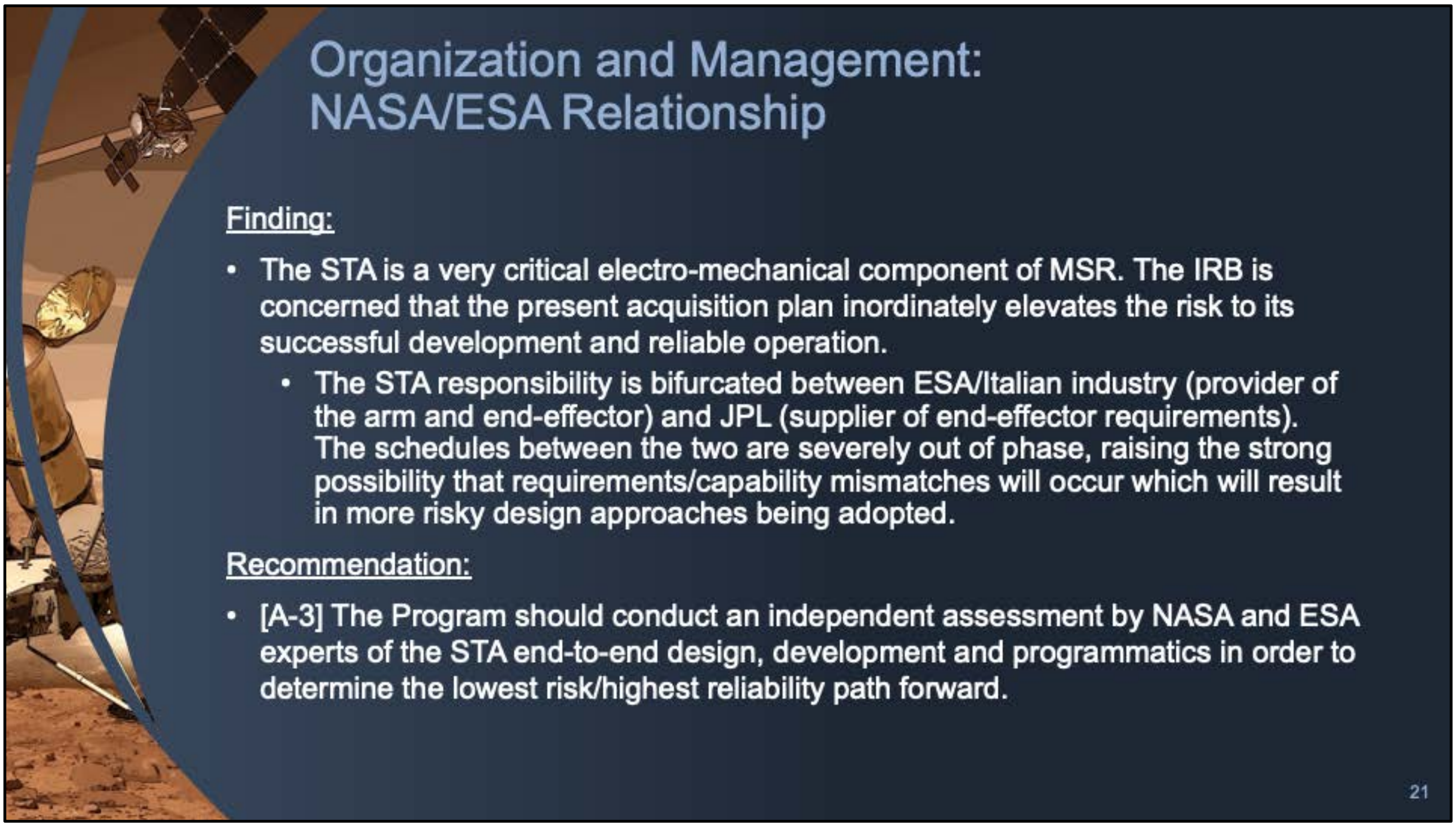
Organization and Management: NASA/ESA Relationship

Recommendations:

- [A-1] NASA and ESA should scrutinize their normal business practices to identify adjustments needed to maximize program success, including using common management information and integrated schedule tracking and risk management tools.
- [A-2] ESA should establish a small office at JPL and NASA should establish a similar office at ESTEC to enhance MSR interactions and problem resolution.

  Alternative opinion to A-2: Can't do this anytime soon. I agree this could be helpful but it depends on who the participating individuals are and the level of transparency in light of export control, etc.

Building on the good relations that currently exist between ESA and NASA, here are two other ideas we recommend the agencies look into to facilitate the strongest possible interactions as the MSR program proceeds.



Organization and Management: NASA/ESA Relationship

Finding:

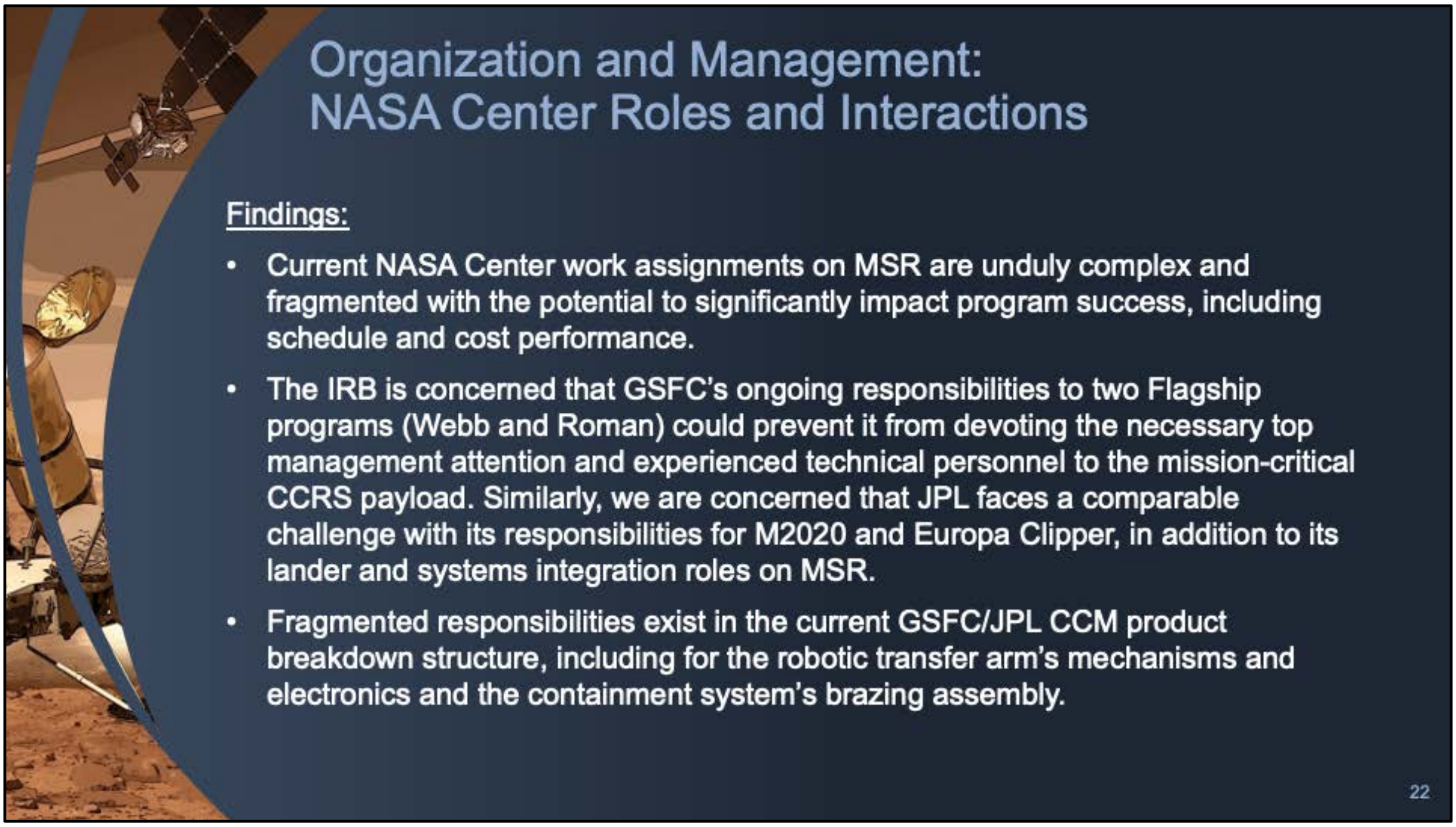
- The STA is a very critical electro-mechanical component of MSR. The IRB is concerned that the present acquisition plan inordinately elevates the risk to its successful development and reliable operation.
  - The STA responsibility is bifurcated between ESA/Italian industry (provider of the arm and end-effector) and JPL (supplier of end-effector requirements). The schedules between the two are severely out of phase, raising the strong possibility that requirements/capability mismatches will occur which will result in more risky design approaches being adopted.

Recommendation:

- [A-3] The Program should conduct an independent assessment by NASA and ESA experts of the STA end-to-end design, development and programmatics in order to determine the lowest risk/highest reliability path forward.

21

A critical area where close trans-Atlantic collaboration is especially important is the SRL-mounted Sample Transfer Arm. During our review, the IRB was concerned that schedule mismatches exist between the JPL-developed performance requirements for the STA and the Leonardo design capabilities for it. We recommend that an independent group of NASA and ESA experts examine the current development plan and related allocations of responsibilities to determine the lowest-risk path forward.



Organization and Management: NASA Center Roles and Interactions

Findings:

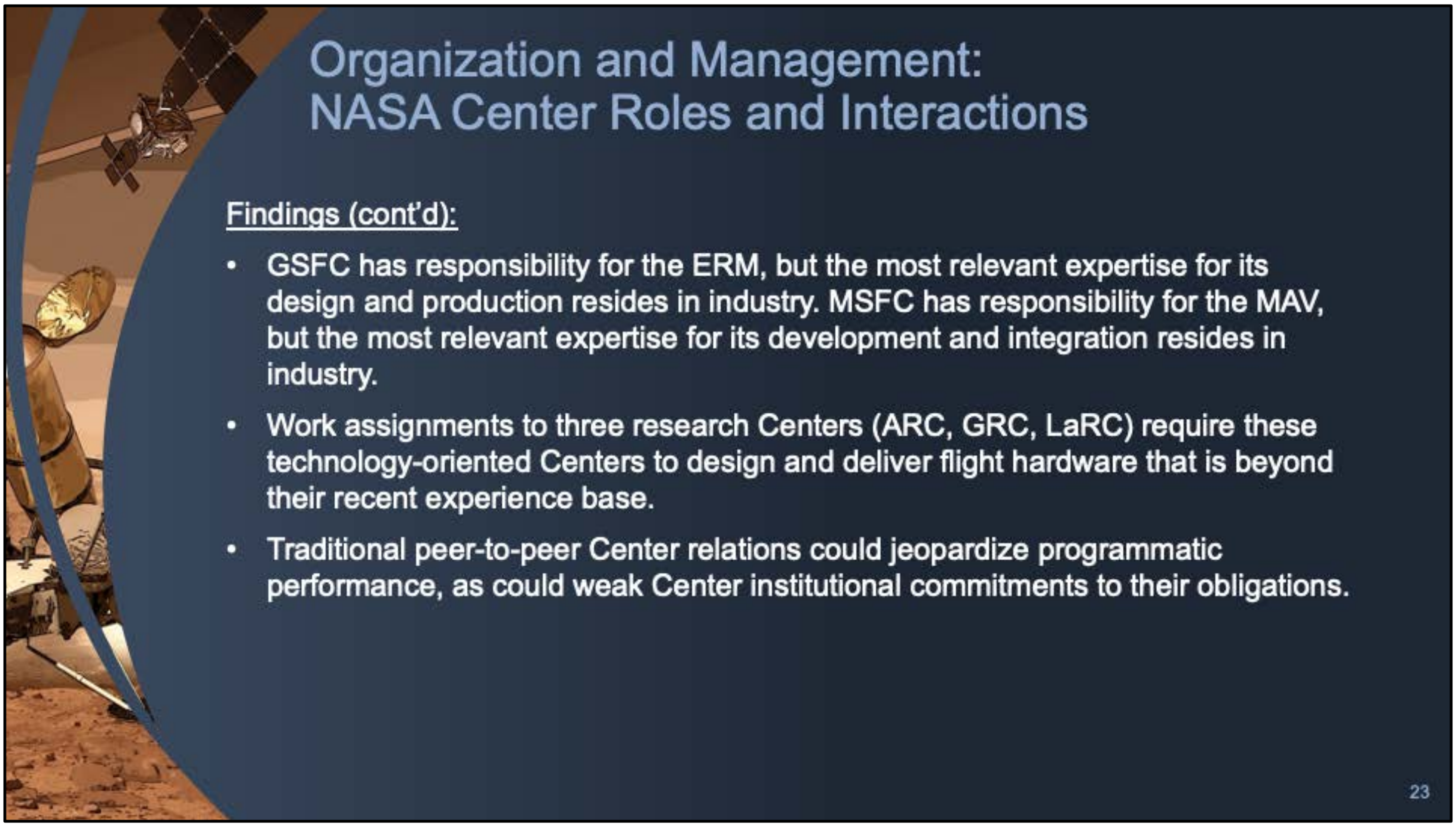
- Current NASA Center work assignments on MSR are unduly complex and fragmented with the potential to significantly impact program success, including schedule and cost performance.
- The IRB is concerned that GSFC's ongoing responsibilities to two Flagship programs (Webb and Roman) could prevent it from devoting the necessary top management attention and experienced technical personnel to the mission-critical CCRS payload. Similarly, we are concerned that JPL faces a comparable challenge with its responsibilities for M2020 and Europa Clipper, in addition to its lander and systems integration roles on MSR.
- Fragmented responsibilities exist in the current GSFC/JPL CCM product breakdown structure, including for the robotic transfer arm's mechanisms and electronics and the containment system's brazing assembly.

22

One of the IRB's earliest reactions to the MSR program plan was the unduly complex set of work assignments and related subsystems interfaces spread across the various NASA Centers, which in our view represent a substantial challenge to overall program success.

This situation manifests itself primarily in the ERO's mission-critical payload, the CCRS, and its modules and subsystems, for which GSFC has the lead responsibility and JPL and other Centers have supporting roles. Among other concerns, the IRB is worried that higher-priority commitments at GSFC, particularly to the Webb and Roman programs, may prevent the Center from assigning adequate managerial and technical personnel to CCRS. However, the same concern exist with simply adding the CCRS project to JPL's primary responsibilities, unless alternative acquisition approaches to its other MSR obligations (such as outsourcing the SRL to industry) can be found.

Independent of this CCRS system-level issue, the IRB also found potentially unnecessary fragmentation in subsystems and component responsibilities in the CCM between GSFC and JPL, and in the ERM between GSFC and LaRC/ARC.



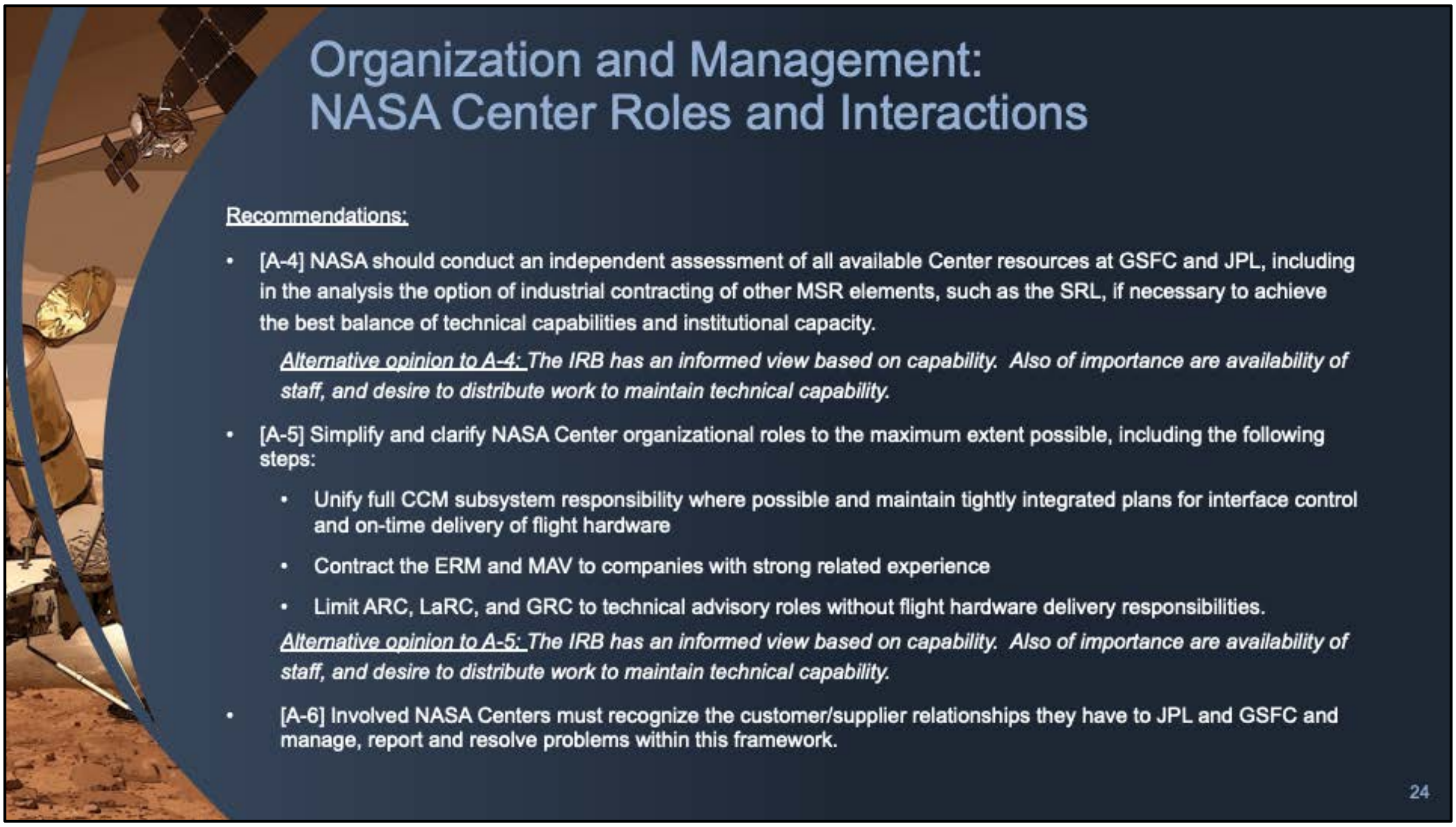
Organization and Management: NASA Center Roles and Interactions

Findings (cont'd):

- GSFC has responsibility for the ERM, but the most relevant expertise for its design and production resides in industry. MSFC has responsibility for the MAV, but the most relevant expertise for its development and integration resides in industry.
- Work assignments to three research Centers (ARC, GRC, LaRC) require these technology-oriented Centers to design and deliver flight hardware that is beyond their recent experience base.
- Traditional peer-to-peer Center relations could jeopardize programmatic performance, as could weak Center institutional commitments to their obligations.

Expanding on our CCRS findings, we also pointed out the opportunities to bring to bear demonstrated industry capabilities for detailed design, production and system integration of the ERM. We note that NASA’s research-oriented Centers do have much to offer in the areas of technical advise, but they lack recent flight hardware fabrication and contracting experience of relevance to MSR.

We have similar concerns with the MAV and recommend that the program look for opportunities to bring to bear demonstrated industrial system integration capabilities.



Organization and Management: NASA Center Roles and Interactions

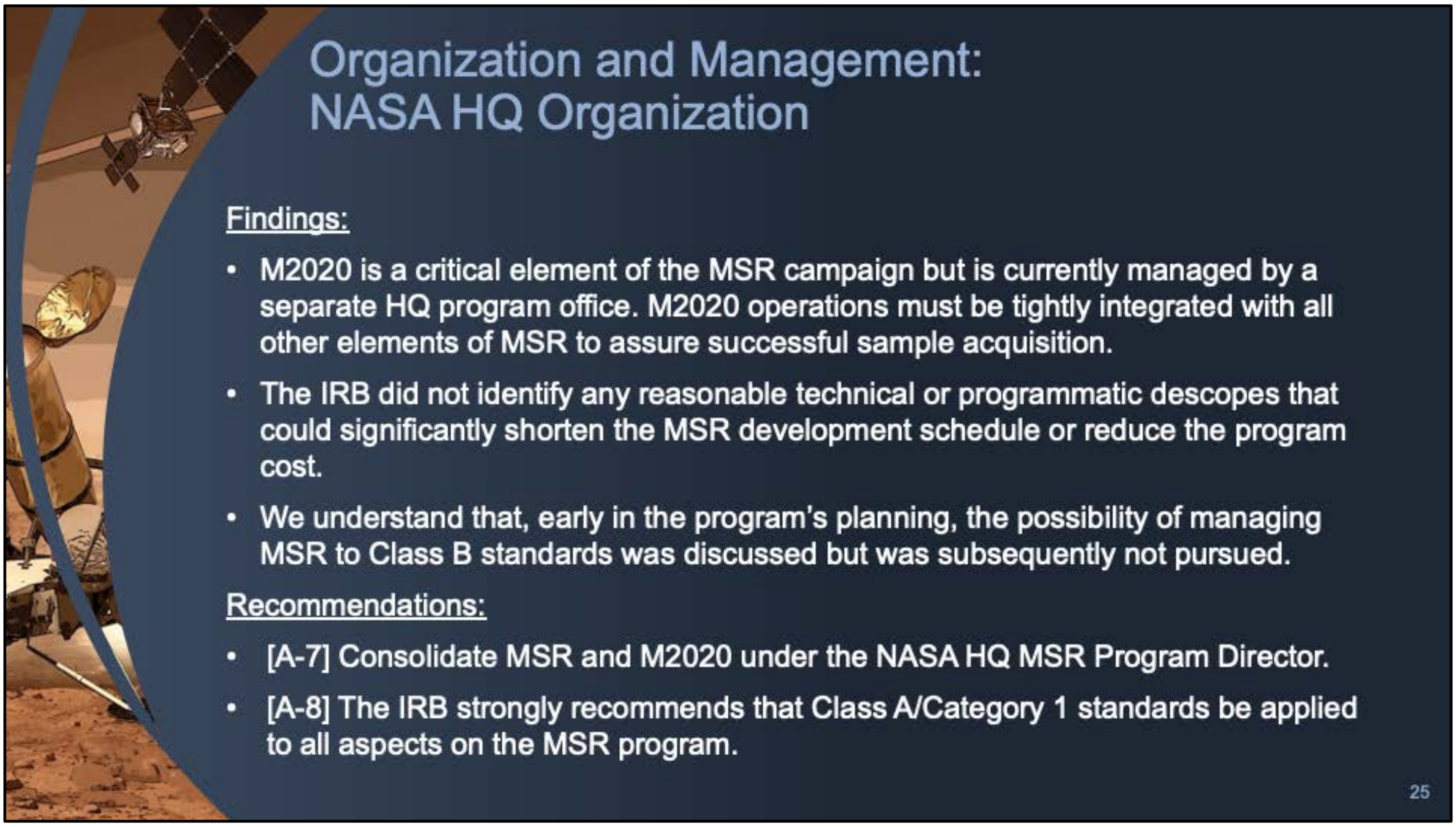
Recommendations:

- [A-4] NASA should conduct an independent assessment of all available Center resources at GSFC and JPL, including in the analysis the option of industrial contracting of other MSR elements, such as the SRL, if necessary to achieve the best balance of technical capabilities and institutional capacity.

  Alternative opinion to A-4: *The IRB has an informed view based on capability. Also of importance are availability of staff, and desire to distribute work to maintain technical capability.*
- [A-5] Simplify and clarify NASA Center organizational roles to the maximum extent possible, including the following steps:
  - Unify full CCM subsystem responsibility where possible and maintain tightly integrated plans for interface control and on-time delivery of flight hardware
  - Contract the ERM and MAV to companies with strong related experience
  - Limit ARC, LaRC, and GRC to technical advisory roles without flight hardware delivery responsibilities.

  Alternative opinion to A-5: *The IRB has an informed view based on capability. Also of importance are availability of staff, and desire to distribute work to maintain technical capability.*
- [A-6] Involved NASA Centers must recognize the customer/supplier relationships they have to JPL and GSFC and manage, report and resolve problems within this framework.

The IRB’s recommendations concerning CCRS project management and that of its major elements, the CCM and ERM, is covered on this chart. As it shows, we believe these aspects of the MSR program are so important that they deserve another look at whether all internal NASA resources are being deployed to best advantage, and whether the use of greater industry outsourcing could provide both additional options for assigning Center responsibilities and stronger relevant experience in production and systems integration.



Organization and Management: NASA HQ Organization

Findings:

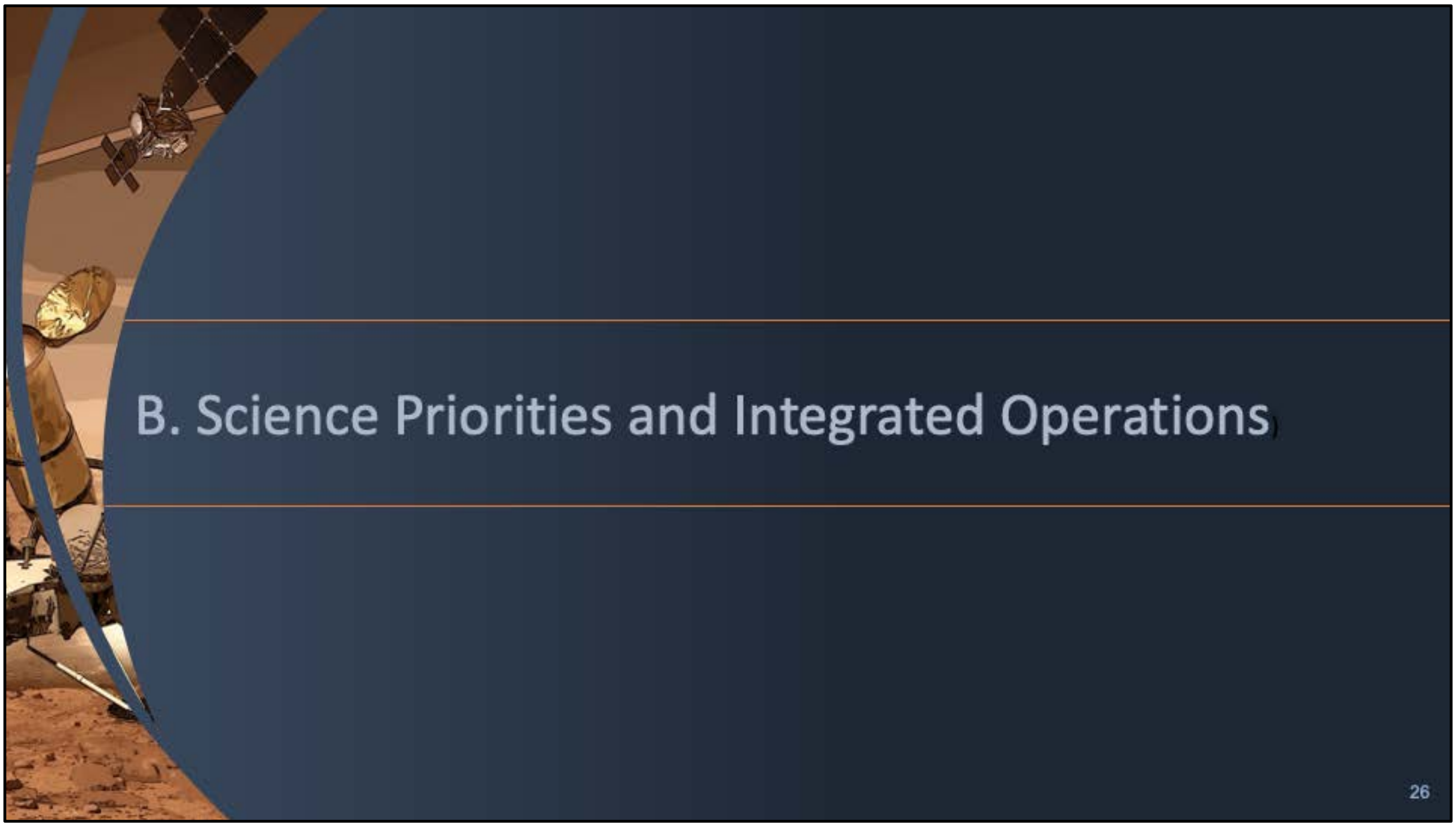
- M2020 is a critical element of the MSR campaign but is currently managed by a separate HQ program office. M2020 operations must be tightly integrated with all other elements of MSR to assure successful sample acquisition.
- The IRB did not identify any reasonable technical or programmatic descopes that could significantly shorten the MSR development schedule or reduce the program cost.
- We understand that, early in the program's planning, the possibility of managing MSR to Class B standards was discussed but was subsequently not pursued.

Recommendations:

- [A-7] Consolidate MSR and M2020 under the NASA HQ MSR Program Director.
- [A-8] The IRB strongly recommends that Class A/Category 1 standards be applied to all aspects on the MSR program.

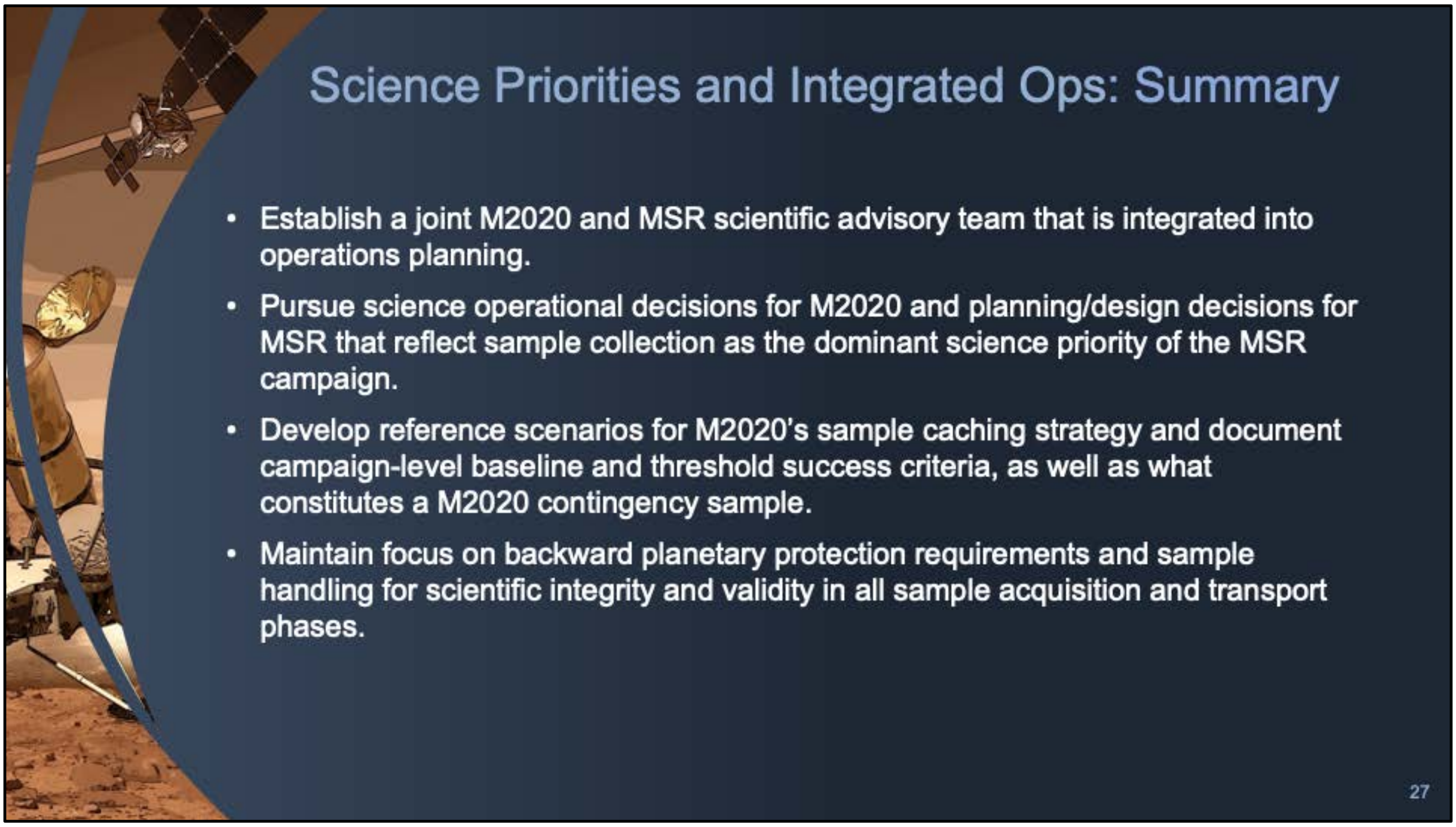
Since M2020 and MSR are two essential parts of the same Mars sample acquisition and return campaign, they must be highly integrated at all managerial and operational levels. Therefore, we recommend that M2020 and MSR be placed under the MSR Program Director at NASA HQ. We will have more to say about M2020/MSR integration at the operational level in the report's next section.

The IRB strongly believes that MSR must be implemented to the highest of NASA's standards, and tailoring must be minimized and carefully reviewed by institutional independent technical authority.



B. Science Priorities and Integrated Operations

In our report’s second category, science priorities and integrated operations, the IRB presents five findings and nine recommendations. Here we stress the dominant scientific priority of the campaign — “it’s all about the samples!” — and the importance of tight integration of all aspects of M2020 and MSR.



Science Priorities and Integrated Ops: Summary

- Establish a joint M2020 and MSR scientific advisory team that is integrated into operations planning.
- Pursue science operational decisions for M2020 and planning/design decisions for MSR that reflect sample collection as the dominant science priority of the MSR campaign.
- Develop reference scenarios for M2020's sample caching strategy and document campaign-level baseline and threshold success criteria, as well as what constitutes a M2020 contingency sample.
- Maintain focus on backward planetary protection requirements and sample handling for scientific integrity and validity in all sample acquisition and transport phases.

A summary of the IRB's recommendations on the criticality of scientific/operational interactions between M2020 and MSR is presented above. It elaborates on the "all about the samples" theme in several ways.

Science Priorities and Integrated Operations

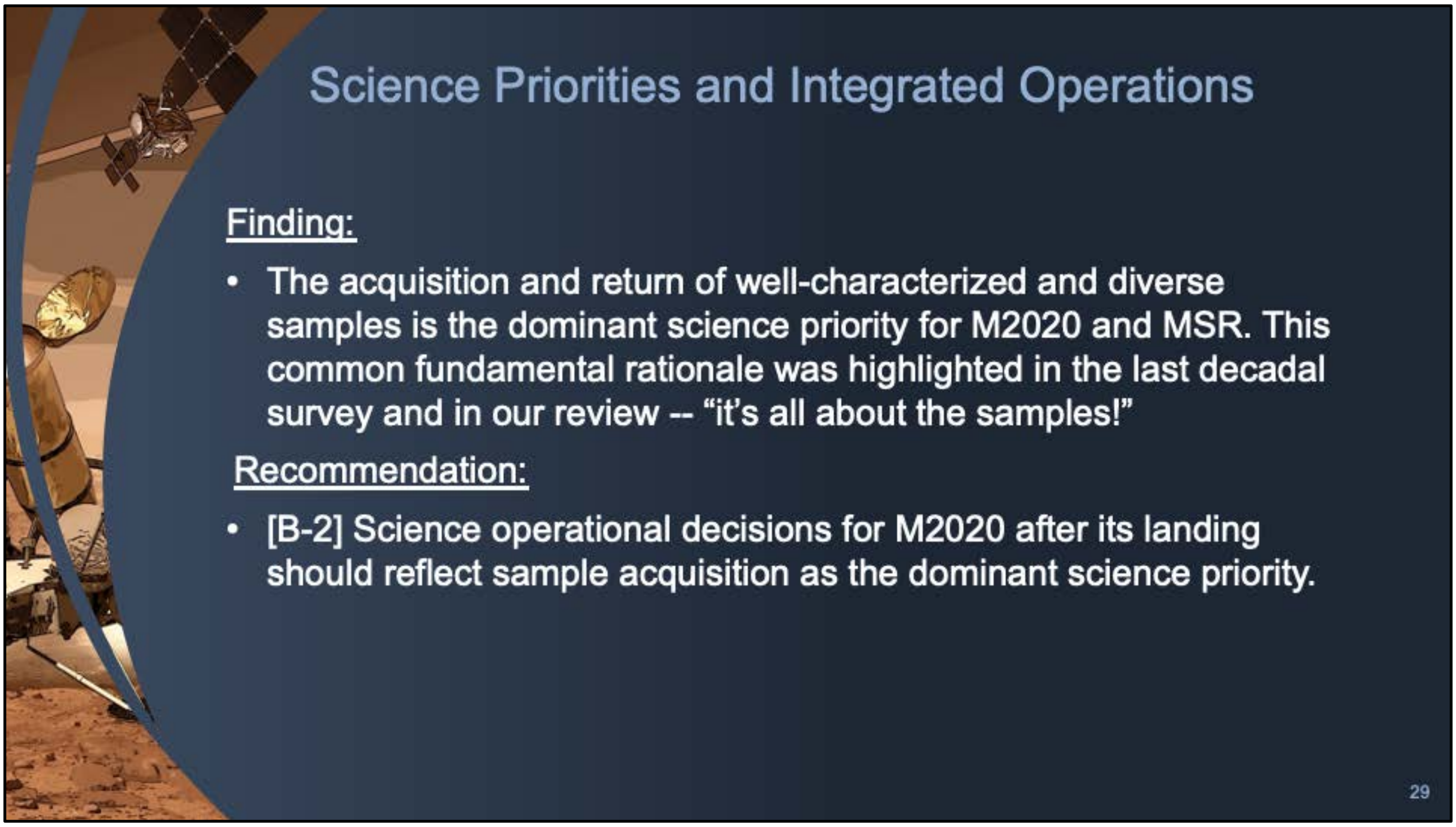
Findings:

- M2020 and MSR are tightly-coupled programs that require integration at all levels to fully achieve common scientific goals. This integration cannot be achieved solely via the reporting structure at NASA HQ.
- Due to workforce and funding limitations, scientific and operational teams on M2020 and MSR have had limited communication and coordination.
- As a result of this apparent disconnect, opportunities may be missed for campaign-level optimization of sample collection and caching by M2020 and sample retrieval and Earth return by MSR.

Recommendation:

- [B-1] A scientific advisory team (or dedicated subgroup) for both M2020 and MSR should be formed immediately and integrated into operations planning. The membership of this team should include leading sample analysis and mission operations experts.

The IRB believes that sample scientists should be an integral part of M2020 surface operations and sample acquisition planning and implementation. The IRB recognizes and applauds the fact that several sample scientists were competitively selected recently as part of the Mars Returned Sample Science Participating Scientist program; these sample analysis experts should be integrated immediately into the M2020 surface operations. Moreover, a subset of the M2020 sample analysis and mission operations experts working on sample acquisition planning and implementation should be part of the recommended scientific advisory team that should additionally involve personnel involved with MSR planning and operations. This integration between the sample scientists and surface operations personnel for M2020 and MSR will be essential for ensuring compatibility between M2020 and MSR (for example, ensuring that the M2020 sample caching and depot locations are compatible with the surface lifetime and mobility requirements for the Sample Fetch Rover for MSR).



Science Priorities and Integrated Operations

Finding:

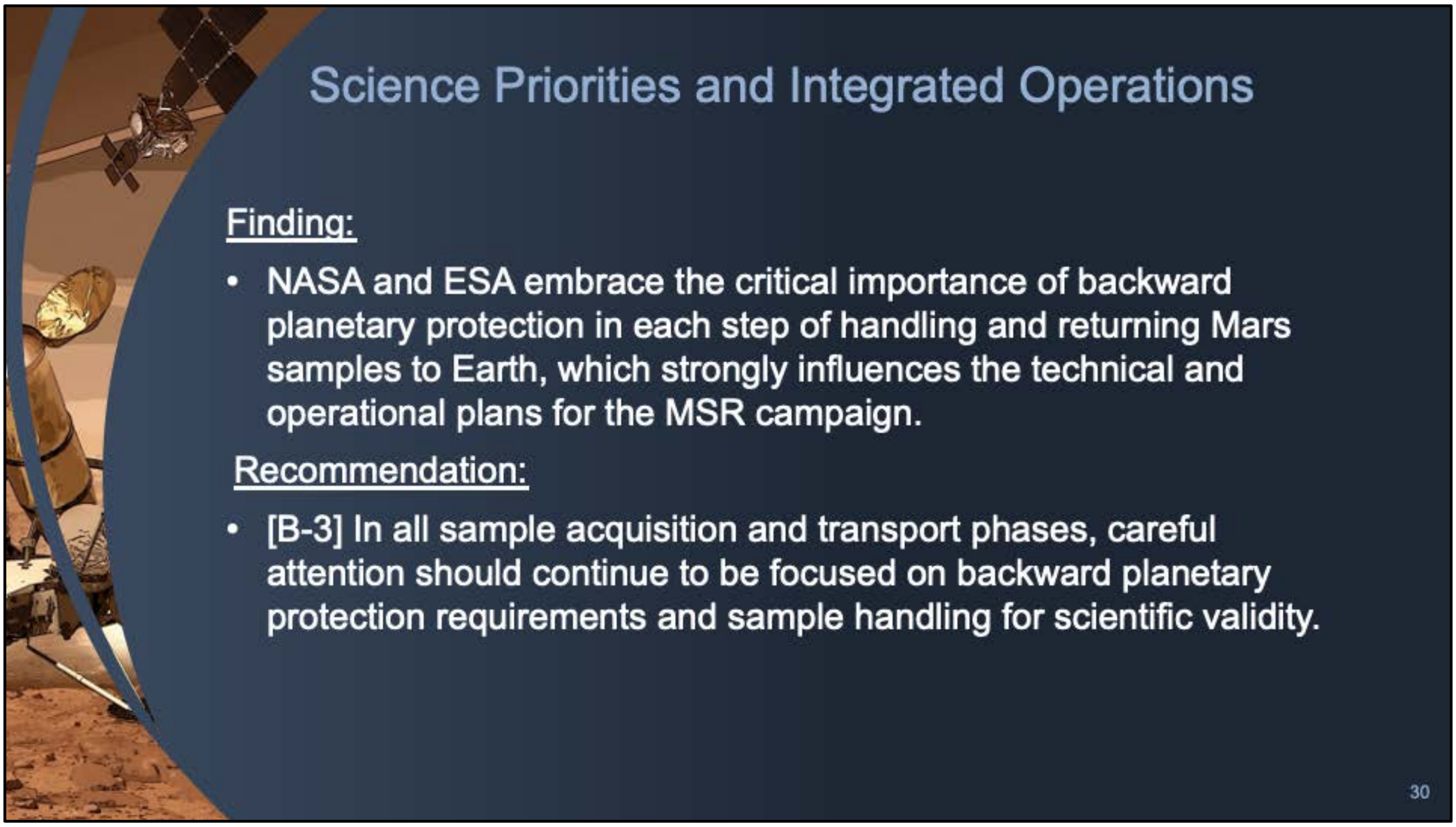
- The acquisition and return of well-characterized and diverse samples is the dominant science priority for M2020 and MSR. This common fundamental rationale was highlighted in the last decadal survey and in our review -- "it's all about the samples!"

Recommendation:

- [B-2] Science operational decisions for M2020 after its landing should reflect sample acquisition as the dominant science priority.

29

Despite the impressive capabilities of the M2020 instruments and payloads to conduct a variety of secondary scientific and ISRU-focused investigations, priority must be given to fulfilling the primary mission, i.e., the acquisition of a well-characterized and diverse sample suite.



Science Priorities and Integrated Operations

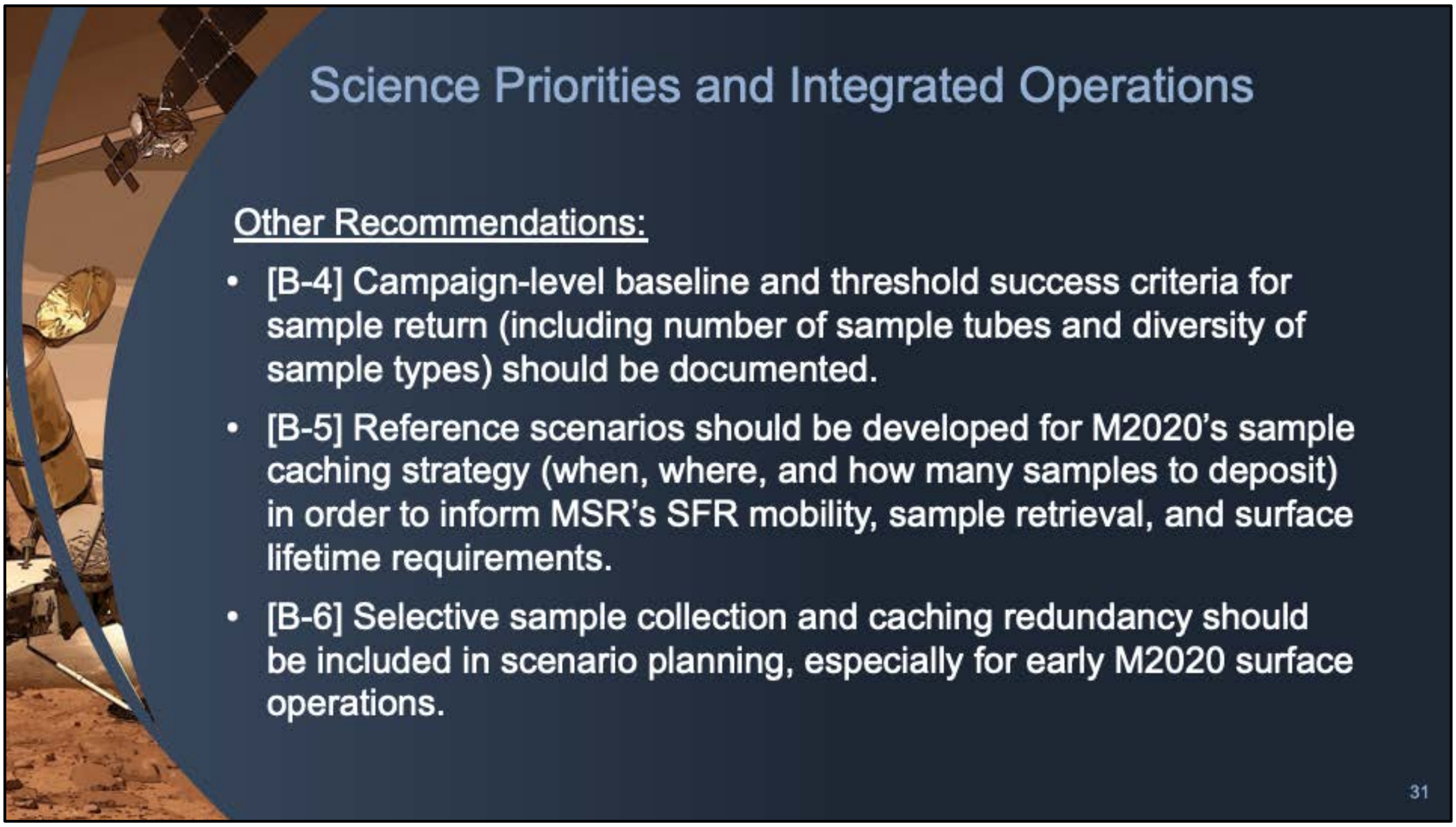
Finding:

- NASA and ESA embrace the critical importance of backward planetary protection in each step of handling and returning Mars samples to Earth, which strongly influences the technical and operational plans for the MSR campaign.

Recommendation:

- [B-3] In all sample acquisition and transport phases, careful attention should continue to be focused on backward planetary protection requirements and sample handling for scientific validity.

MSR will be the first restricted Earth return mission since Apollo. This will require careful planning in the area of backward planetary protection as well as timely coordination with other agencies (such as NEPA).

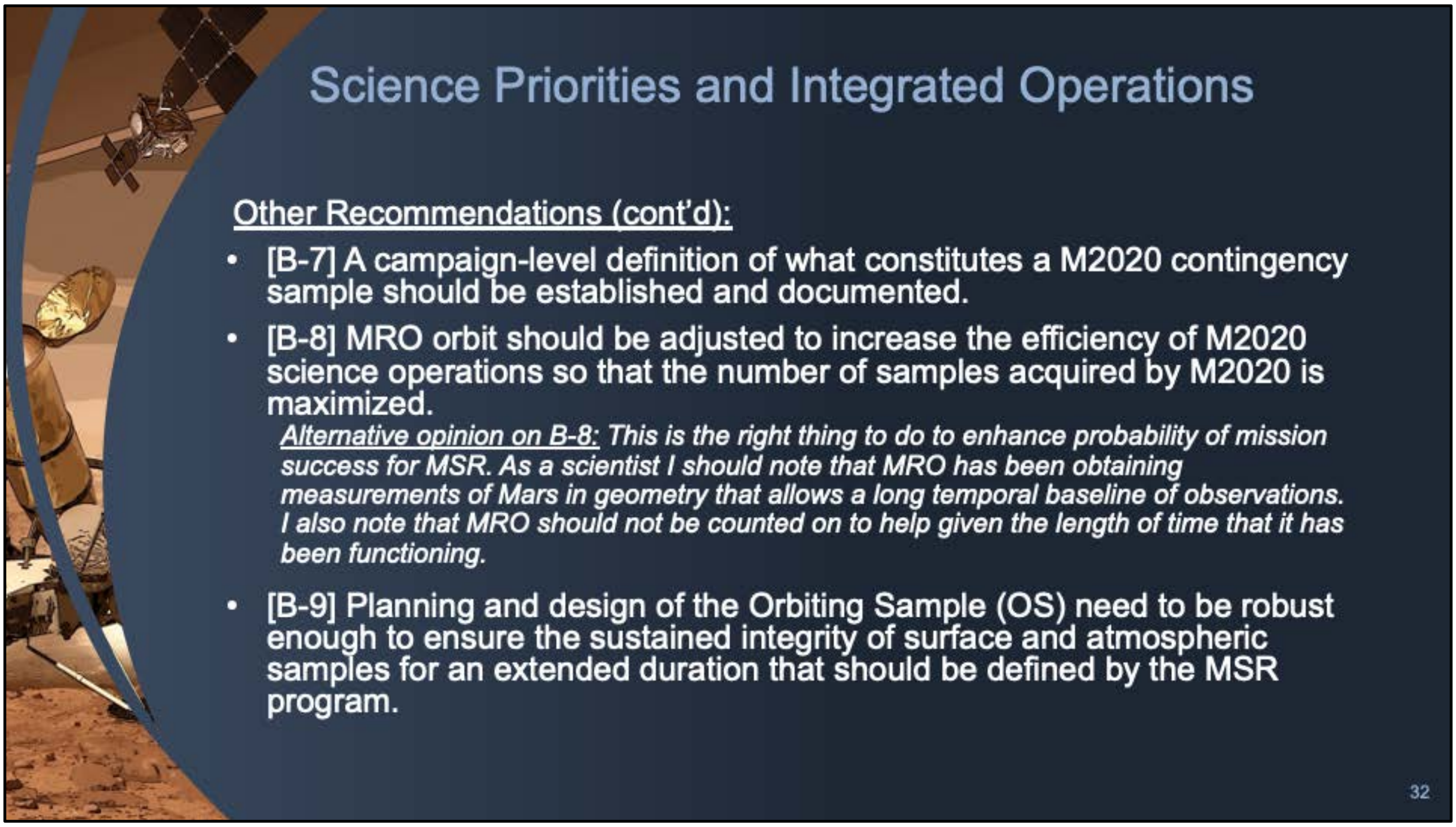


Science Priorities and Integrated Operations

Other Recommendations:

- [B-4] Campaign-level baseline and threshold success criteria for sample return (including number of sample tubes and diversity of sample types) should be documented.
- [B-5] Reference scenarios should be developed for M2020's sample caching strategy (when, where, and how many samples to deposit) in order to inform MSR's SFR mobility, sample retrieval, and surface lifetime requirements.
- [B-6] Selective sample collection and caching redundancy should be included in scenario planning, especially for early M2020 surface operations.

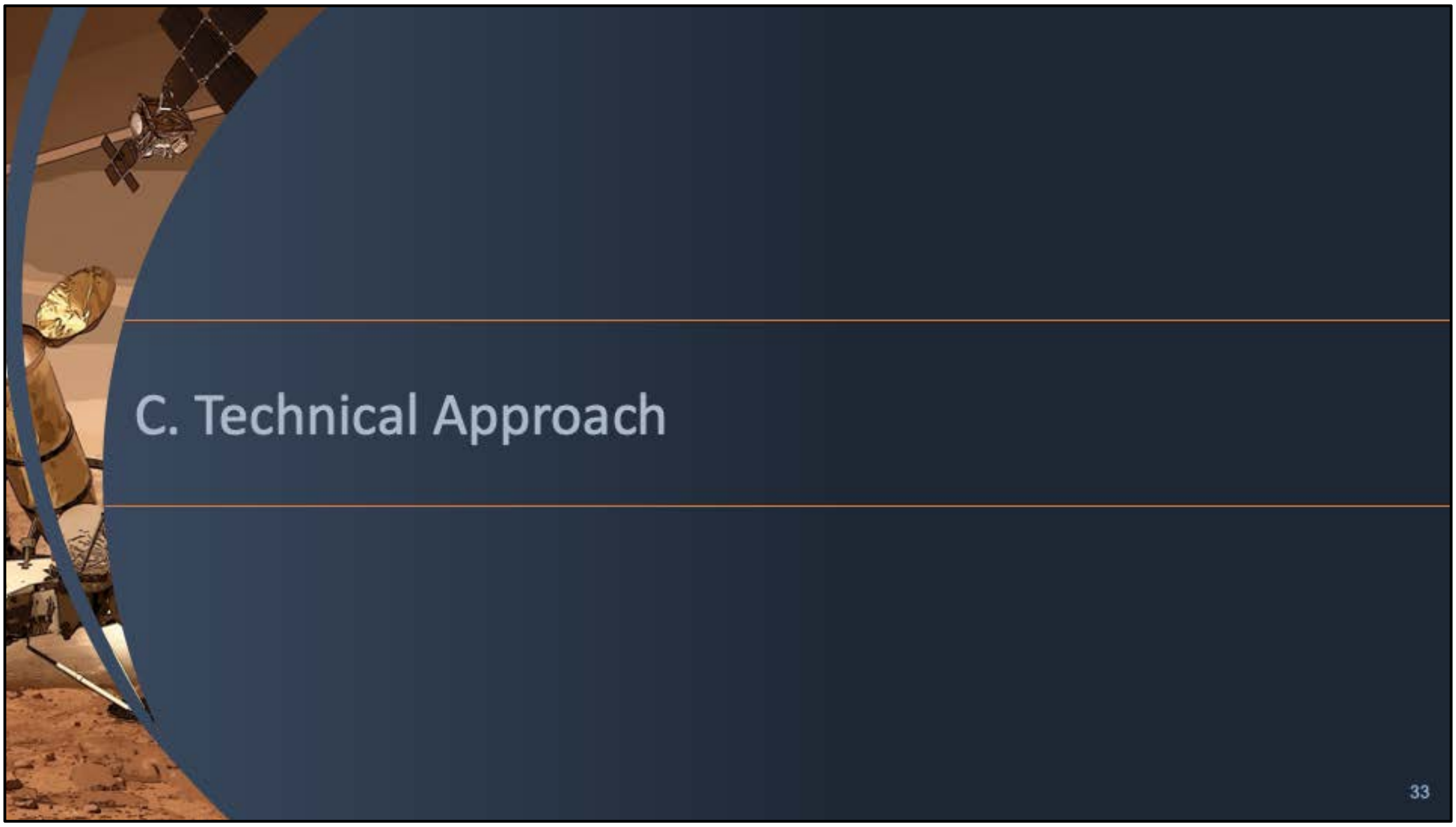
In addition to the previous recommendations in the area of science priorities and integrated operations that follow from findings, the IRB has additional recommendations to safeguard samples and maximize the scientific impact of MSR.



Science Priorities and Integrated Operations

Other Recommendations (cont’d):

- [B-7] A campaign-level definition of what constitutes a M2020 contingency sample should be established and documented.
- [B-8] MRO orbit should be adjusted to increase the efficiency of M2020 science operations so that the number of samples acquired by M2020 is maximized.
  Alternative opinion on B-8: This is the right thing to do to enhance probability of mission success for MSR. As a scientist I should note that MRO has been obtaining measurements of Mars in geometry that allows a long temporal baseline of observations. I also note that MRO should not be counted on to help given the length of time that it has been functioning.
- [B-9] Planning and design of the Orbiting Sample (OS) need to be robust enough to ensure the sustained integrity of surface and atmospheric samples for an extended duration that should be defined by the MSR program.

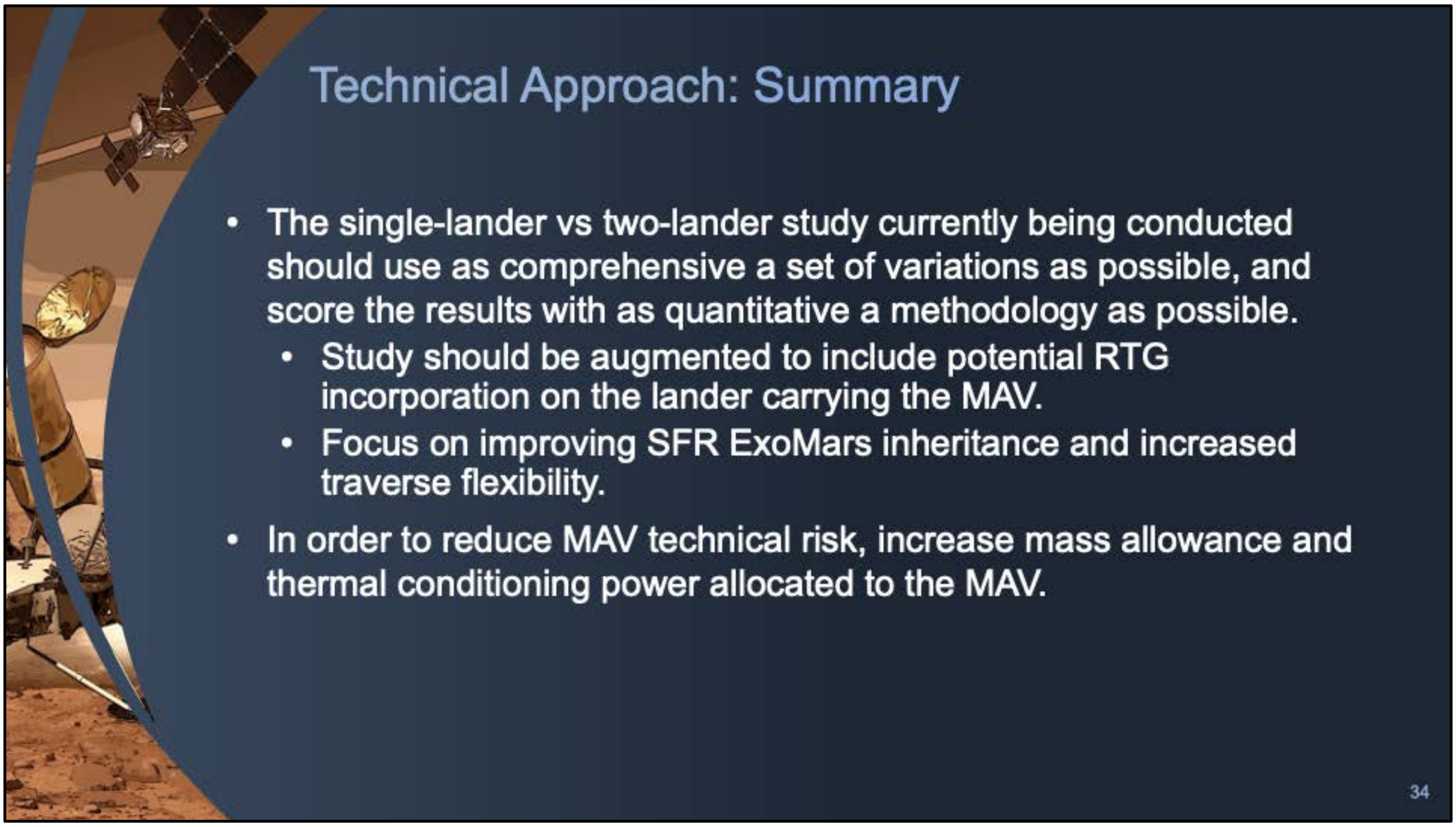


C. Technical Approach

Our third section, covering the broad topic of the mission’s technical architecture and system design approaches, consists of 21 findings and 17 recommendations.

We set the stage for this part of our report by noting the long string of serial events that are inherent and unavoidable in the MSR mission, including these eight first-time challenges:
- High-precision planetary landing
- Small object location in an unstructured environment
- Sample collection and transfer from one surface vehicle to another
- First launch from another planet
- Fully autonomous orbital rendezvous and capture
- Robotic sample handling and sealing to break-the-chain standards
- Departure from Mars orbit on Earth-return trajectory
- Safe atmospheric entry and landing under restricted return constraints

Successfully carrying out these and other mission-critical events, in many cases using newly-developed systems based on not-yet-proven technologies and with stringent design and performance requirements, highlights the substantial technical challenges facing the MSR team.



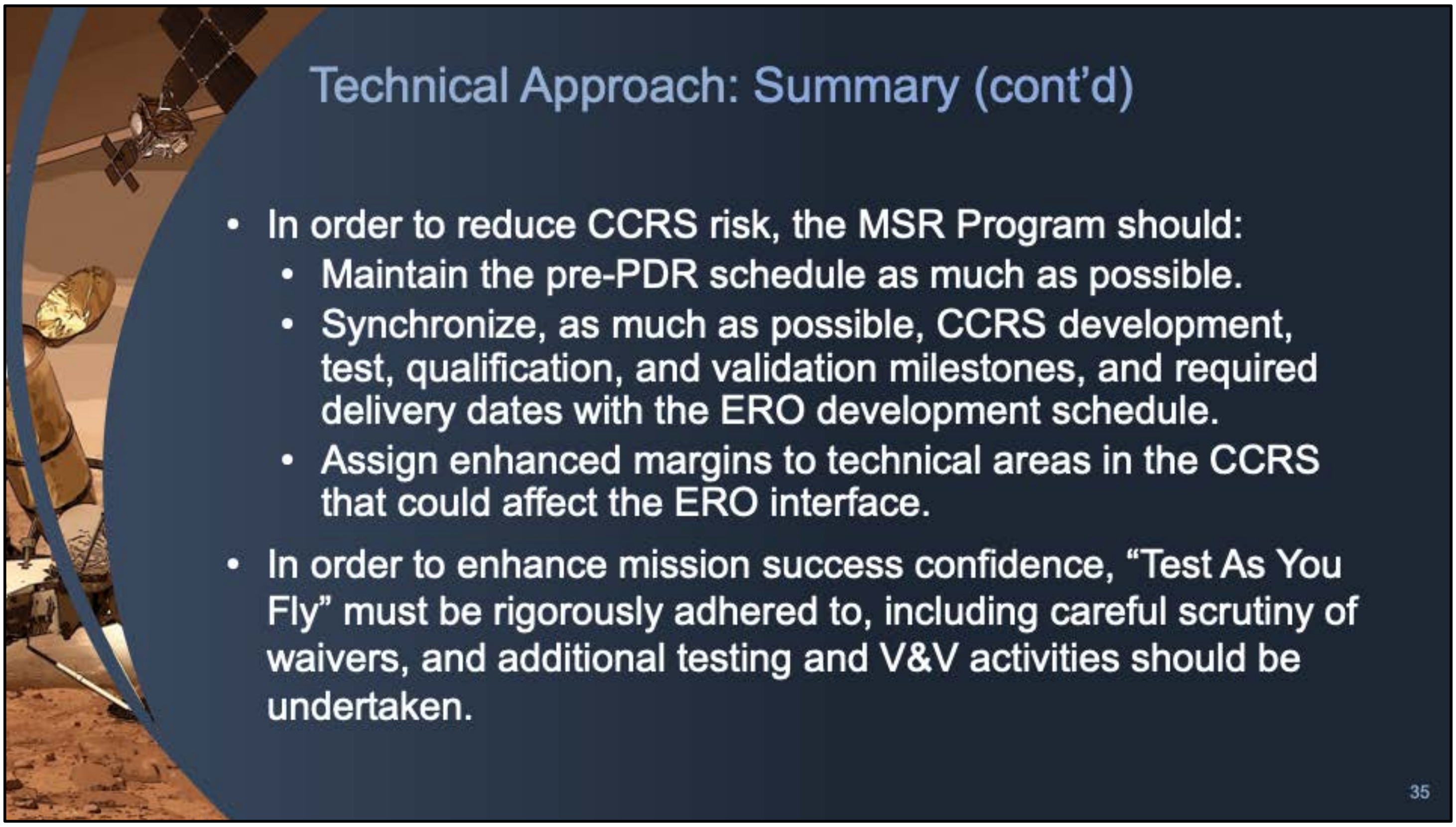
Technical Approach: Summary

- The single-lander vs two-lander study currently being conducted should use as comprehensive a set of variations as possible, and score the results with as quantitative a methodology as possible.
  - Study should be augmented to include potential RTG incorporation on the lander carrying the MAV.
  - Focus on improving SFR ExoMars inheritance and increased traverse flexibility.
- In order to reduce MAV technical risk, increase mass allowance and thermal conditioning power allocated to the MAV.

The IRB’s review of the technical approach to the MSR mission was quite extensive, facilitated by the excellent cooperation we received from JPL, GSFC, MSFC and ESA experts. As discussed on this and the following charts, our recommendations are organized into four main categories:

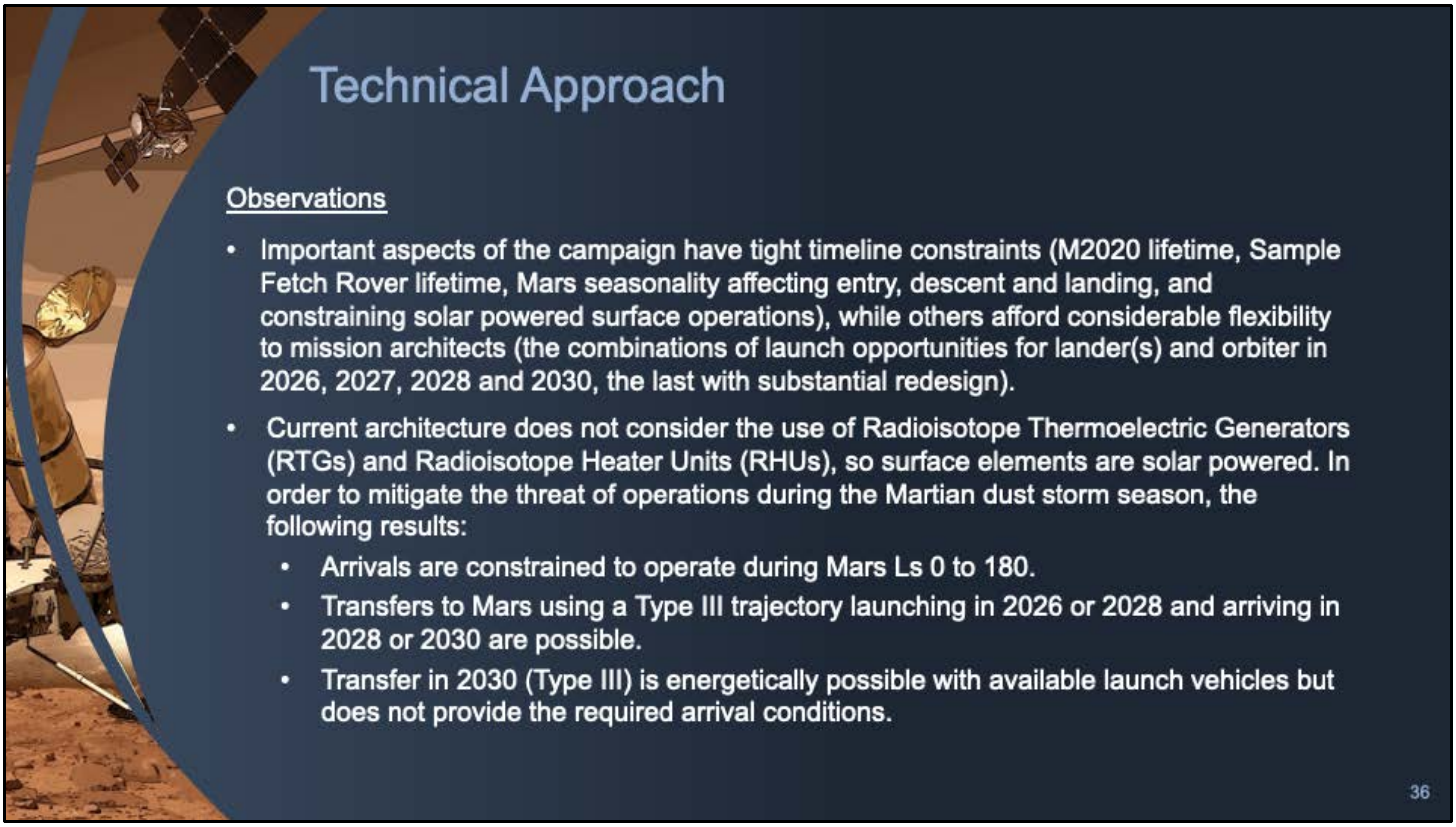
- Sample Retrieval Lander architectural options
- Mars Ascent Vehicle design and environmental factors
- Capture, Containment and Return System interfaces and schedules
- Validation and Verification discipline

We also discuss some of the ERO and SFR development challenges and highlight the importance of additional work on “safe havens” for the sample container at various phases in the MSR mission.



Technical Approach: Summary (cont'd)

- In order to reduce CCRS risk, the MSR Program should:
  - Maintain the pre-PDR schedule as much as possible.
  - Synchronize, as much as possible, CCRS development, test, qualification, and validation milestones, and required delivery dates with the ERO development schedule.
  - Assign enhanced margins to technical areas in the CCRS that could affect the ERO interface.
- In order to enhance mission success confidence, "Test As You Fly" must be rigorously adhered to, including careful scrutiny of waivers, and additional testing and V&V activities should be undertaken.



Technical Approach

Observations

- Important aspects of the campaign have tight timeline constraints (M2020 lifetime, Sample Fetch Rover lifetime, Mars seasonality affecting entry, descent and landing, and constraining solar powered surface operations), while others afford considerable flexibility to mission architects (the combinations of launch opportunities for lander(s) and orbiter in 2026, 2027, 2028 and 2030, the last with substantial redesign).
- Current architecture does not consider the use of Radioisotope Thermoelectric Generators (RTGs) and Radioisotope Heater Units (RHUs), so surface elements are solar powered. In order to mitigate the threat of operations during the Martian dust storm season, the following results:
  - Arrivals are constrained to operate during Mars Ls 0 to 180.
  - Transfers to Mars using a Type III trajectory launching in 2026 or 2028 and arriving in 2028 or 2030 are possible.
  - Transfer in 2030 (Type III) is energetically possible with available launch vehicles but does not provide the required arrival conditions.

Beyond normal schedule constraints arising from orbital mechanics that most planetary missions face, MSR must deal with additional timeline factors relating to M2020 and SFR operational lifetimes and Mars seasonal weather patterns. Launch windows and transfer trajectories are available for the ERO in 2027 and 2028, and for the SRL in 2028. Launches in the 2030 opportunity have arrival conditions which are incompatible with MSR requirements. Important lander design decisions, particularly the possibility of using radioisotope power units, may contribute to relaxing some of the most critical timeline constraints, as discussed later in this section.

Technical Approach: Overall Campaign Architecture

Findings:

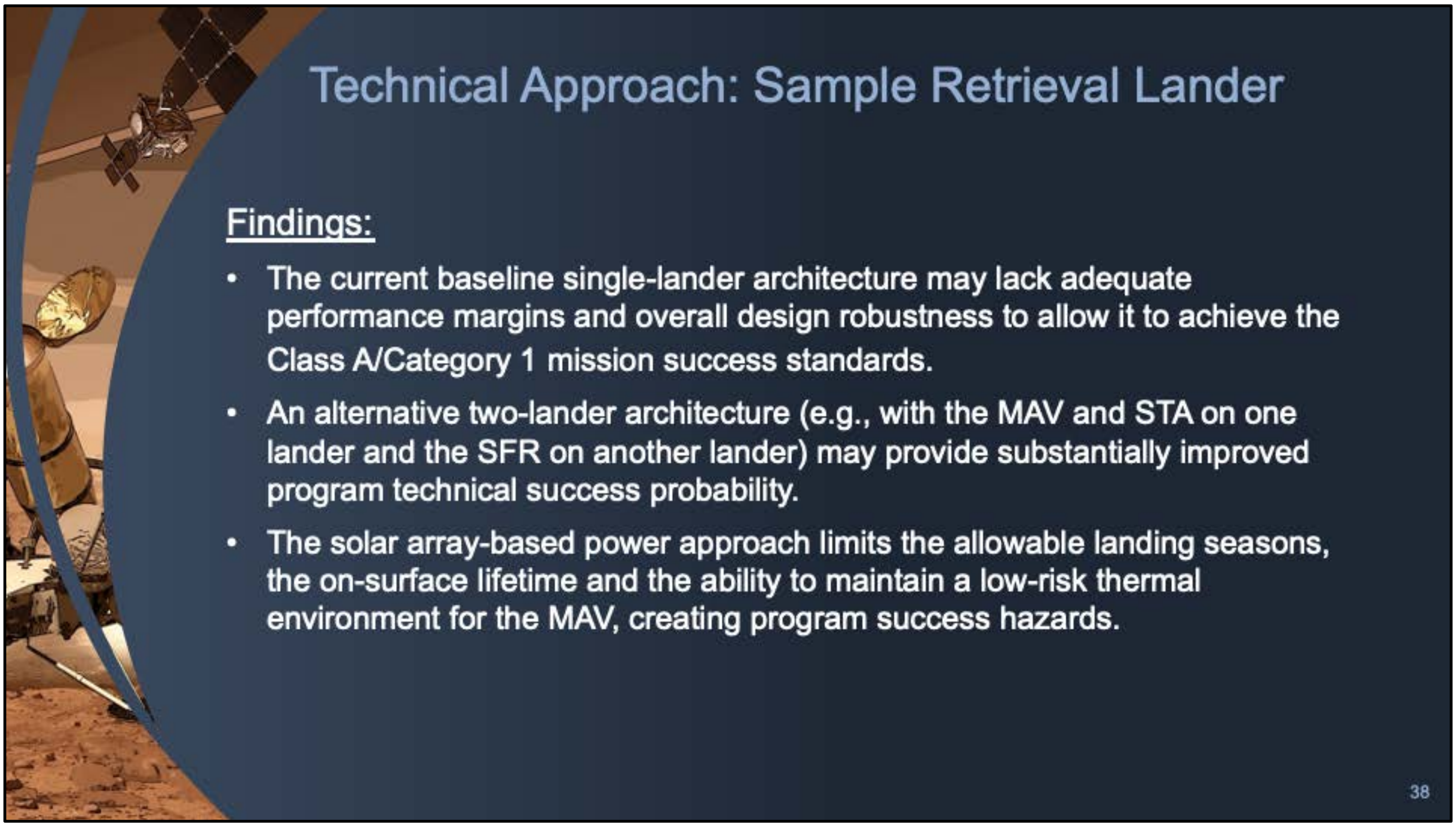
- The MSR architecture is extremely complex, requiring a long series of critical events, all being carried out with high precision and reliability and many of them being accomplished for the first time.
- The project is engaged in a series of studies to be completed early in Phase A with the goals of improving technical margins, reducing product complexity, and/or reducing cost and schedule risk.

Recommendation:

- [C-1] Complete Pre-Phase A and Phase A studies on the present schedule with an emphasis on architectural trades.

As noted earlier, the MSR campaign must complete a long series of critical events requiring high precision and reliability, all of which are essential to the success of sample return. The program team has already properly considered and eliminated numerous potential architectures. Several fundamental alternatives are still being assessed and are to be completed in Phase A . They are focused on further reductions in technical and operational risks, improvements in technical margins and design flexibility, and reductions in product complexity, with consequent improvements in program success probability and reductions in cost and schedule risk.

The IRB’s perspective on these alternatives, which mainly revolve around lander options and trade-offs, are discussed in the following pages.

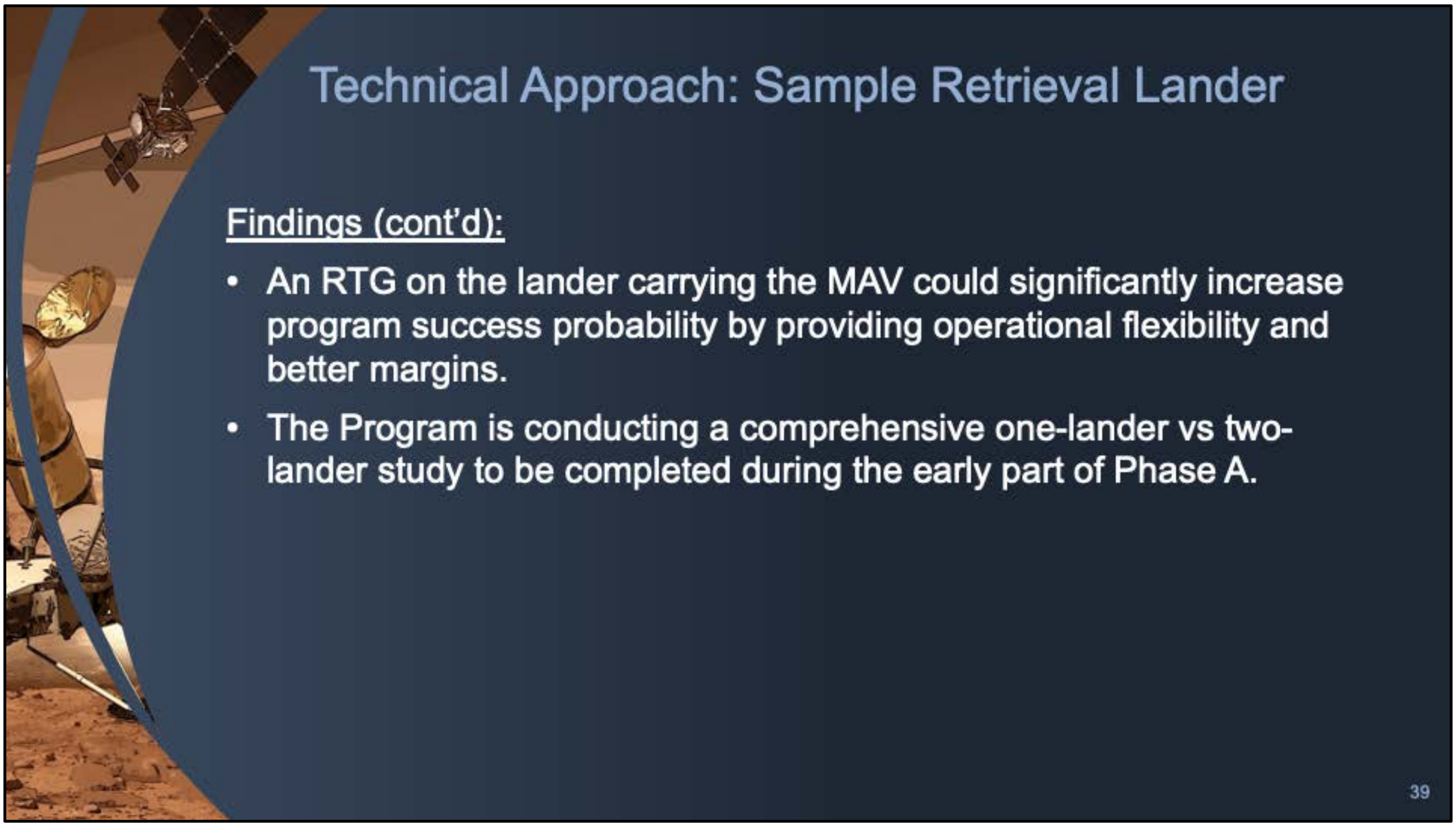


Technical Approach: Sample Retrieval Lander

Findings:

- The current baseline single-lander architecture may lack adequate performance margins and overall design robustness to allow it to achieve the Class A/Category 1 mission success standards.
- An alternative two-lander architecture (e.g., with the MAV and STA on one lander and the SFR on another lander) may provide substantially improved program technical success probability.
- The solar array-based power approach limits the allowable landing seasons, the on-surface lifetime and the ability to maintain a low-risk thermal environment for the MAV, creating program success hazards.

The IRB is concerned about the limited technical margins and restricted design flexibility in the current single-vehicle SRL architecture. We believe a two-lander alternative may open up increased margins and design flexibility, enable greater use of already-developed systems and subsystems.

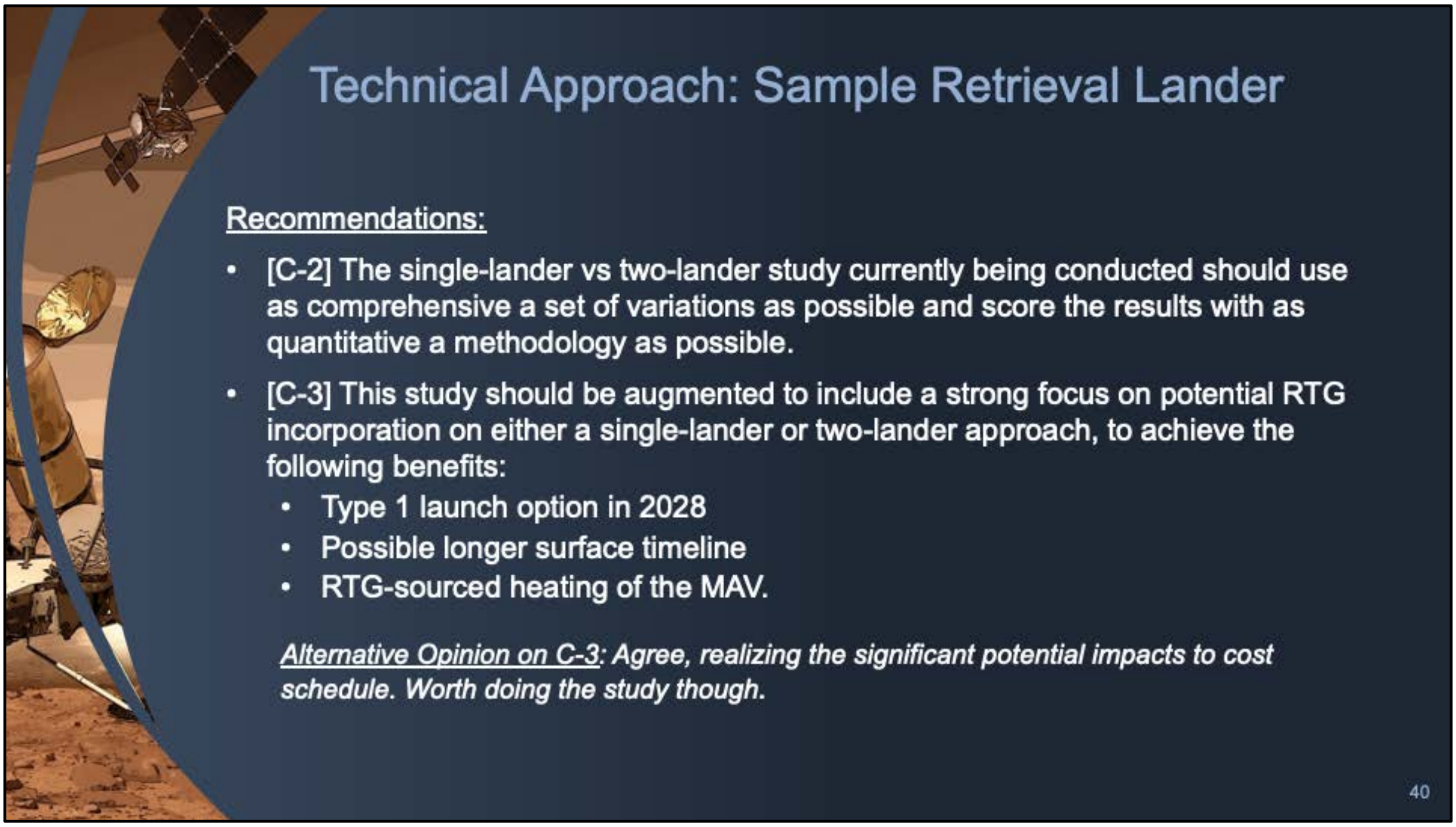


Technical Approach: Sample Retrieval Lander

Findings (cont'd):

- An RTG on the lander carrying the MAV could significantly increase program success probability by providing operational flexibility and better margins.
- The Program is conducting a comprehensive one-lander vs two-lander study to be completed during the early part of Phase A.

When coupled with the use of an RTG on the lander containing the MAV, the design may afford extended surface lifetimes, and reduced risk in the MAV's surface thermal environment.



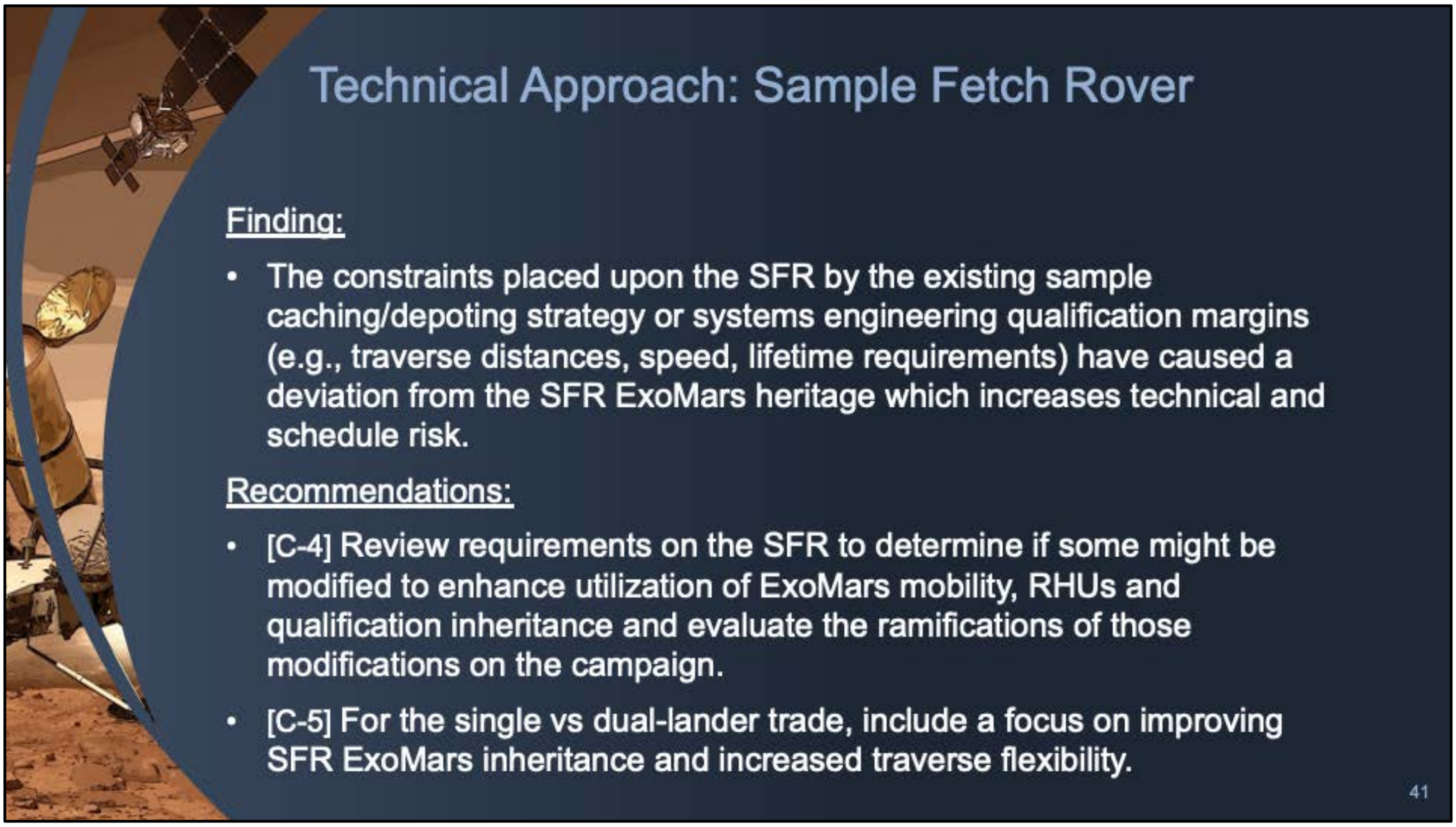
Technical Approach: Sample Retrieval Lander

Recommendations:

- [C-2] The single-lander vs two-lander study currently being conducted should use as comprehensive a set of variations as possible and score the results with as quantitative a methodology as possible.
- [C-3] This study should be augmented to include a strong focus on potential RTG incorporation on either a single-lander or two-lander approach, to achieve the following benefits:
  - Type 1 launch option in 2028
  - Possible longer surface timeline
  - RTG-sourced heating of the MAV.

Alternative Opinion on C-3: Agree, realizing the significant potential impacts to cost schedule. Worth doing the study though.

We recommend that the MSR program’s upcoming evaluation of the one- vs. two-lander trade use a comprehensive range of technical features (e.g., EDL systems, MAV guidance systems, SFR designs) and assess the options with probabilistic reliability models and similar quantitative tools. An essential factor to be considered is the range of benefits enabled by RTG use on the lander containing the MAV.



Technical Approach: Sample Fetch Rover

Finding:

- The constraints placed upon the SFR by the existing sample caching/depoting strategy or systems engineering qualification margins (e.g., traverse distances, speed, lifetime requirements) have caused a deviation from the SFR ExoMars heritage which increases technical and schedule risk.

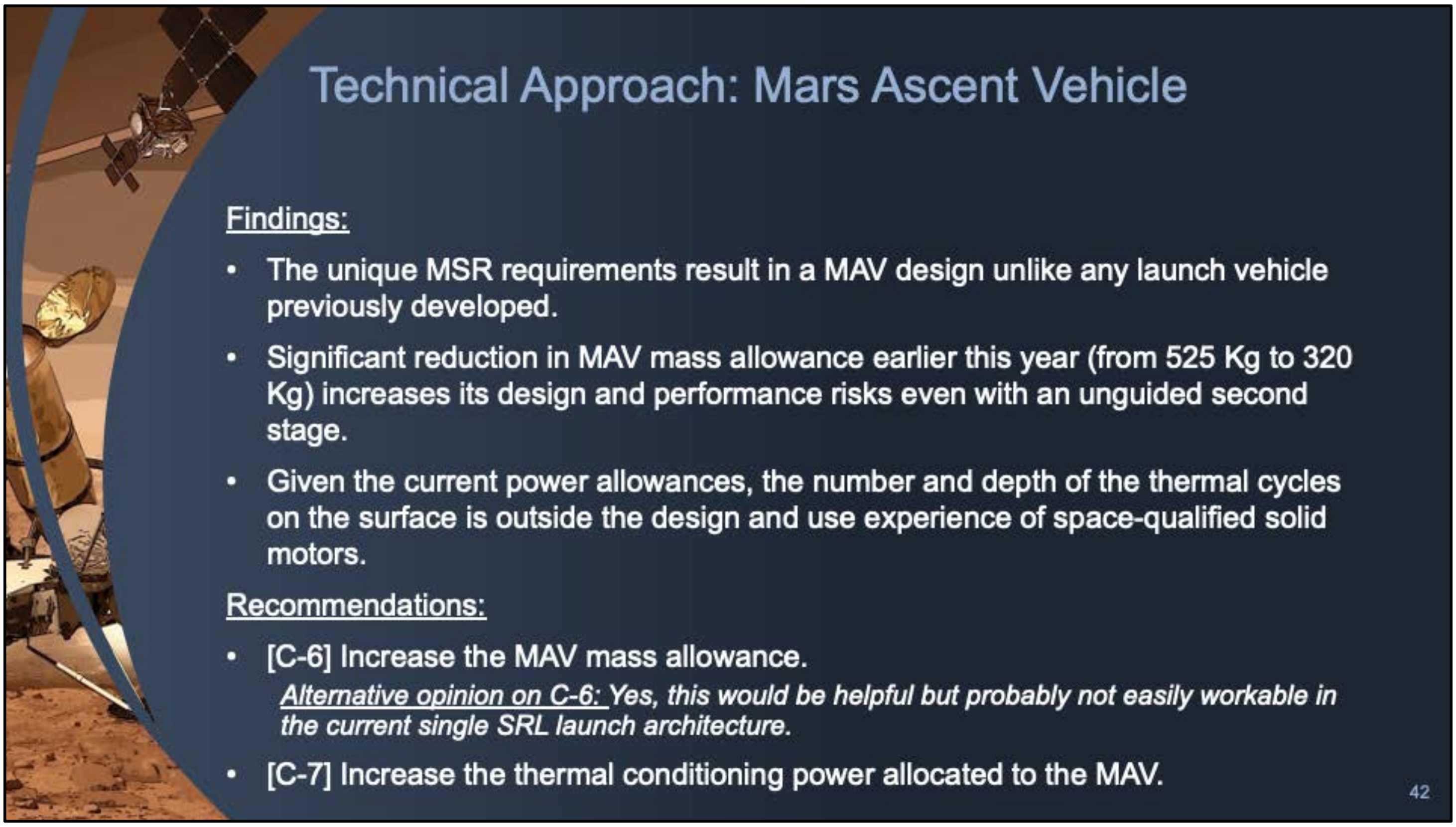
Recommendations:

- [C-4] Review requirements on the SFR to determine if some might be modified to enhance utilization of ExoMars mobility, RHUs and qualification inheritance and evaluate the ramifications of those modifications on the campaign.
- [C-5] For the single vs dual-lander trade, include a focus on improving SFR ExoMars inheritance and increased traverse flexibility.

41

The project is working issues related to the SFR design and requirements changes that would improve inheritance from ExoMars rover design. However, those trades are still ongoing and conclusions were not presented to the IRB.

If increased traverse flexibility were possible, it would maximize sample collection options.



Technical Approach: Mars Ascent Vehicle

Findings:

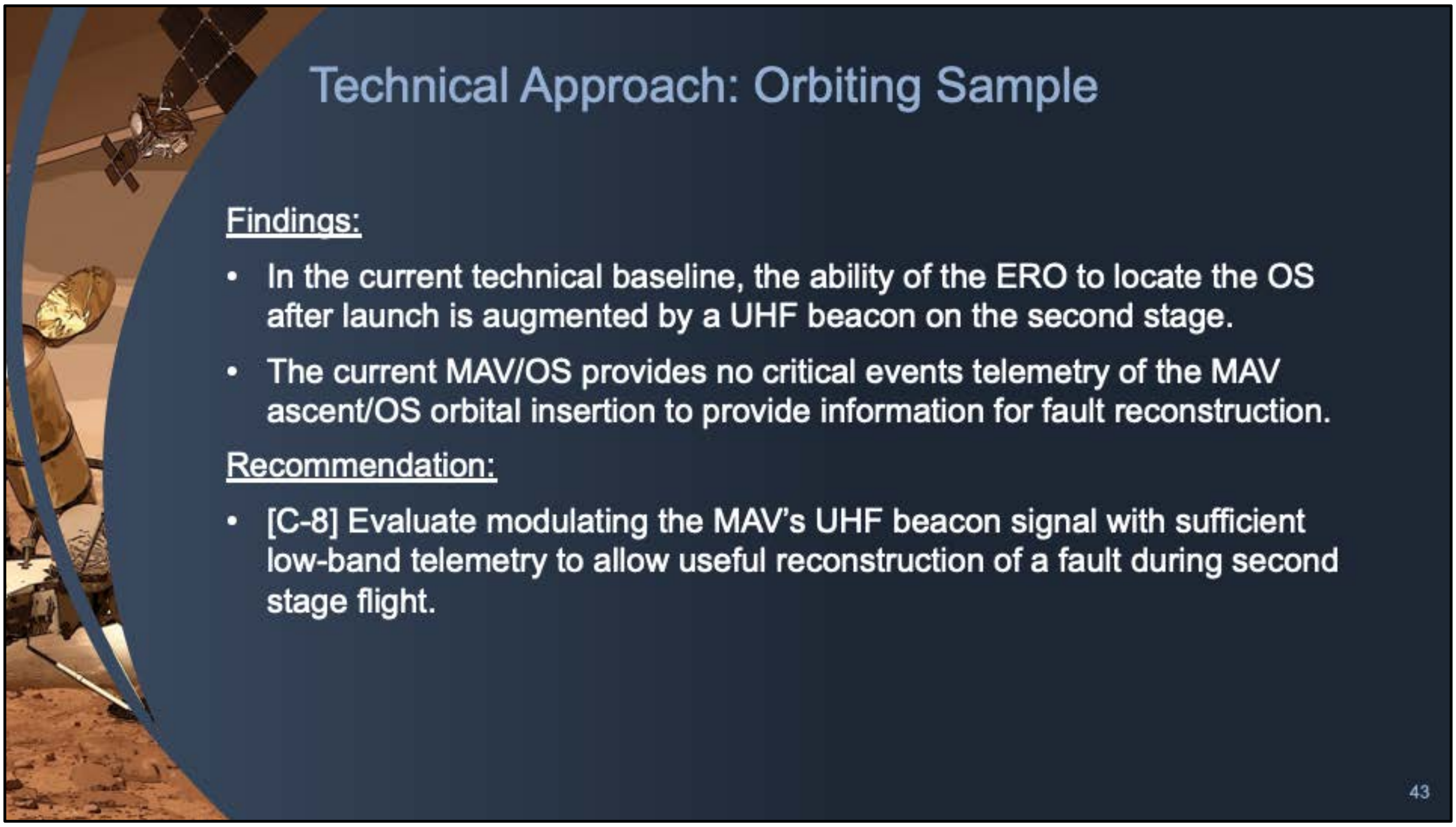
- The unique MSR requirements result in a MAV design unlike any launch vehicle previously developed.
- Significant reduction in MAV mass allowance earlier this year (from 525 Kg to 320 Kg) increases its design and performance risks even with an unguided second stage.
- Given the current power allowances, the number and depth of the thermal cycles on the surface is outside the design and use experience of space-qualified solid motors.

Recommendations:

- [C-6] Increase the MAV mass allowance.
  Alternative opinion on C-6: Yes, this would be helpful but probably not easily workable in the current single SRL launch architecture.
- [C-7] Increase the thermal conditioning power allocated to the MAV.

The fixed-mass-allocation design strategy chosen for the MAV is reasonable but subject to the risk of over-running the allocation, from which there is no design escape. Experience has shown that the smaller a launch vehicle, the more sensitive its dry mass to design uncertainty. The IRB recommends significantly larger dry mass and impulse margins than referenced in traditional standards.

Given a traditional power budget for a solar panel-powered SRL it is unlikely that more than 50W would be available to thermal conditioning of the MAV. This would require the graphite-cased MAV solid motors to experience over 300 day/night thermal cycles for which we have no experience data base. This risk can be reduced by increasing the thermal power allocation to reduce the depth of these cycles.



Technical Approach: Orbiting Sample

Findings:

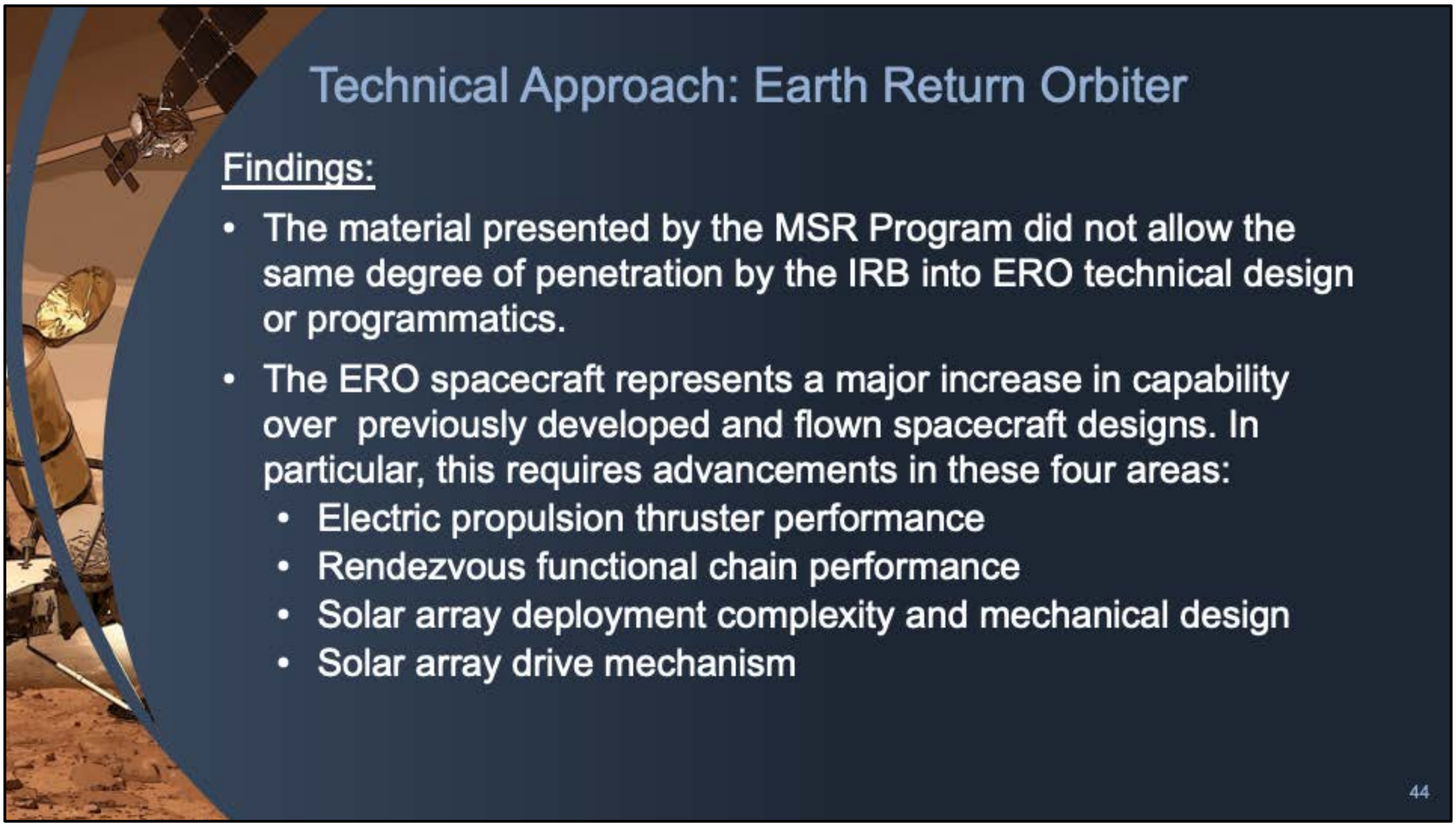
- In the current technical baseline, the ability of the ERO to locate the OS after launch is augmented by a UHF beacon on the second stage.
- The current MAV/OS provides no critical events telemetry of the MAV ascent/OS orbital insertion to provide information for fault reconstruction.

Recommendation:

- [C-8] Evaluate modulating the MAV's UHF beacon signal with sufficient low-band telemetry to allow useful reconstruction of a fault during second stage flight.

The IRB members were originally briefed that the ERO relied only on optical acquisition of either the OS or the nearby MAV second stage and had formulated a recommendation that an RF system be used to aid in the acquisition. We have since been briefed that indeed a UHF "beacon" will be included in the second stage and applaud this decision.

We therefore suggest that it would be a simple and low-mass impact addition to modulate this signal with a modicum of low-bandwidth telemetry conveying information about the MAV events and performance during the ascent, including critical events up to and including OS separation.



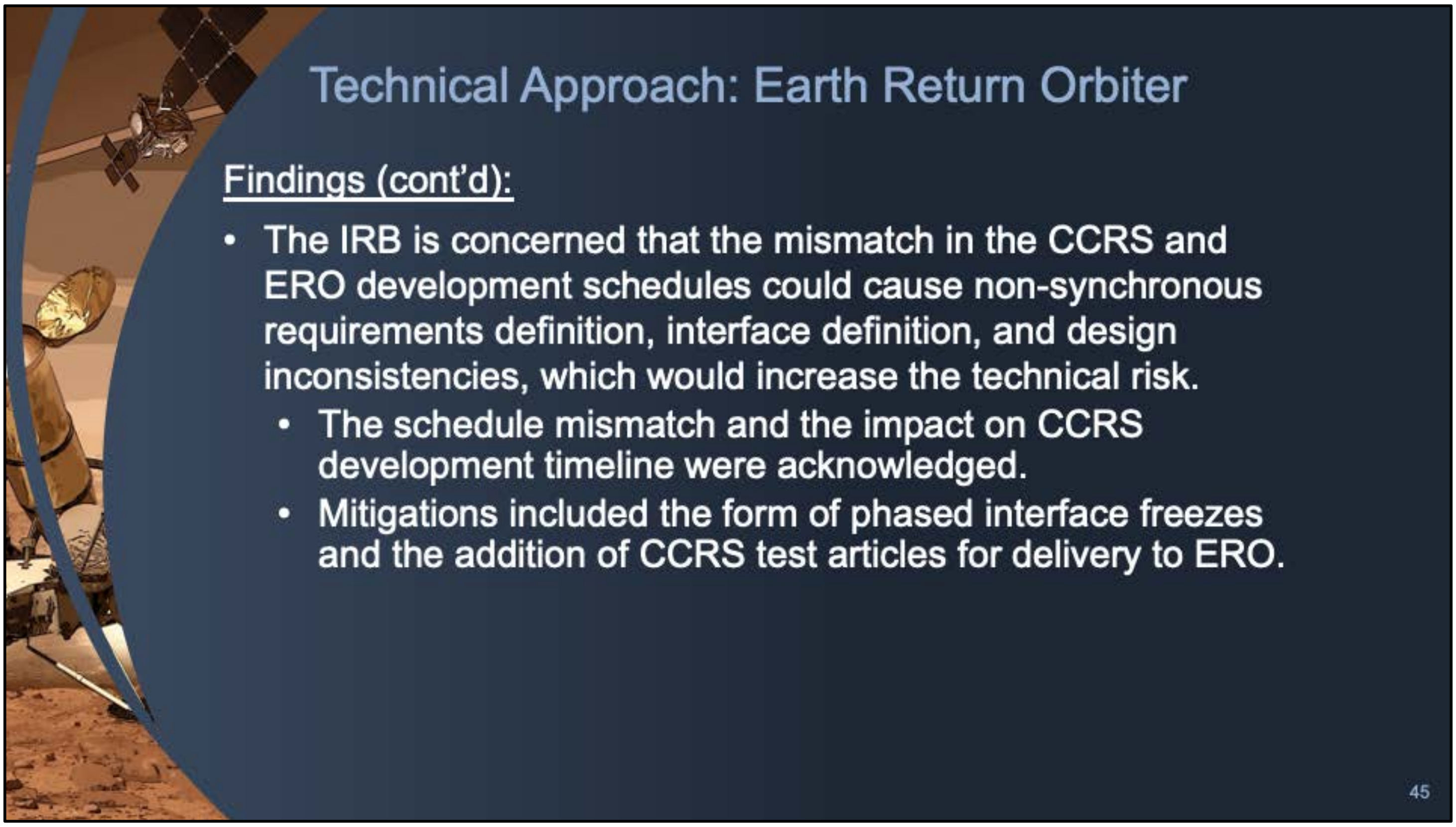
Technical Approach: Earth Return Orbiter

Findings:

- The material presented by the MSR Program did not allow the same degree of penetration by the IRB into ERO technical design or programmatics.
- The ERO spacecraft represents a major increase in capability over previously developed and flown spacecraft designs. In particular, this requires advancements in these four areas:
  - Electric propulsion thruster performance
  - Rendezvous functional chain performance
  - Solar array deployment complexity and mechanical design
  - Solar array drive mechanism

The IRB was not able to review the ESA-supplied ERO in the same level of detail as most other elements of MSR hardware. However, we did note that the ERO spacecraft is a very large and high-power vehicle, with a wingspan of nearly 40 meters and a solar array power level of almost 40 kilowatts (BoL at Earth). With this design, the ERO spacecraft will be among the largest solar-powered robotic space vehicle ever built and will exceed previous deep-space solar-powered probes by almost a factor of three. Therefore, we believe ESA's and its industrial supplier's focus on propulsion and power systems is appropriate.

In the following pages, our findings address the ERO's payload interfaces with the NASA-provided CCRS, and its mission-critical role in OS location, rendezvous and capture while in Mars orbit.



Technical Approach: Earth Return Orbiter

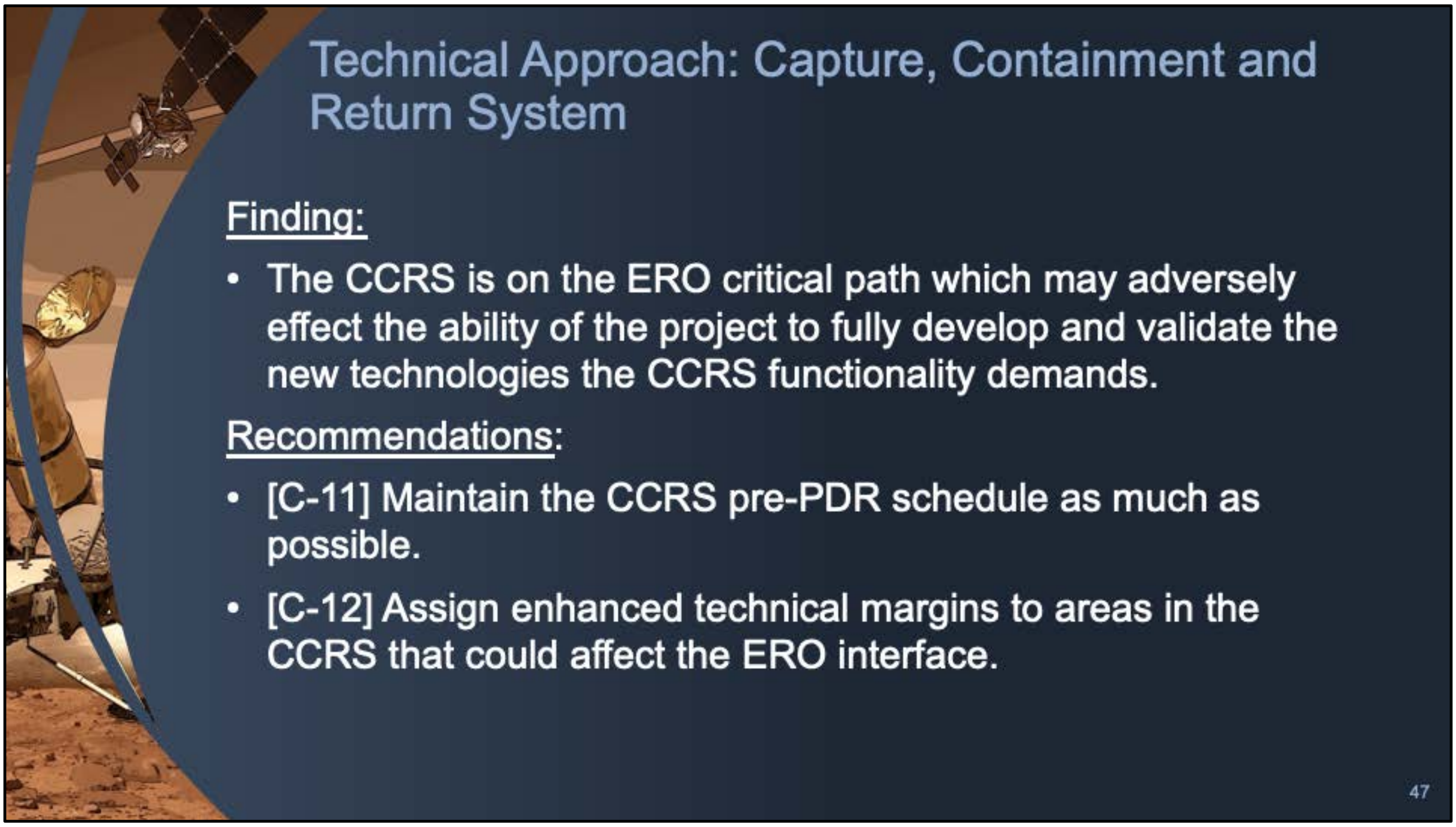
Findings (cont’d):

- The IRB is concerned that the mismatch in the CCRS and ERO development schedules could cause non-synchronous requirements definition, interface definition, and design inconsistencies, which would increase the technical risk.
  - The schedule mismatch and the impact on CCRS development timeline were acknowledged.
  - Mitigations included the form of phased interface freezes and the addition of CCRS test articles for delivery to ERO.

Technical Approach: Earth Return Orbiter

Recommendations:

- [C-9] Accelerate the definitization of the CCRS specifications that the ERO program requires.
- [C-10] Synchronize, as much as possible, CCRS development, test, qualification, and validation milestones, and required delivery dates with the ERO development schedule.



Technical Approach: Capture, Containment and Return System

Finding:

- The CCRS is on the ERO critical path which may adversely effect the ability of the project to fully develop and validate the new technologies the CCRS functionality demands.

Recommendations:

- [C-11] Maintain the CCRS pre-PDR schedule as much as possible.
- [C-12] Assign enhanced technical margins to areas in the CCRS that could affect the ERO interface.

The integration of the CCRS into the ERO is a substantial payload integration challenge and it needs to be recognized as such by both NASA and ESA.

The CCRS schedule is on the critical path for the ERO launch. From what the IRB members have seen, the ERO spacecraft could probably support a 2027 launch but may need to move to 2028 due to the CCRS schedule.

Technical Approach: Earth Entry Vehicle

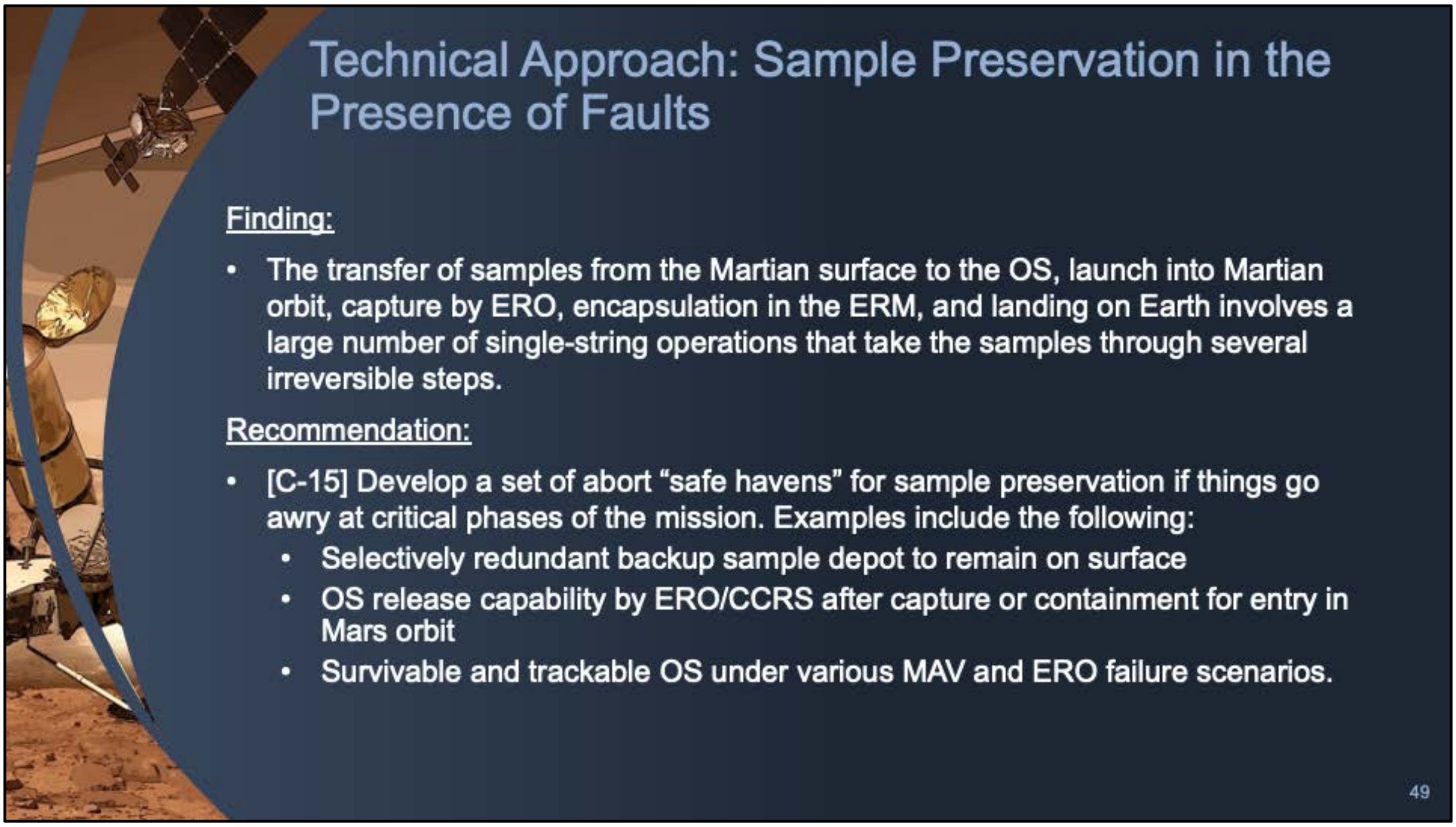
Findings:

- The spin-up and deployment system for the EEV is a new development.
- The EEV integrity is demonstrated through analysis rather than actual sensing.

Recommendations:

- [C-13] Bring to bear relevant expertise from similar Earth-return missions (e.g., Stardust, Genesis, OSIRIS-REx) to EEV design, development, and test.
- [C-14] Examine the possibility of EEV integrity sensors being incorporated in the design.

The Earth Entry Vehicle (EEV), another element of the CCRS, also presents some first-time challenges.



Technical Approach: Sample Preservation in the Presence of Faults

Finding:

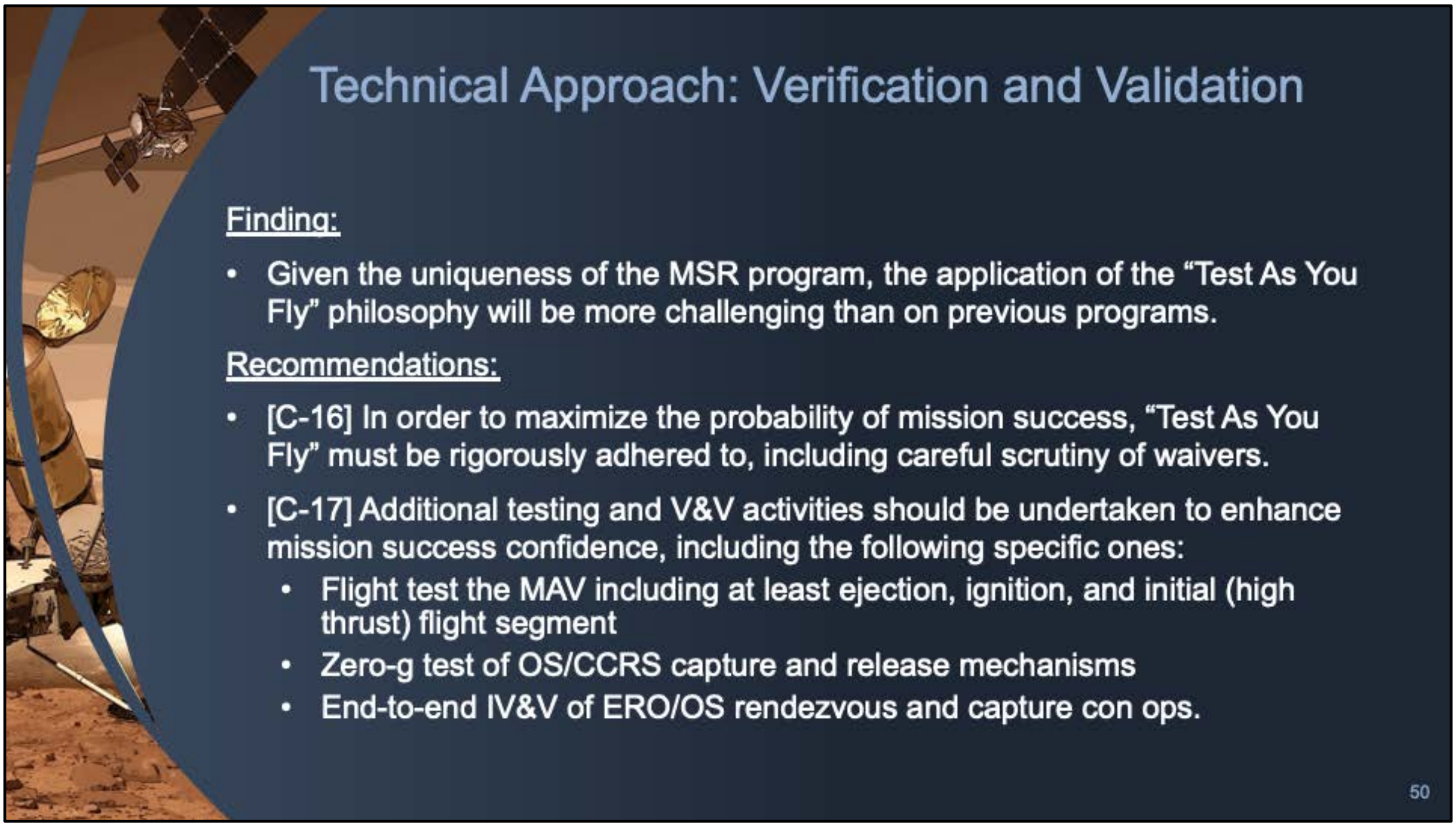
- The transfer of samples from the Martian surface to the OS, launch into Martian orbit, capture by ERO, encapsulation in the ERM, and landing on Earth involves a large number of single-string operations that take the samples through several irreversible steps.

Recommendation:

- [C-15] Develop a set of abort “safe havens” for sample preservation if things go awry at critical phases of the mission. Examples include the following:
  - Selectively redundant backup sample depot to remain on surface
  - OS release capability by ERO/CCRS after capture or containment for entry in Mars orbit
  - Survivable and trackable OS under various MAV and ERO failure scenarios.

49

The IRB is making this recommendation looking for ways to “safe” the OS in case of failure in order to mitigate the consequences. We admit that the examples we have noted are of uncertain feasibility. They are intended to excite creative thinking by the team in furtherance of this goal.



Technical Approach: Verification and Validation

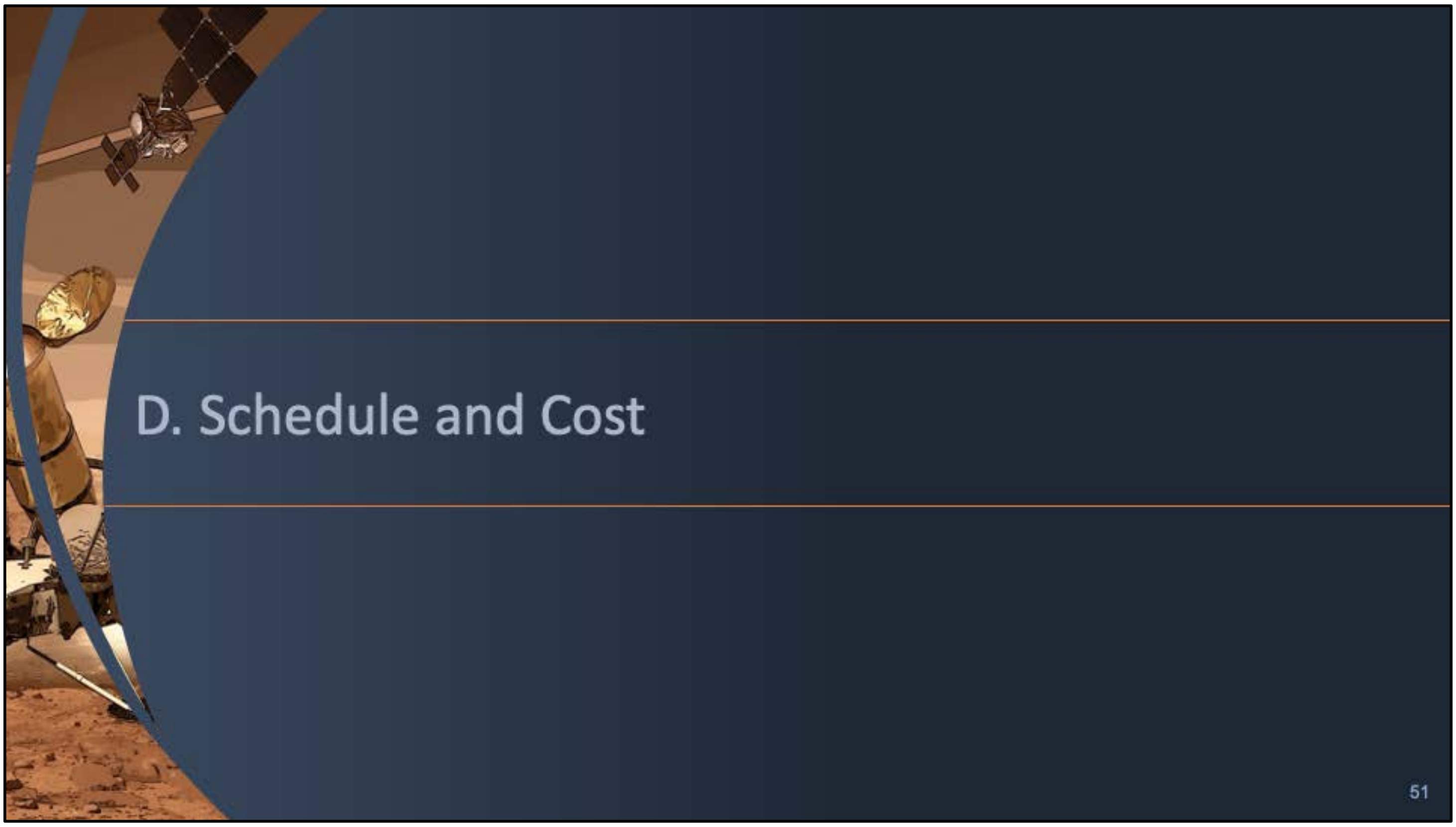
Finding:

- Given the uniqueness of the MSR program, the application of the "Test As You Fly" philosophy will be more challenging than on previous programs.

Recommendations:

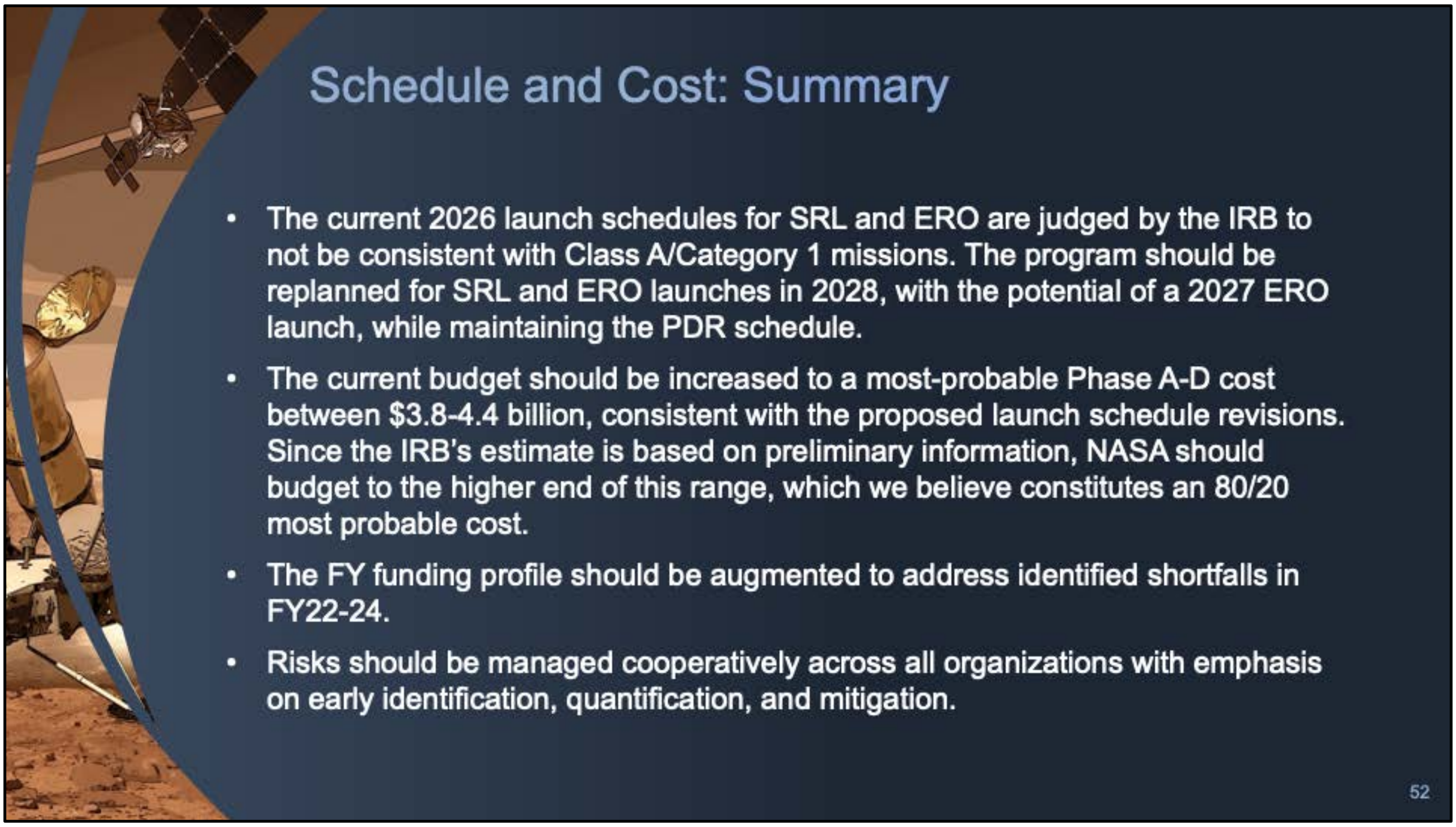
- [C-16] In order to maximize the probability of mission success, "Test As You Fly" must be rigorously adhered to, including careful scrutiny of waivers.
- [C-17] Additional testing and V&V activities should be undertaken to enhance mission success confidence, including the following specific ones:
  - Flight test the MAV including at least ejection, ignition, and initial (high thrust) flight segment
  - Zero-g test of OS/CCRS capture and release mechanisms
  - End-to-end IV&V of ERO/OS rendezvous and capture con ops.

The suggested MAV flight test would verify the dynamics of lander-to-vehicle release, the thrust vector control and ignition of the first-stage motor, and the initial guidance capability to maintain attitude and azimuth for the vehicle. A full-up flight test might also be possible, which is being studied by the program.



D. Schedule and Cost

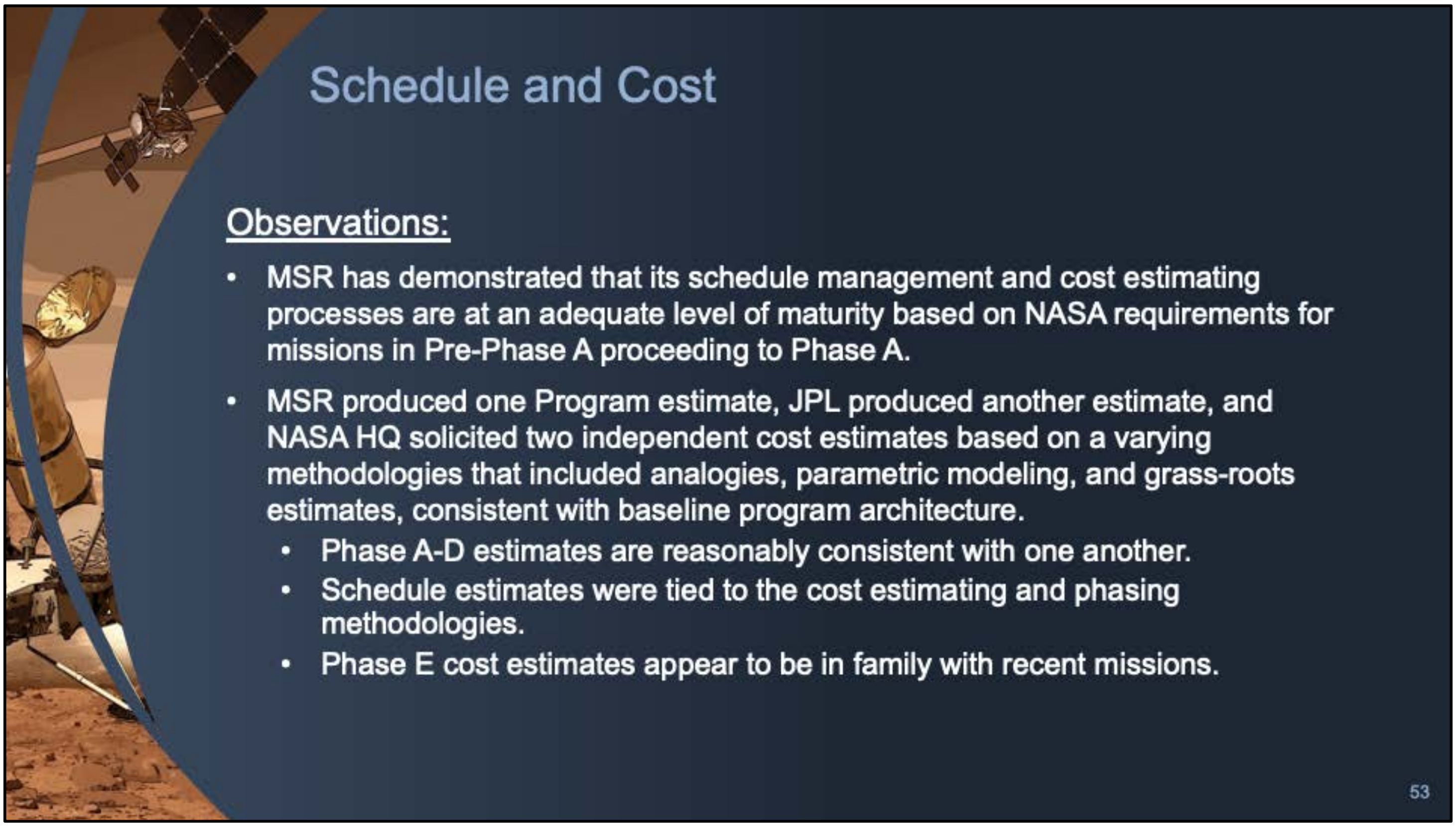
In our final area, schedule and cost assessments, the IRB generated six findings and nine recommendations. In short, we believe MSR will require additional development time as well as increased funding totals and early-year budgets to ensure the highest levels of mission success. We also note that our estimated cost range is based on preliminary information, as the program is just completing pre-Phase A work, and could change substantially as final technical and organizational decisions are made.



Schedule and Cost: Summary

- The current 2026 launch schedules for SRL and ERO are judged by the IRB to not be consistent with Class A/Category 1 missions. The program should be replanned for SRL and ERO launches in 2028, with the potential of a 2027 ERO launch, while maintaining the PDR schedule.
- The current budget should be increased to a most-probable Phase A-D cost between $3.8-4.4 billion, consistent with the proposed launch schedule revisions. Since the IRB's estimate is based on preliminary information, NASA should budget to the higher end of this range, which we believe constitutes an 80/20 most probable cost.
- The FY funding profile should be augmented to address identified shortfalls in FY22-24.
- Risks should be managed cooperatively across all organizations with emphasis on early identification, quantification, and mitigation.

Our assessments of schedules and costs for the MSR program were informed by comparisons to the actual timelines of several recent robotic missions of similar difficulty and by internal and external estimates of development and operational costs based on preliminary program plans. The major results of our work relating to launch schedules, total Phase A-D costs, and early-year funding levels are listed above.



Schedule and Cost

Observations:

- MSR has demonstrated that its schedule management and cost estimating processes are at an adequate level of maturity based on NASA requirements for missions in Pre-Phase A proceeding to Phase A.
- MSR produced one Program estimate, JPL produced another estimate, and NASA HQ solicited two independent cost estimates based on a varying methodologies that included analogies, parametric modeling, and grass-roots estimates, consistent with baseline program architecture.
  - Phase A-D estimates are reasonably consistent with one another.
  - Schedule estimates were tied to the cost estimating and phasing methodologies.
  - Phase E cost estimates appear to be in family with recent missions.

MSR has programmatic teams in place at the Program and HQ levels with combined Class A/Category 1 program and Mars mission experience, which is evident in the current maturity of MSR's programmatic products.

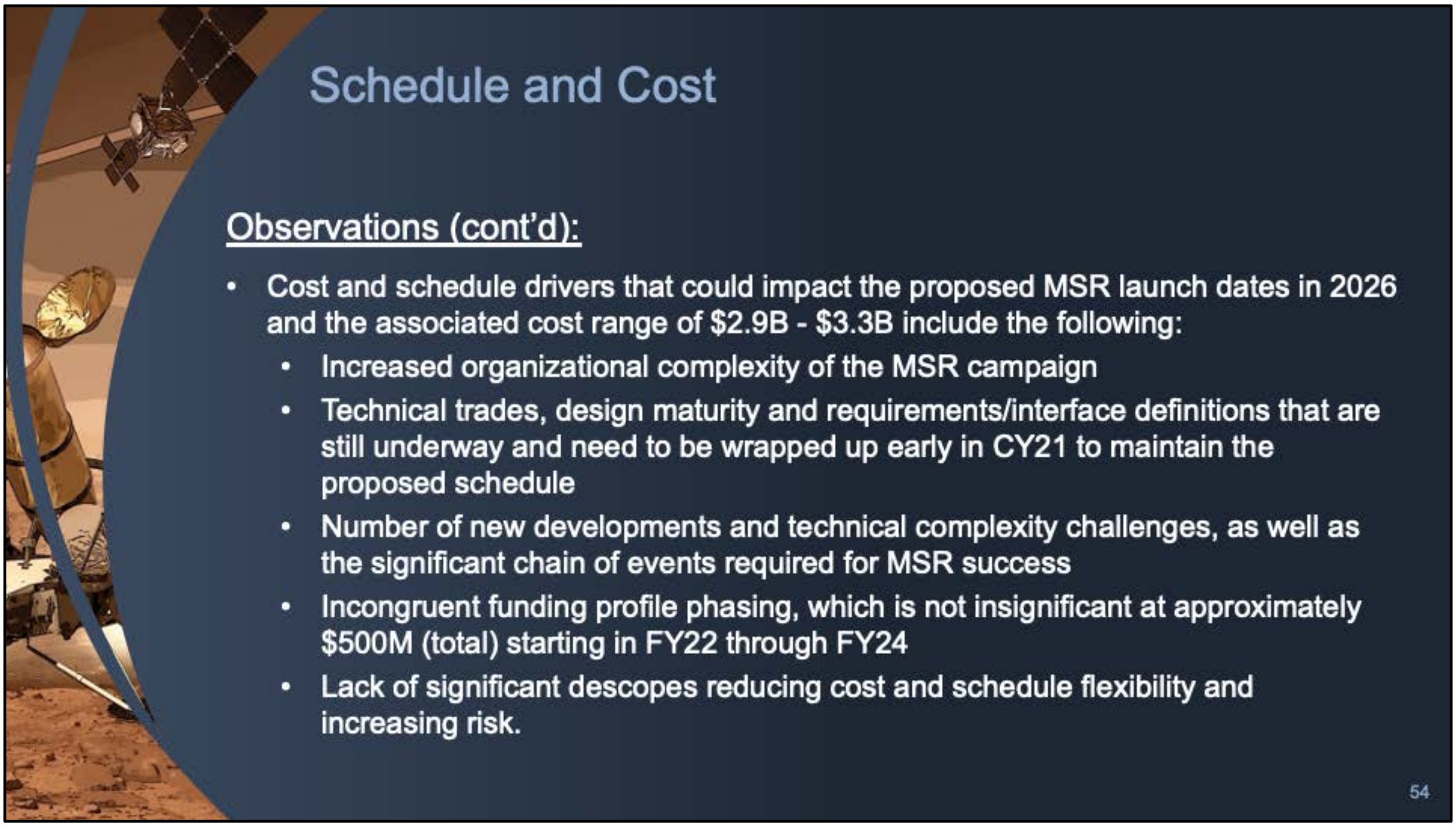
Because of Pre-Phase A work completed over the past 3+ years, the MSR Program has more than a notional understanding of the responsibilities and overall workflow that is typically seen in Pre-Phase A. Thus, the decisions already made as a result of the Pre-Phase A work provide the basis for the current cost and schedule estimates. The Program provided summary-level bases of estimate (BOEs), referencing modeling approaches and traceability to analogies used for estimates. However, detailed BOEs are still being developed for the cost, schedule, and workforce estimates.

The MSR estimates were built upon model-based parametric approaches for many elements of the program and grass roots estimates for some elements where detailed information exists. This was in addition to the high-level analogies typically seen in Pre-Phase A. For MSR, limited Program-level analogies exist from which to make comparisons (i.e., MSL and M2020); however, additional analogies exist at the component level, which were also modeled.

The Phase A-D cost estimates were reasonably consistent with each other when normalizing the results according to various risk postures (e.g., design threats, schedule threats, etc.). Phase E cost estimates included an appropriate level of Unallocated Future Expense (UFE) given the uncertainty associated with the level of maturity of the Phase E definition. MSR's Current Planning Budget ($2.935B) and Current Cost Estimate ($3.045B) are within the Program's 50%-70% range estimate.

The schedule estimates were tied to the cost estimating and phasing methodologies and assessed risk to the planned July 2026 launch date. The initial integrated master schedule (IMS) includes a top-level breakdown of work tasks and milestones, with logical sequencing established for many of the activities, including major integration points and key handoffs. Work remains on several trade studies before the IMS can be fully developed to a discrete level of detail and fully integrated and sequenced, but the Program is in well positioned to continue maturing the IMS as a management tool.

As additional trade studies are completed and technical architecture decisions and interfaces are finalized, the Program will be able to refine its cost and schedule estimates based on further grassroots and probabilistic risk approaches during the upcoming Phase A period.



Schedule and Cost

Observations (cont'd):

- Cost and schedule drivers that could impact the proposed MSR launch dates in 2026 and the associated cost range of $2.9B - $3.3B include the following:
    - Increased organizational complexity of the MSR campaign
    - Technical trades, design maturity and requirements/interface definitions that are still underway and need to be wrapped up early in CY21 to maintain the proposed schedule
    - Number of new developments and technical complexity challenges, as well as the significant chain of events required for MSR success
    - Incongruent funding profile phasing, which is not insignificant at approximately $500M (total) starting in FY22 through FY24
    - Lack of significant descopes reducing cost and schedule flexibility and increasing risk.

MSR has a number of cost and schedule drivers that could impact the proposed MSR launch schedules and associated cost range.

As organizational complexity increases, technical decisions tend to be costlier. MSR has a large number of total integrating activities/organizations, which could slow decisions and impact cost. There exists a potential for misaligning decision authority and mission responsibility, making the decision-making process less efficient, and resulting in cost and schedule growth.

In terms of NASA/ESA coordination, it will be necessary to have clear arrangements and documentation to mature the architecture, control the design, and develop, test, integrate and verify the product before acceptance and delivery.

Since MSR is a complex Class A/Category 1 program and is still early in its lifecycle, its design will continue to evolve through Phase B; thus, its expected life cycle cost is a moving target.

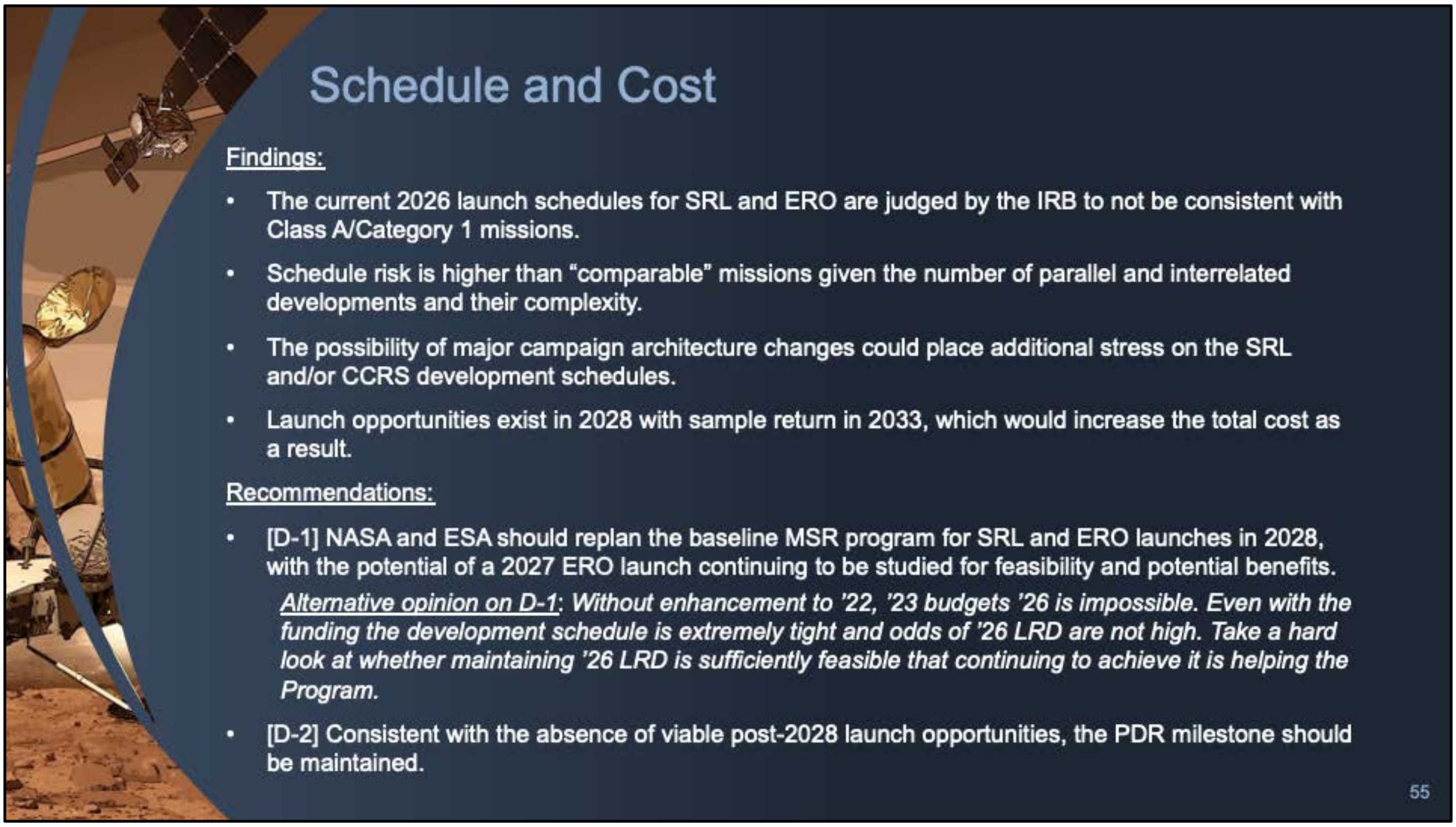
MSR architectural trade studies are still underway, and the remaining technical decisions could induce cost growth by introducing additional design and process. The degree to which requirements are solidified and interfaces are defined early can impact MSR cost and schedule success. ESA is ahead of NASA on many elements, requiring NASA to make decisions as rapidly as possible. Should the process to define interfaces be slower than planned, schedule delays and/or increases in cost can result.

The degree of new design to undertake versus the choice of heritage systems can impact cost and schedule (e.g., new development challenges include the SRL, MAV, CCM, and ERM). It is imperative that technical readiness be achieved early in the MSR life cycle.

MSR is in an environment where funding must be approved annually, which can lead to difficulties in managing large programs.

Delays in funding availability cause the cost to meet schedule to escalate, requiring more funding than planned/requested on an annual basis. MSR is already anticipating a potential reduction in FY21 due to M2020 Phase E needs, although this will not be confirmed until the final appropriation is enacted. In addition, based on current estimates, MSR anticipates needing more funds than requested for FY22 and FY23 (approximately $500M total).

MSR has identified ~$180M worth of descopes, but most do not appear feasible to the IRB. The IRB did not identify any additional, significant descopes that would provide meaningful programmatic benefits. The lack of descopes decreases flexibility in cost and schedule.



Schedule and Cost

Findings:

- The current 2026 launch schedules for SRL and ERO are judged by the IRB to not be consistent with Class A/Category 1 missions.
- Schedule risk is higher than "comparable" missions given the number of parallel and interrelated developments and their complexity.
- The possibility of major campaign architecture changes could place additional stress on the SRL and/or CCRS development schedules.
- Launch opportunities exist in 2028 with sample return in 2033, which would increase the total cost as a result.

Recommendations:

- [D-1] NASA and ESA should replan the baseline MSR program for SRL and ERO launches in 2028, with the potential of a 2027 ERO launch continuing to be studied for feasibility and potential benefits.

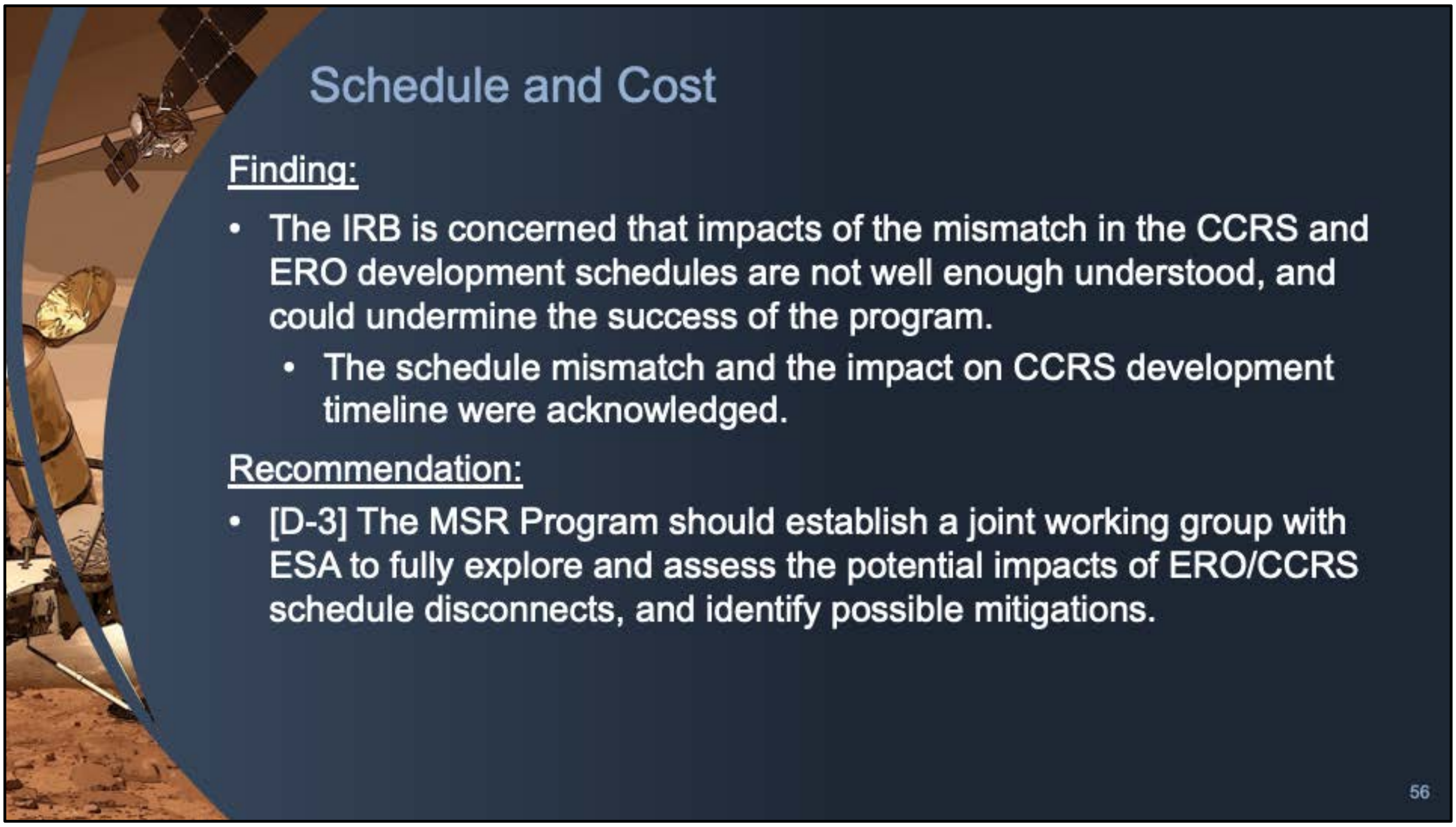
  Alternative opinion on D-1: Without enhancement to '22, '23 budgets '26 is impossible. Even with the funding the development schedule is extremely tight and odds of '26 LRD are not high. Take a hard look at whether maintaining '26 LRD is sufficiently feasible that continuing to achieve it is helping the Program.
- [D-2] Consistent with the absence of viable post-2028 launch opportunities, the PDR milestone should be maintained.

The current plan for a 67-month A-D schedule for SRL, a 69-month A-D schedule for ERO/CCRS, and both launching in 2026, is judged by the IRB to not be consistent with Class A/Category 1 mission risk levels (similar to MSL and M2020).

The SRL landing system is currently on the critical path, followed by propulsion. SRL is approximately 13-17 shorter for the Phase A-D durations when compared to its nearest analogies (MSL and M2020). The IRB's analysis placed the 80% confidence level launch date at February 2028.

CCRS's schedule is 18-21 months shorter than the Phase A-D durations of similar elements of MSL (SA/SPaH) and M2020 (SCS). The largest disconnect in the CCRS Phase A-D duration stems from the CDR to Delivery duration, which appears to be out-of-family at 22 months versus approximately 40 months. A separate comparison with similar OSIRIS-REx elements reiterated that CCRS durations are out-of-family in the CDR to I&T timeframe.

While MSR has been working to 2026 launch dates for both SRL and ERO/CCRS for the past year, the Program has identified schedule as its primary risk. Based on current analysis, the IRB recommends that NASA and ESA replan the baseline MSR program for SRL and ERO launches in 2028, with the potential of a 2027 ERO launch continuing to be studied for feasibility and potential benefits.



Schedule and Cost

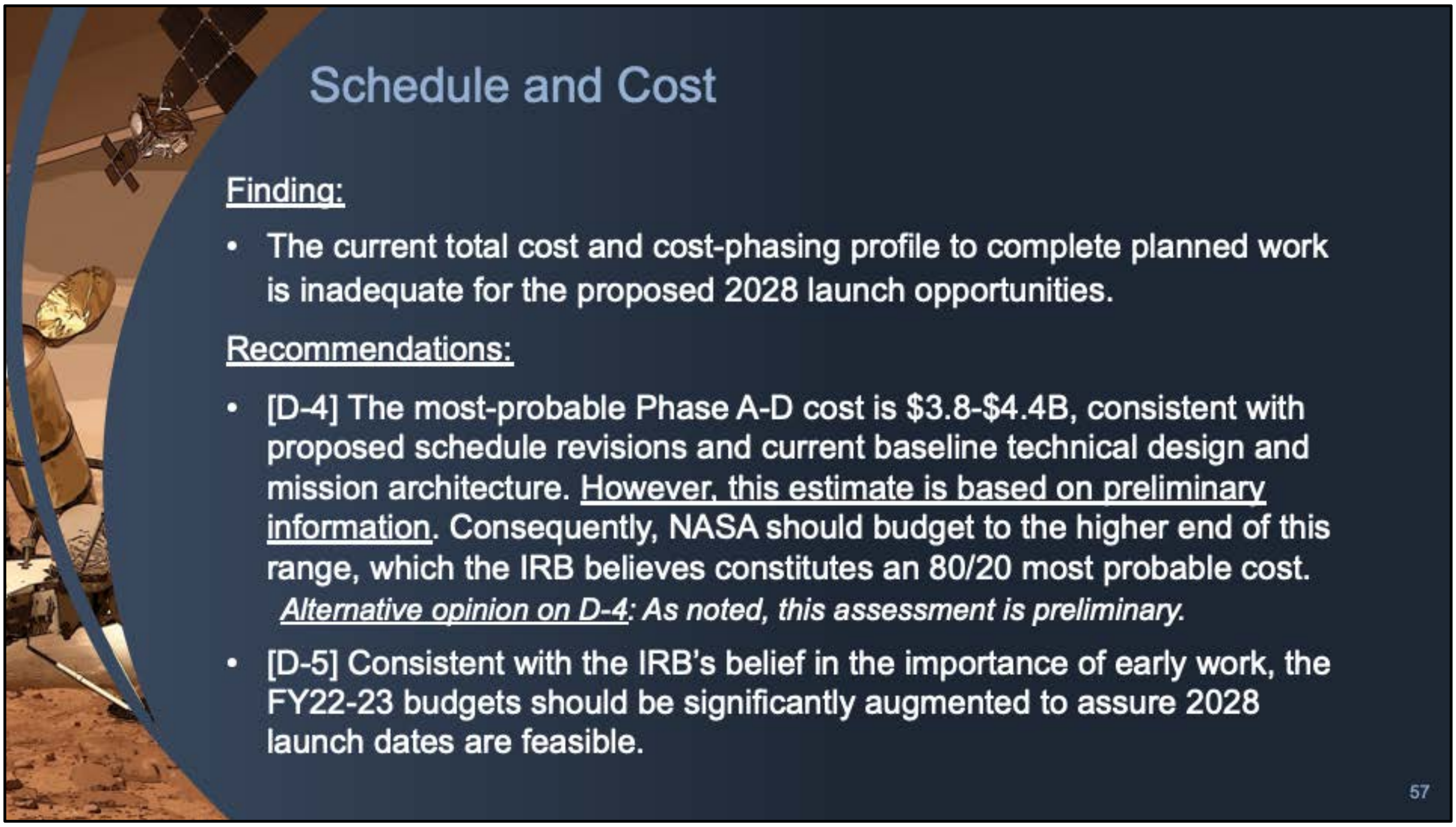
Finding:

- The IRB is concerned that impacts of the mismatch in the CCRS and ERO development schedules are not well enough understood, and could undermine the success of the program.
  - The schedule mismatch and the impact on CCRS development timeline were acknowledged.

Recommendation:

- [D-3] The MSR Program should establish a joint working group with ESA to fully explore and assess the potential impacts of ERO/CCRS schedule disconnects, and identify possible mitigations.

The ERO development work currently is about one year ahead of the CCRS development work. The ERO PDR is planned for April 2021, whereas CCRS PDR is scheduled in March 2022. The development milestones are not planned to align until their respective CDRs – March 2023 for CCRS and April 2023 for ERO. The potential impacts of the development schedule mismatch are not well understood.



Schedule and Cost

Finding:

- The current total cost and cost-phasing profile to complete planned work is inadequate for the proposed 2028 launch opportunities.

Recommendations:

- [D-4] The most-probable Phase A-D cost is $3.8-$4.4B, consistent with proposed schedule revisions and current baseline technical design and mission architecture. However, this estimate is based on preliminary information. Consequently, NASA should budget to the higher end of this range, which the IRB believes constitutes an 80/20 most probable cost.

  Alternative opinion on D-4: As noted, this assessment is preliminary.
- [D-5] Consistent with the IRB's belief in the importance of early work, the FY22-23 budgets should be significantly augmented to assure 2028 launch dates are feasible.

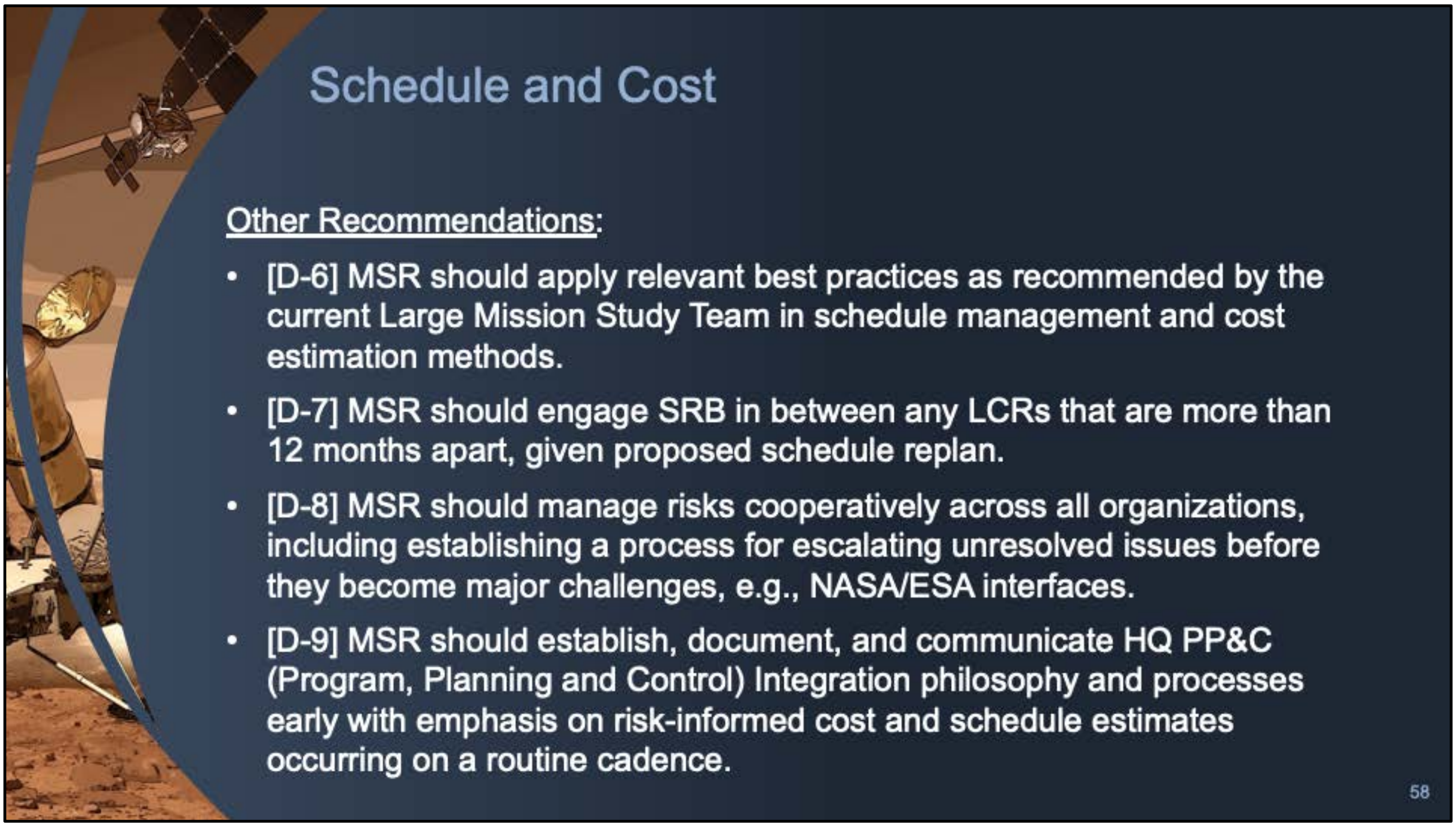
57

Overall, the Campaign's Current Planning Budget of $2.935B and the Current Cost Estimate of $3.045B are both on the low end of the Program's 50% Confidence Level (CL) range estimate of $2.9-3.3 billion. In the Program's assessment of the budget against 2027/2028 launch options, both the Current Planning Budget and the Current Cost Estimate fall below the Program's 50% CL range.

Two independent cost estimates (ICEs) were completed, representing four different risk postures: MSR ICE w/In-House Build, MSR ICE w/System Contractor, MSR ICE w/Design Threats, MSR ICE w/Schedule Threats. Considering the four ICE scenarios, both the Current Planning Budget and the Current Cost Estimate fall below the 70% CL for all ICE scenarios, and below three of four ICE scenarios at the 50% CL.

Per the Campaign's Current Cost Estimate, MSR anticipates a potential budget reduction in FY21 due to M2020 Phase E needs, although, this will not be confirmed until the appropriation is passed. In addition, based on current estimates, MSR expects to need more funds than requested for FY22 and FY23 (approximately $500M total). It will be important for NASA to reconcile this discrepancy as early as possible, since limiting funding in early years can cause further growth in later years while work is deferred and the schedule is stretched even more.

Based on the IRBs assessment of the range of cost estimates, and consistent with the IRB's proposed launch schedule revisions, the current MSR budget is assessed to be inadequate. The MSR budget should be increased to a most-probable Phase A-D cost between $3.8-4.4 billion.



Schedule and Cost

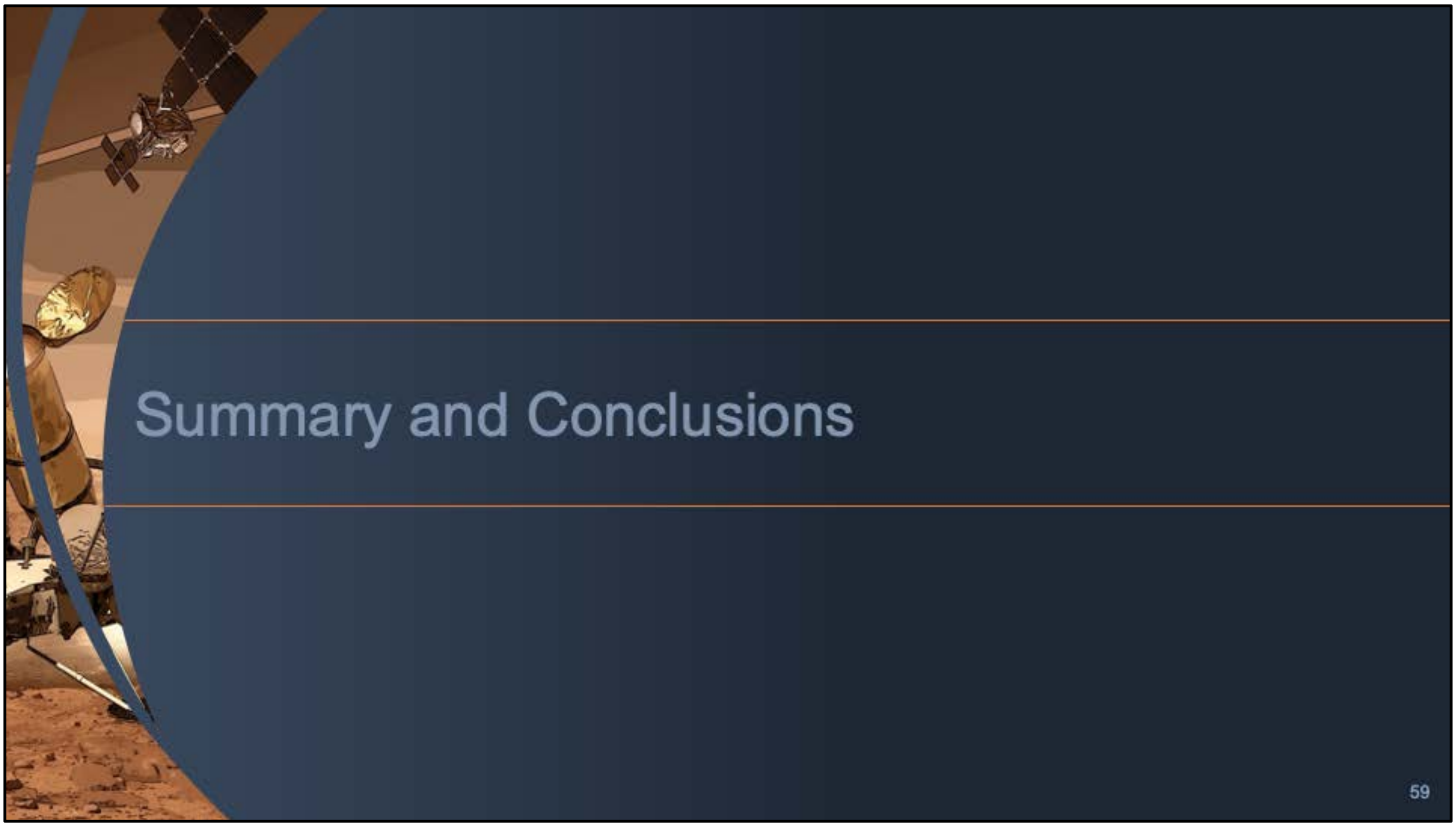
Other Recommendations:

- [D-6] MSR should apply relevant best practices as recommended by the current Large Mission Study Team in schedule management and cost estimation methods.
- [D-7] MSR should engage SRB in between any LCRs that are more than 12 months apart, given proposed schedule replan.
- [D-8] MSR should manage risks cooperatively across all organizations, including establishing a process for escalating unresolved issues before they become major challenges, e.g., NASA/ESA interfaces.
- [D-9] MSR should establish, document, and communicate HQ PP&C (Program, Planning and Control) Integration philosophy and processes early with emphasis on risk-informed cost and schedule estimates occurring on a routine cadence.

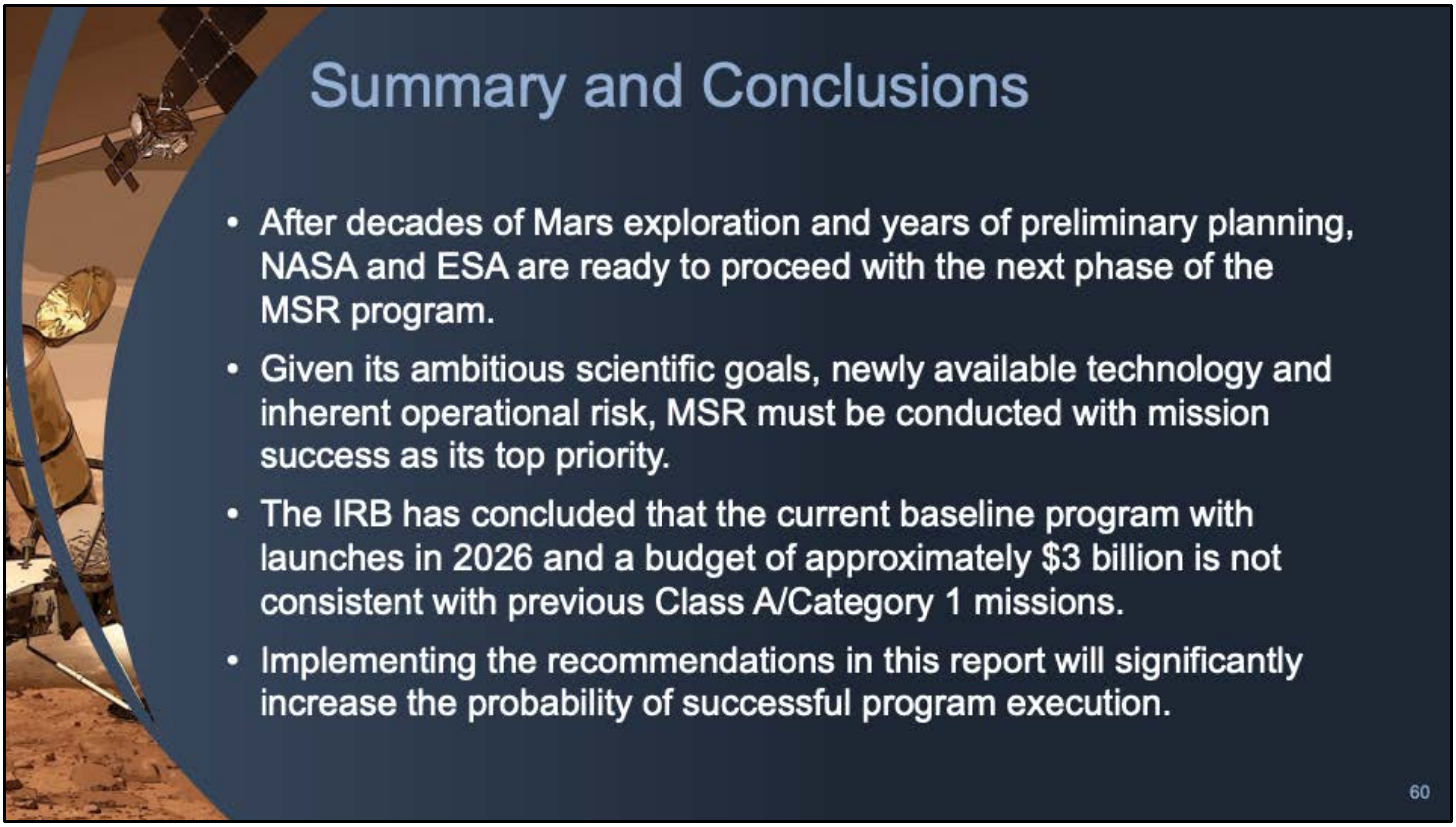
The IRB was briefed on preliminary findings from the Large Mission Study Team, and believes that MSR should consider relevant programmatic recommendations when the study is released. For example, MSR should consider the limitations associated with cost and schedule models and analogies for large missions and work towards establishing grassroots estimates with detailed cost and schedule bases of estimate (BOEs) as early as possible, and perhaps earlier than required. MSR should also consider the Large Mission Study Team's findings related to establishing greater than 70% confidence in cost and schedule commitments with correct phasing, including that of Unallocated Future Expense (UFE).

With the IRB's proposed launch schedule changes, it is expected that several SRB-conducted life cycle reviews (LCRs) could be replanned such that they are more than 12 months apart. NASA Procedural Requirements (NPR) 7120.5 references that the Decision Authority may request checkpoint or other special reviews as prompted by "long periods of time" between LCRs and subsequent Key Decision Points (KDPs) or between KDPs. The IRB also believes that long periods of time between LCRs should be considered (e.g., PDR and CDR). The IRB recommends that MSR engage the SRB during these timeframes, using 12 months as a gauge for "long periods of time," as it is not explicitly defined in 7120.5, nor the NASA Space Flight Program and Project Management Handbook.

As the NASA HQ PP&C Office takes shape, it should work with the JPL Program Office to establish and document the overarching PP&C Integration philosophy and processes early, and communicate them to all organizations. Specifically, the PP&C function should work to establish risk management practices cooperatively across all organizations, such that risks can be assessed in a comprehensive manner. Emphasis should be placed on performing quantitative risk analysis on a routine basis (e.g., quantified pre- and post-mitigated risk impacts, waterfall charts, probabilistic schedule risk analysis trending, etc.) to inform cost and schedule management estimates and risk management decisions.



Summary and Conclusions



Summary and Conclusions

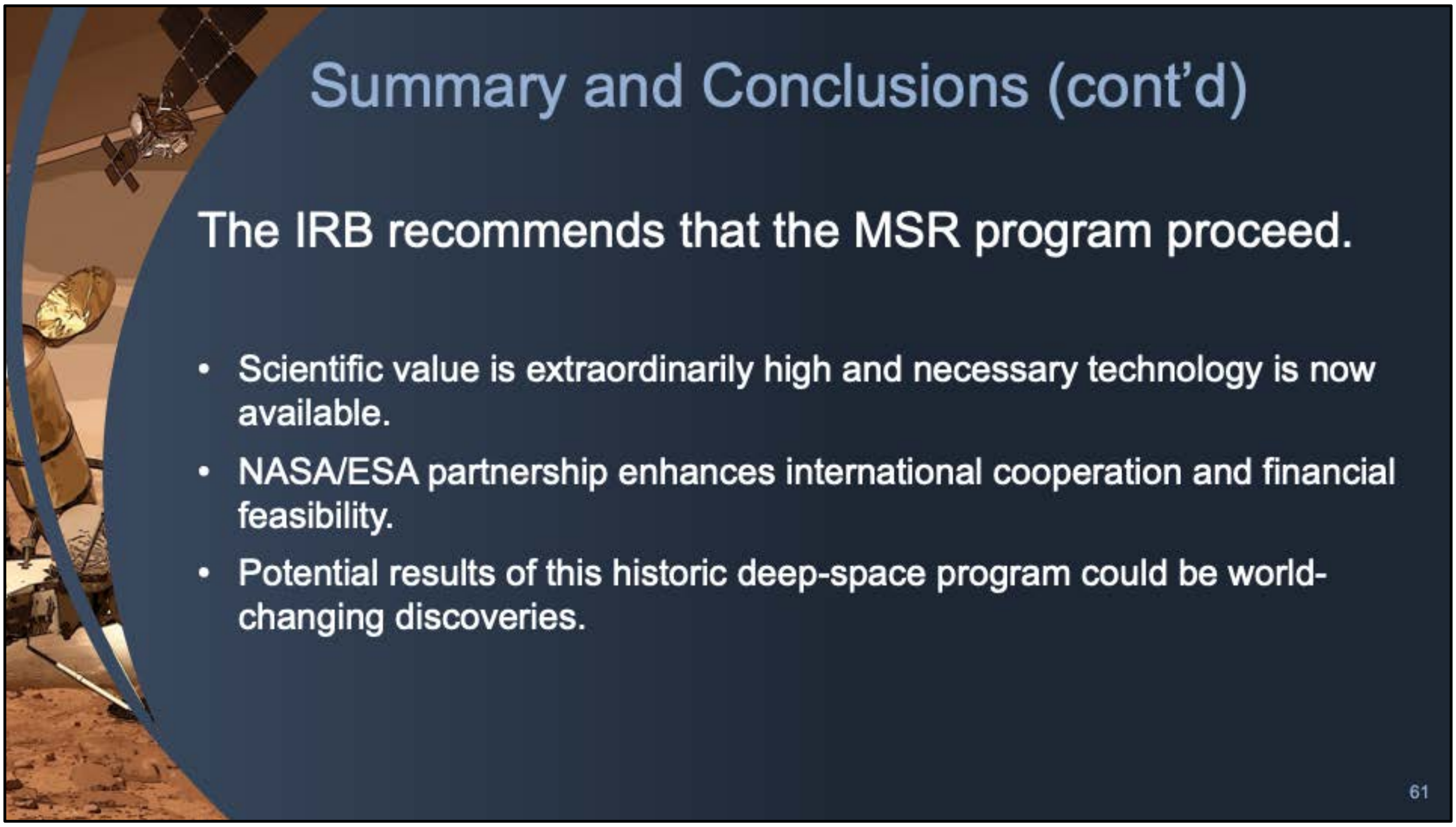
- After decades of Mars exploration and years of preliminary planning, NASA and ESA are ready to proceed with the next phase of the MSR program.
- Given its ambitious scientific goals, newly available technology and inherent operational risk, MSR must be conducted with mission success as its top priority.
- The IRB has concluded that the current baseline program with launches in 2026 and a budget of approximately $3 billion is not consistent with previous Class A/Category 1 missions.
- Implementing the recommendations in this report will significantly increase the probability of successful program execution.

In conclusion, the IRB unanimously believes the time is ripe to proceed with the MSR program.

We strongly recommend that NASA and ESA maintain mission success as the program's top priority in all technical, programmatic and organizational decisions.

While we judge the current baseline mission's development schedule and planning budget to not be consistent with the demands of a Class A/Category 1 mission, we think the recommendations in this report, if considered carefully and implemented diligently, will lead to a substantial increase in the probability of program success.

The IRB does not believe there are descopes available that could significantly reduce budget or shorten the schedule.



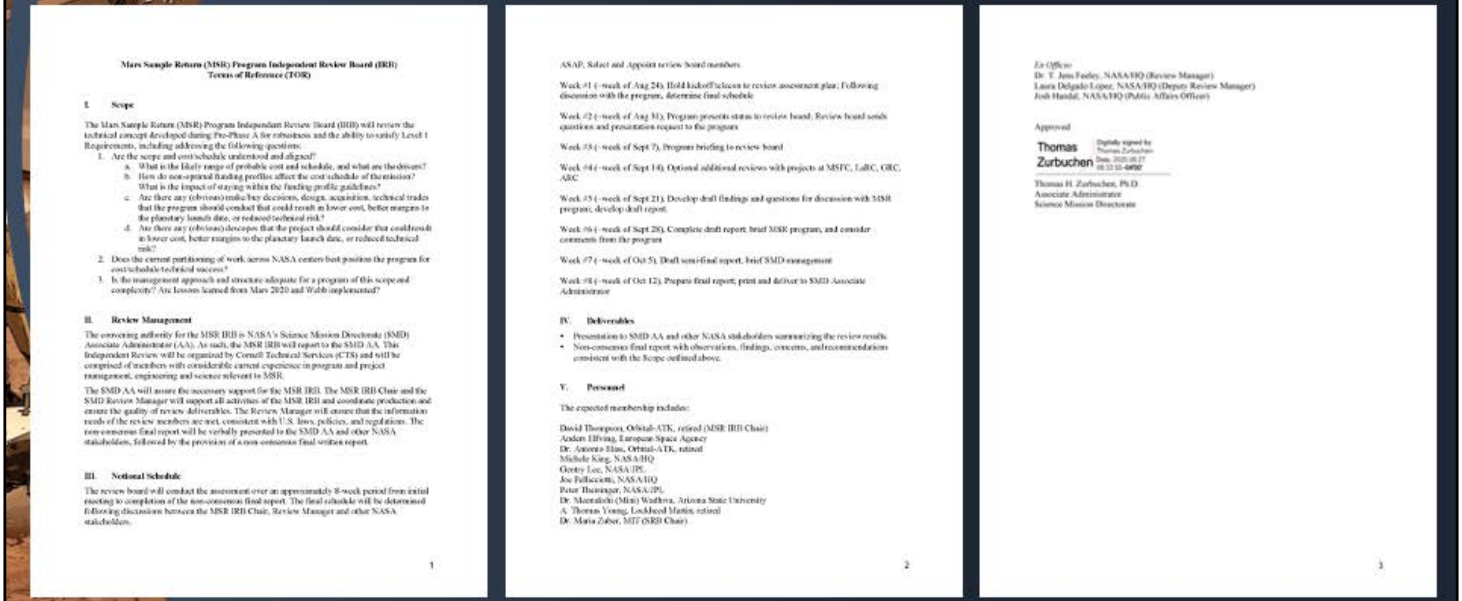
Summary and Conclusions (cont'd)

The IRB recommends that the MSR program proceed.

- Scientific value is extraordinarily high and necessary technology is now available.
- NASA/ESA partnership enhances international cooperation and financial feasibility.
- Potential results of this historic deep-space program could be world-changing discoveries.

Appendices

Appendix: Terms of Reference



Mars Sample Return (MSR) Program Independent Review Board (IRB)
Terms of Reference (TOR)

I. Scope

The Mars Sample Return (MSR) Program Independent Review Board (IRB) will review the technical concept developed during Pre-Phase A for robustness and the ability to satisfy Level 1 Requirements, including addressing the following questions:

1. Are the scope and cost/schedule understood and aligned?
    a. What is the likely range of probable cost and schedule, and what are the drivers?
    b. How do non-optimal funding profiles affect the cost/schedule of the mission? What is the impact of staying within the funding profile guidelines?
    c. Are there any (obvious) make/buy decisions, design, acquisition, technical trades that the program should conduct that could result in lower cost, better margins to the planetary launch date, or reduced technical risk?
    d. Are there any (obvious) descopes that the project should consider that could result in lower cost, better margins to the planetary launch date, or reduced technical risk?
2. Does the current partitioning of work across NASA centers best position the program for cost/schedule/technical success?
3. Is the management approach and structure adequate for a program of this scope and complexity? Are lessons learned from Mars 2020 and Webb implemented?

II. Review Management

The convening authority for the MSR IRB is NASA's Science Mission Directorate (SMD) Associate Administrator (AA). As such, the MSR IRB will report to the SMD AA. This Independent Review will be organized by Cornell Technical Services (CTS) and will be comprised of members with considerable current experience in program and project management, engineering and science relevant to MSR.

The SMD AA will assure the necessary support for the MSR IRB. The MSR IRB Chair and the SMD Review Manager will support all activities of the MSR IRB and coordinate production and ensure the quality of review deliverables. The Review Manager will ensure that the information needs of the review members are met, consistent with U.S. laws, policies, and regulations. The non-consensus final report will be verbally presented to the SMD AA and other NASA stakeholders, followed by the provision of a non-consensus final written report.

III. Notional Schedule

The review board will conduct the assessment over an approximately 8-week period from initial meeting to completion of the non-consensus final report. The final schedule will be determined following discussions between the MSR IRB Chair, Review Manager and other NASA stakeholders.

1

ASAP, Select and Appoint review board members

Week #1 (~week of Aug 24), Hold kickoff telecon to review assessment plan; Following discussion with the program, determine final schedule

Week #2 (~week of Aug 31), Program presents status to review board; Review board sends questions and presentation request to the program

Week #3 (~week of Sept 7), Program briefing to review board

Week #4 (~week of Sept 14), Optional additional reviews with projects at MSFC, LaRC, GRC, ARC

Week #5 (~week of Sept 21), Develop draft findings and questions for discussion with MSR program; develop draft report

Week #6 (~week of Sept 28), Complete draft report; brief MSR program, and consider comments from the program

Week #7 (~week of Oct 5), Draft semi-final report, brief SMD management

Week #8 (~week of Oct 12), Prepare final report; print and deliver to SMD Associate Administrator

IV. Deliverables

- Presentation to SMD AA and other NASA stakeholders summarizing the review results.
- Non-consensus final report with observations, findings, concerns, and recommendations consistent with the Scope outlined above.

V. Personnel

The expected membership includes:

David Thompson, Orbital-ATK, retired (MSR IRB Chair)
Anders Elfving, European Space Agency
Dr. Antonio Elias, Orbital-ATK, retired
Michele King, NASA/HQ
Gentry Lee, NASA/JPL
Joe Pellicciotti, NASA/HQ
Peter Theisinger, NASA/JPL
Dr. Meenakshi (Mini) Wadhwa, Arizona State University
A. Thomas Young, Lockheed Martin, retired
Dr. Maria Zuber, MIT (SRB Chair)

2

Ex Officio
Dr. T. Jens Feeley, NASA/HQ (Review Manager)
Laura Delgado Lopez, NASA/HQ (Deputy Review Manager)
Josh Handal, NASA/HQ (Public Affairs Officer)

Approved

Thomas Zurbuchen
Digitally signed by Thomas Zurbuchen
Date: 2020.08.27 08:33:55 -04'00'

Thomas H. Zurbuchen, Ph.D.
Associate Administrator
Science Mission Directorate

3

Appendix: Biographies

Anders Elfving – Mr. Elfving holds an MSc in Applied Physics from the Royal Institute of Technology in Stockholm, Sweden. After two years of working with industrial automation in Swedish manufacturing companies, he joined the European Space Agency in 1984. At ESA he has held engineering and management position in many different Scientific, Exploration and Earth Observation projects. He has earned two ESA achievement awards, one as Spacecraft Manager for the Herschel and Planck missions and one as Project Manager for the Aeolus mission, the first ever UV lidar for space applications. In parallel of completing, launching and commissioning the Aeolus satellite, he led the FLEX project as of 2015, the ESA photosynthesis mission. Anders handed over his FLEX project responsibility in September 2020 in preparation for his retirement end of 2020.

Mr. Elfving has served as a panel chairman for more the 40 different mission and spacecraft reviews. He has conducted many Independent Assessments of new missions as input to their mission approvals. He has also supported the construction and execution of the ESA Project Management training program and is a lead of this program for the coming years.

Antonio L. Elias – Dr. Elias retired from Orbital ATK, Inc. as Executive Vice President and Chief Technical Officer. Prior to the merger between Orbital Sciences and ATK he served as Orbital Sciences Corporation Chief Technical Officer, and founder and first General Manager of its Advanced Programs Group. He was the lead architect of the Cygnus cargo resupply spacecraft and headed the design teams of Orbital's Pegasus Launch Vehicle, APEX and Sea Star satellites and X-34 hypersonic research vehicle. Dr. Elias came to Orbital from the faculty of the Massachusetts Institute of Technology.

Dr. Elias is the current secretary of the Virginia Academy of Science, Engineering and Medicine (VASEM). Elected to the National Academy of Engineering in 2001, he is a fellow of the American Institute of Aeronautics and Astronautics (AIAA), the American Astronautical Society (AAS), and the International Academy of Astronautics. His awards include the AIAA Engineer of the Year, the AIAA Aircraft Design Award, AIAA Von Karman lectureship and the AAS Brouwer Award. He is a co-recipient of the 1991 National Medal of Technology and the National Air and Space Museum Trophy. He has a Ph.D. from the Department of Aeronautics and Astronautics of the Massachusetts Institute of Technology.

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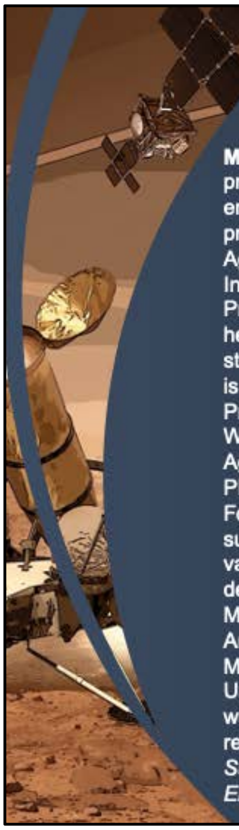
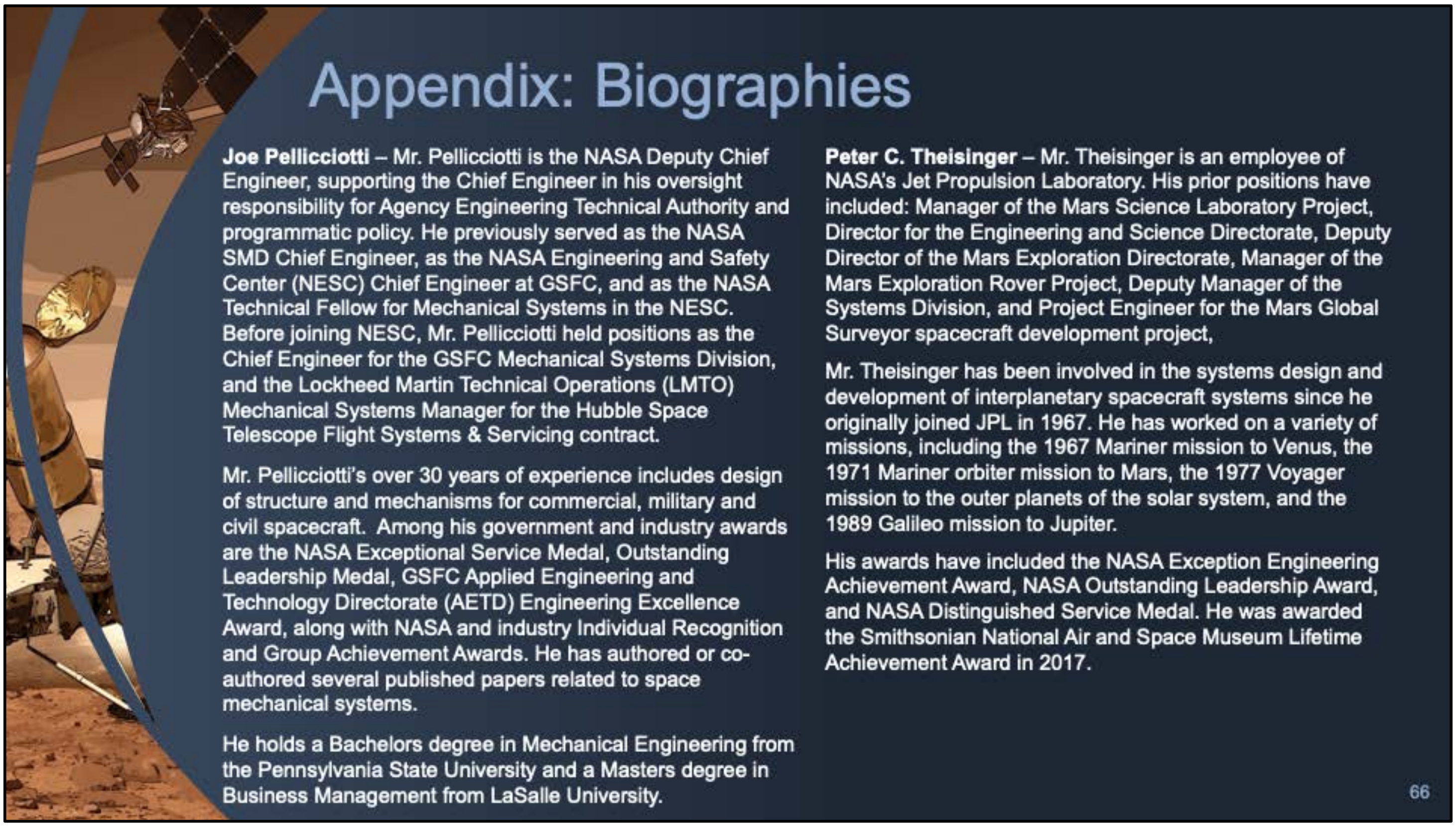


Michele T. King – Ms. King is a PMP and CSEP-certified programmatic analyst for NASA with experience in engineering, risk management, schedule risk analysis, and project management. She currently serves as the lead for the Agency's Schedule Initiative under NASA OCFO's Strategic Investment Division. She contributes to the Agency's Programmatic Assessment Capability Leadership function, helping to enhance and develop new programmatic standards, policies, and capabilities across the Agency. She is also leading the Agency-wide Schedule Community of Practice (SCoPe). Ms. King is a member of numerous Working Groups internal and external to NASA, including Agency working groups for Risk Management, EVM, and PP&C, as well as for GAO and the JSCC's Scheduler's Forum. Ms. King has served as a programmatic risk analyst, supporting the Agency's independent review process for a variety of programs/projects through the IPAO. She led the development of the NASA handbook on Program/Project Management of Problems, Nonconformances, and Anomalies for the NESC. Ms. King holds both a B.S. and an M.E. in Mechanical Engineering from Old Dominion University in Norfolk, VA. She has been recognized for her work by NASA and the local engineering community, having received the following honors: *NASA Top Community Support Award, IPAO Certificate of Recognition,* and *Doug Ensor Young Engineer of the Year Award*.

Gentry Lee – Mr. Lee is Chief Engineer for the Solar System Exploration Directorate at JPL. In that position, Mr. Lee is responsible for the engineering integrity of the robotic planetary missions managed by JPL for NASA, including the Juno mission to Jupiter, the Dawn mission to the asteroids Vesta and Ceres, the InSight mission to Mars, and the Curiosity rover mission that landed on Mars in August 2012.

Mr. Lee was Chief Engineer for the Galileo project from 1977-1988 and, after working in a variety of positions on the Viking project from 1968-76, was Director of Science Analysis and Mission Planning during the Viking operations. He has received several prestigious awards for his engineering work, including the Simon Ramo Medal from the IEEE for "career excellence in engineering," the Harold Masursky Award from the American Astronomical Society, and NASA's highest award, the Distinguished Service Medal. From 1976 until 1981, Mr. Lee was the late Carl Sagan's partner in the creation, design, development and implementation of COSMOS, the highly successful science documentary series for television that won several Emmys and the prestigious Peabody Award. Between 1989 and 1994, he co-authored four novels, CRADLE, RAMA II, THE GARDEN OF RAMA and RAMA REVEALED, with science fiction grandmaster Arthur C. Clarke. All four books were New York Times bestsellers and were translated into more than 28 languages.



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Joe Pellicciotti – Mr. Pellicciotti is the NASA Deputy Chief Engineer, supporting the Chief Engineer in his oversight responsibility for Agency Engineering Technical Authority and programmatic policy. He previously served as the NASA SMD Chief Engineer, as the NASA Engineering and Safety Center (NESC) Chief Engineer at GSFC, and as the NASA Technical Fellow for Mechanical Systems in the NESC. Before joining NESC, Mr. Pellicciotti held positions as the Chief Engineer for the GSFC Mechanical Systems Division, and the Lockheed Martin Technical Operations (LMTO) Mechanical Systems Manager for the Hubble Space Telescope Flight Systems & Servicing contract.

Mr. Pellicciotti's over 30 years of experience includes design of structure and mechanisms for commercial, military and civil spacecraft. Among his government and industry awards are the NASA Exceptional Service Medal, Outstanding Leadership Medal, GSFC Applied Engineering and Technology Directorate (AETD) Engineering Excellence Award, along with NASA and industry Individual Recognition and Group Achievement Awards. He has authored or co-authored several published papers related to space mechanical systems.

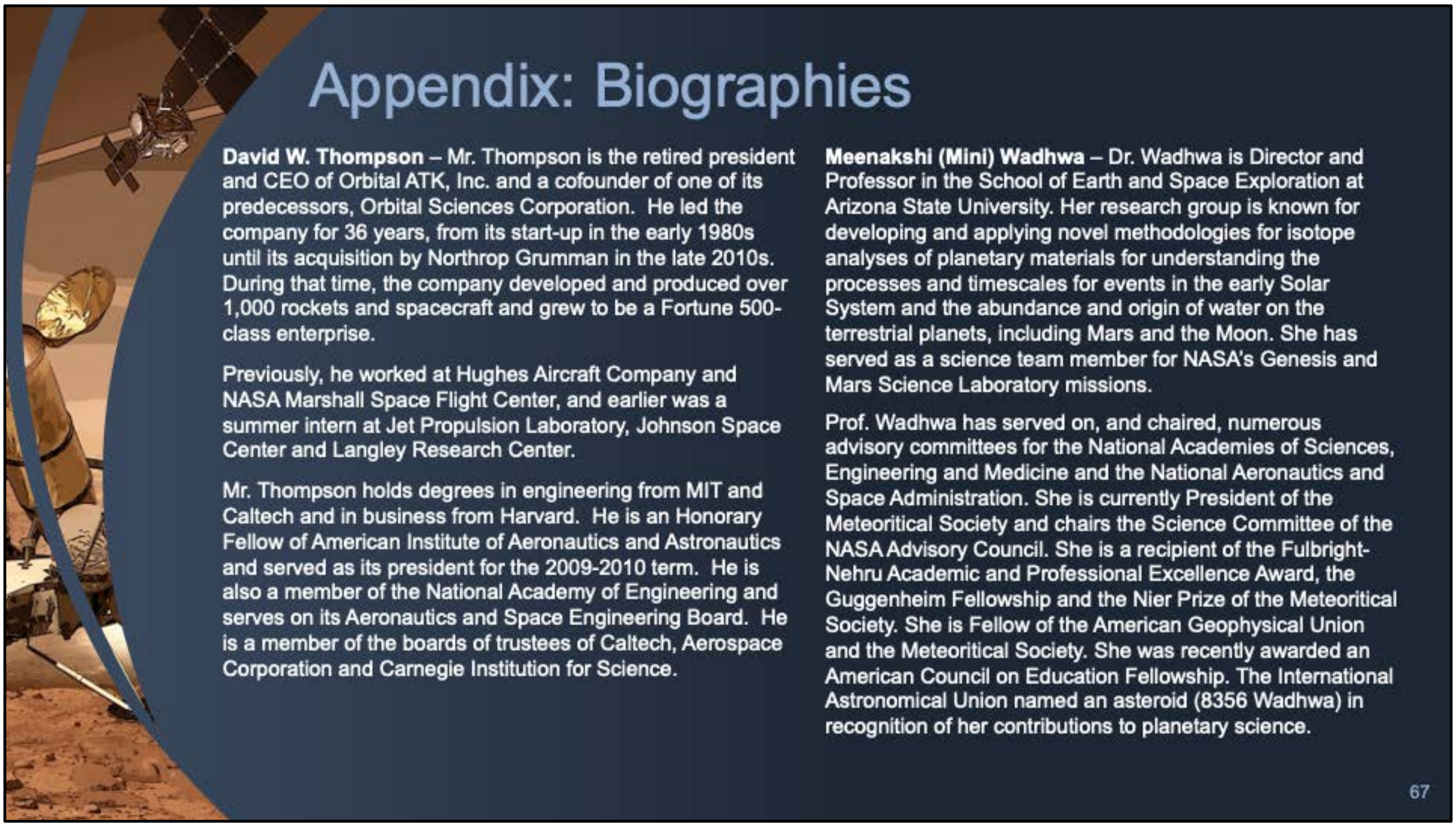
He holds a Bachelors degree in Mechanical Engineering from the Pennsylvania State University and a Masters degree in Business Management from LaSalle University.

Peter C. Theisinger – Mr. Theisinger is an employee of NASA's Jet Propulsion Laboratory. His prior positions have included: Manager of the Mars Science Laboratory Project, Director for the Engineering and Science Directorate, Deputy Director of the Mars Exploration Directorate, Manager of the Mars Exploration Rover Project, Deputy Manager of the Systems Division, and Project Engineer for the Mars Global Surveyor spacecraft development project,

Mr. Theisinger has been involved in the systems design and development of interplanetary spacecraft systems since he originally joined JPL in 1967. He has worked on a variety of missions, including the 1967 Mariner mission to Venus, the 1971 Mariner orbiter mission to Mars, the 1977 Voyager mission to the outer planets of the solar system, and the 1989 Galileo mission to Jupiter.

His awards have included the NASA Exception Engineering Achievement Award, NASA Outstanding Leadership Award, and NASA Distinguished Service Medal. He was awarded the Smithsonian National Air and Space Museum Lifetime Achievement Award in 2017.

66



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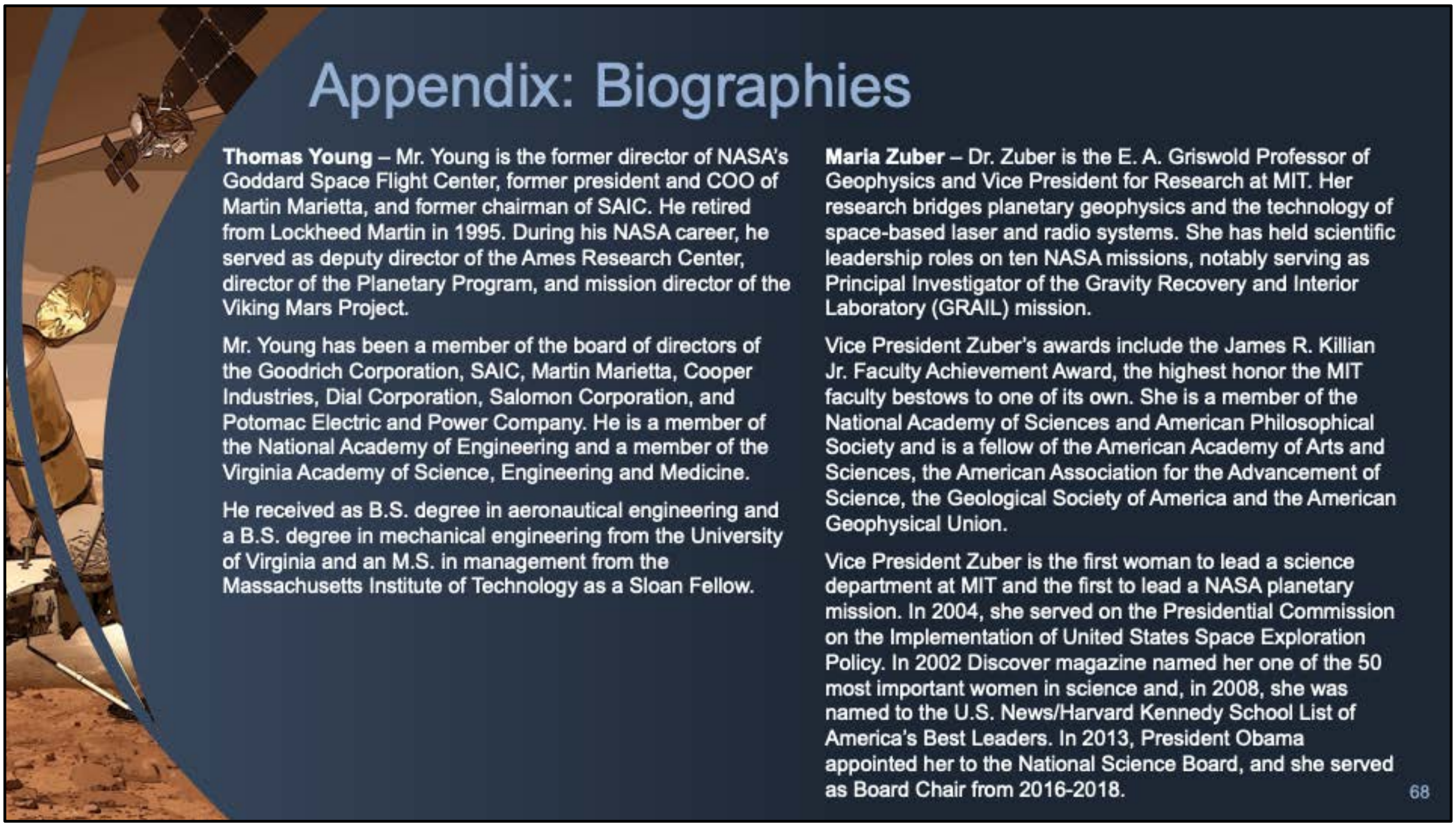
David W. Thompson – Mr. Thompson is the retired president and CEO of Orbital ATK, Inc. and a cofounder of one of its predecessors, Orbital Sciences Corporation. He led the company for 36 years, from its start-up in the early 1980s until its acquisition by Northrop Grumman in the late 2010s. During that time, the company developed and produced over 1,000 rockets and spacecraft and grew to be a Fortune 500-class enterprise.

Previously, he worked at Hughes Aircraft Company and NASA Marshall Space Flight Center, and earlier was a summer intern at Jet Propulsion Laboratory, Johnson Space Center and Langley Research Center.

Mr. Thompson holds degrees in engineering from MIT and Caltech and in business from Harvard. He is an Honorary Fellow of American Institute of Aeronautics and Astronautics and served as its president for the 2009-2010 term. He is also a member of the National Academy of Engineering and serves on its Aeronautics and Space Engineering Board. He is a member of the boards of trustees of Caltech, Aerospace Corporation and Carnegie Institution for Science.

Meenakshi (Mini) Wadhwa – Dr. Wadhwa is Director and Professor in the School of Earth and Space Exploration at Arizona State University. Her research group is known for developing and applying novel methodologies for isotope analyses of planetary materials for understanding the processes and timescales for events in the early Solar System and the abundance and origin of water on the terrestrial planets, including Mars and the Moon. She has served as a science team member for NASA's Genesis and Mars Science Laboratory missions.

Prof. Wadhwa has served on, and chaired, numerous advisory committees for the National Academies of Sciences, Engineering and Medicine and the National Aeronautics and Space Administration. She is currently President of the Meteoritical Society and chairs the Science Committee of the NASA Advisory Council. She is a recipient of the Fulbright-Nehru Academic and Professional Excellence Award, the Guggenheim Fellowship and the Nier Prize of the Meteoritical Society. She is Fellow of the American Geophysical Union and the Meteoritical Society. She was recently awarded an American Council on Education Fellowship. The International Astronomical Union named an asteroid (8356 Wadhwa) in recognition of her contributions to planetary science.



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Thomas Young – Mr. Young is the former director of NASA's Goddard Space Flight Center, former president and COO of Martin Marietta, and former chairman of SAIC. He retired from Lockheed Martin in 1995. During his NASA career, he served as deputy director of the Ames Research Center, director of the Planetary Program, and mission director of the Viking Mars Project.

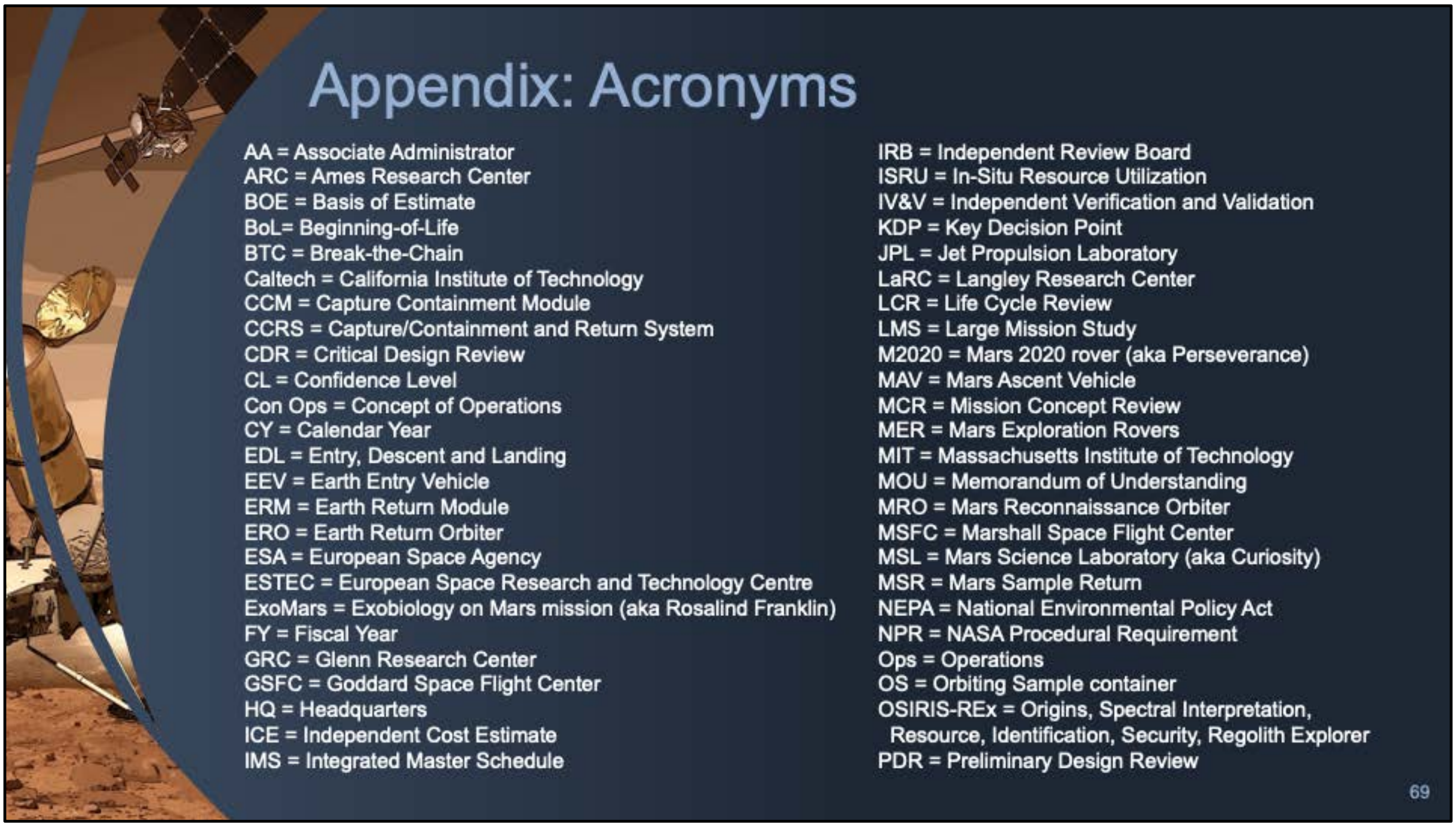
Mr. Young has been a member of the board of directors of the Goodrich Corporation, SAIC, Martin Marietta, Cooper Industries, Dial Corporation, Salomon Corporation, and Potomac Electric and Power Company. He is a member of the National Academy of Engineering and a member of the Virginia Academy of Science, Engineering and Medicine.

He received as B.S. degree in aeronautical engineering and a B.S. degree in mechanical engineering from the University of Virginia and an M.S. in management from the Massachusetts Institute of Technology as a Sloan Fellow.

Maria Zuber – Dr. Zuber is the E. A. Griswold Professor of Geophysics and Vice President for Research at MIT. Her research bridges planetary geophysics and the technology of space-based laser and radio systems. She has held scientific leadership roles on ten NASA missions, notably serving as Principal Investigator of the Gravity Recovery and Interior Laboratory (GRAIL) mission.

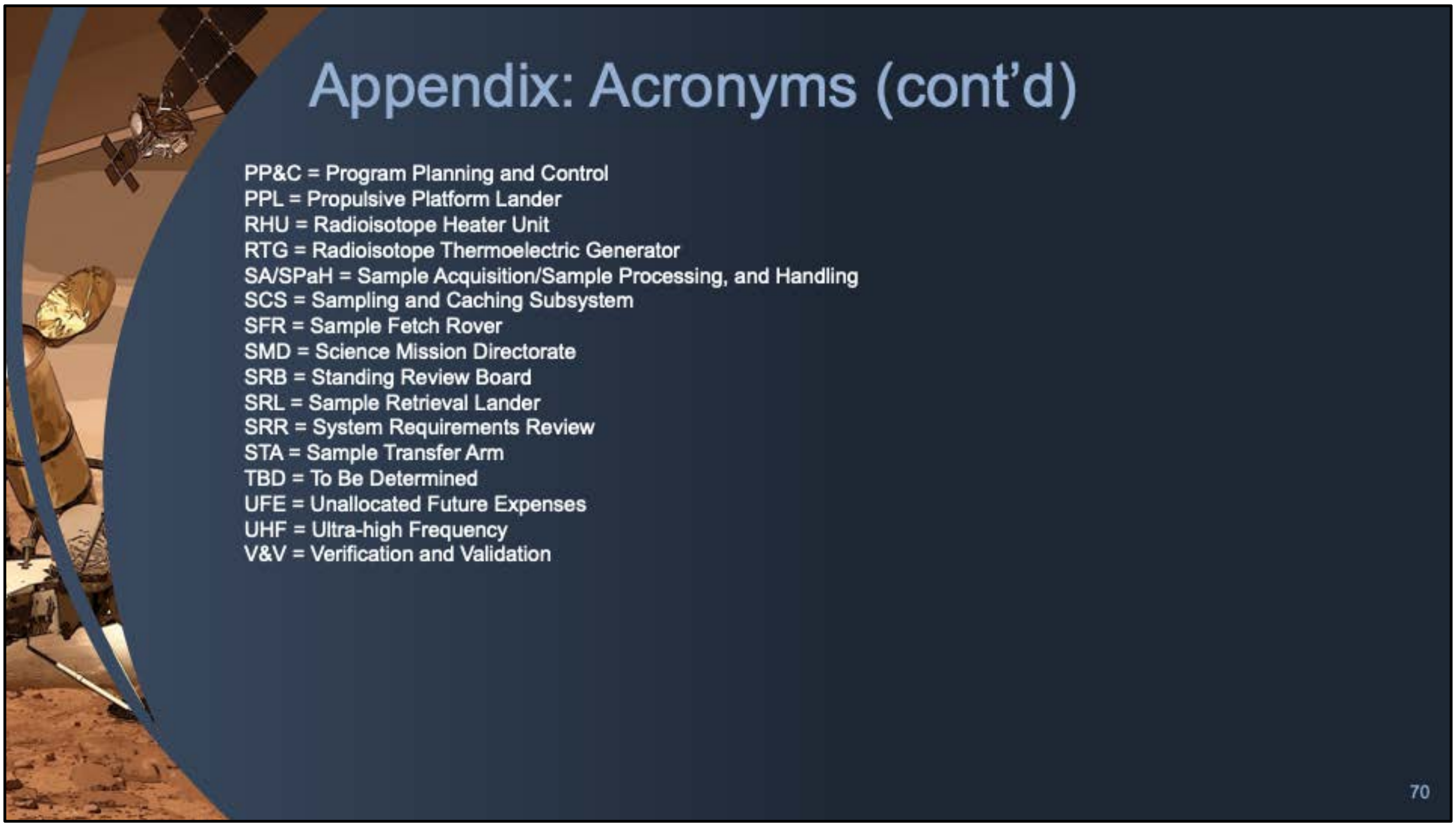
Vice President Zuber's awards include the James R. Killian Jr. Faculty Achievement Award, the highest honor the MIT faculty bestows to one of its own. She is a member of the National Academy of Sciences and American Philosophical Society and is a fellow of the American Academy of Arts and Sciences, the American Association for the Advancement of Science, the Geological Society of America and the American Geophysical Union.

Vice President Zuber is the first woman to lead a science department at MIT and the first to lead a NASA planetary mission. In 2004, she served on the Presidential Commission on the Implementation of United States Space Exploration Policy. In 2002 Discover magazine named her one of the 50 most important women in science and, in 2008, she was named to the U.S. News/Harvard Kennedy School List of America's Best Leaders. In 2013, President Obama appointed her to the National Science Board, and she served as Board Chair from 2016-2018.



Appendix: Acronyms

AA = Associate Administrator
ARC = Ames Research Center
BOE = Basis of Estimate
BoL= Beginning-of-Life
BTC = Break-the-Chain
Caltech = California Institute of Technology
CCM = Capture Containment Module
CCRS = Capture/Containment and Return System
CDR = Critical Design Review
CL = Confidence Level
Con Ops = Concept of Operations
CY = Calendar Year
EDL = Entry, Descent and Landing
EEV = Earth Entry Vehicle
ERM = Earth Return Module
ERO = Earth Return Orbiter
ESA = European Space Agency
ESTEC = European Space Research and Technology Centre
ExoMars = Exobiology on Mars mission (aka Rosalind Franklin)
FY = Fiscal Year
GRC = Glenn Research Center
GSFC = Goddard Space Flight Center
HQ = Headquarters
ICE = Independent Cost Estimate
IMS = Integrated Master Schedule
IRB = Independent Review Board
ISRU = In-Situ Resource Utilization
IV&V = Independent Verification and Validation
KDP = Key Decision Point
JPL = Jet Propulsion Laboratory
LaRC = Langley Research Center
LCR = Life Cycle Review
LMS = Large Mission Study
M2020 = Mars 2020 rover (aka Perseverance)
MAV = Mars Ascent Vehicle
MCR = Mission Concept Review
MER = Mars Exploration Rovers
MIT = Massachusetts Institute of Technology
MOU = Memorandum of Understanding
MRO = Mars Reconnaissance Orbiter
MSFC = Marshall Space Flight Center
MSL = Mars Science Laboratory (aka Curiosity)
MSR = Mars Sample Return
NEPA = National Environmental Policy Act
NPR = NASA Procedural Requirement
Ops = Operations
OS = Orbiting Sample container
OSIRIS-REx = Origins, Spectral Interpretation, Resource, Identification, Security, Regolith Explorer
PDR = Preliminary Design Review



Appendix: Acronyms (cont'd)

PP&C = Program Planning and Control
PPL = Propulsive Platform Lander
RHU = Radioisotope Heater Unit
RTG = Radioisotope Thermoelectric Generator
SA/SPaH = Sample Acquisition/Sample Processing, and Handling
SCS = Sampling and Caching Subsystem
SFR = Sample Fetch Rover
SMD = Science Mission Directorate
SRB = Standing Review Board
SRL = Sample Retrieval Lander
SRR = System Requirements Review
STA = Sample Transfer Arm
TBD = To Be Determined
UFE = Unallocated Future Expenses
UHF = Ultra-high Frequency
V&V = Verification and Validation