Exploration Capabilities Data Analysis: An Integrated Approach

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Abstract — **In preparation for humanity's return to the Moon, it is necessary to advance technologies and capabilities that will allow for human sustainability on the lunar surface, as well as on eventual missions to send humans to Mars. Guided by Space Policy Directive-1 and through the National Aeronautical and Space Administration (NASA) Artemis program, the advancement and development of technologies on the lunar surface will be leveraged towards technologies and knowledge needed for humans to successfully and safely go to Mars and return. In order to understand the capability needs for lunar and Mars missions, the Capabilities Integration Team identifies integration approaches and overlaps between missions to develop strategies for advancing key capabilities that support those needs. Since 2013, the Capabilities Integration Team has reached out to subject matter experts, principal technologists, and system capability leadership teams throughout NASA to gather information about the critical technologies and capabilities needed in order to support the lunar and Mars exploration missions. To properly gather this data, the Capabilities Integration Team used a capability-driven approach to identify gaps between the current state of the art and the needs of proposed exploration missions, as well as activities that may close those gaps. These inputs are used to shape technology investment strategies and are incorporated in missions to the lunar and Mars surfaces. Data collected included: gap definitions and identifying information; gap closure information and metrics for success; mapping of gaps to elements of NASA's Artemis program and future exploration architecture. . The data collected, specifically from the technology gap list, has been used to support the NASA Human Exploration and Operations Mission Directorate Planning, Programming, Budgeting, and Execution processes, as well as the NASA Space Technology Mission Directorate Strategic Technology Plans. This paper discusses the integration approach used by the Capabilities Integration Team to identify current capability gaps for the Moon to Mars architecture and what capabilities exist or must be developed to support those architecture needs. In addition, this paper also details the performance, gap characterization, current capability gap closure opportunities, and risk impacts towards Artemis, and the overall Moon to Mars architecture.**

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1. INTRODUCTION

Since 2013, the Human Exploration and Operations Mission Directorate (HEOMD) has relied upon technical discipline experts throughout the National Aeronautics and Space Administration (NASA) to provide information about the necessary technologies and capabilities needed to support lunar and Mars exploration missions. In order to accomplish these missions, NASA's Artemis program and exploration goals and objectives, there needs to be an understanding of the current capabilities needed for the Artemis program and future exploration, as well as the capabilities needed to successfully complete these missions. The Capabilities Integration Team (CIT) within HEOMD serves as the connection between all technical disciplines associated with NASA's human exploration and architecture teams in order to adjudicate differences and develop strategies for advancing key capabilities to support the Artemis program and future exploration mission needs.

2. APPROACH

The Capabilities Integration Team collaborates with HEOMD, Space Technology Mission Directorate (STMD), and the Science Mission Directorate (SMD) to align program strategies, plans, and resources to support the development of capabilities needed for the overarching human exploration strategy [1]. In addition to communicating human exploration plans and needs with stakeholders and the public, the CIT ensures that consistent and realistic data and information is used and facilitated across NASA mission architects and capability developers.

The CIT implements a capability-driven approach to understand and identify the critical technologies and capabilities to address the needs of NASA's human spaceflight and exploration missions. In the past, approaches for human spaceflight missions have focused on a distinct mission and destination, and the appropriate transportation and destination elements needed to meet mission requirements. Yet recently, NASA's human spaceflight and exploration programs have altered the approach to be more focused on developing the core capabilities necessary to reach a variety of destinations as the capabilities evolve over time. This capability-driven approach is used by the Capabilities Integration Team to allow for identification of critical items to be addressed as part of NASA's Artemis program, as well as reducing the risk of future human missions to deep space destinations, such as Mars. The information and insights gained through this process are used to inform agency planning and technology investment strategies (Figure 1).

In order to collect the capability data, the Capabilities Integration Team produces an annual request for data, or Data Call, to all the technical disciplines associated with human exploration plans to provide input on the capability gaps for human lunar and Mars exploration associated with their discipline area. The gaps submitted may be the result of either no existing capability, lack of proficiency with the current capability, or the need to improve the existing capability to prevent a future gap. For example, the need for 98% water recovery from urine brine is a capability gap. The current state of the art life support systems on the International Space Station (ISS) experience precipitation and produce a high solids content liquid urine brine, limiting the amount of water that can be recovered; resulting in the need for water resupply, potentially driving an increase in logistics mass. Currently, the Capabilities Integration Team organizes information using the technical discipline areas used within NASA's 2020 Technology Taxonomy in order to align with the Agency's recent Technology Area Breakdown Structure (TABS) and roadmaps. [2]

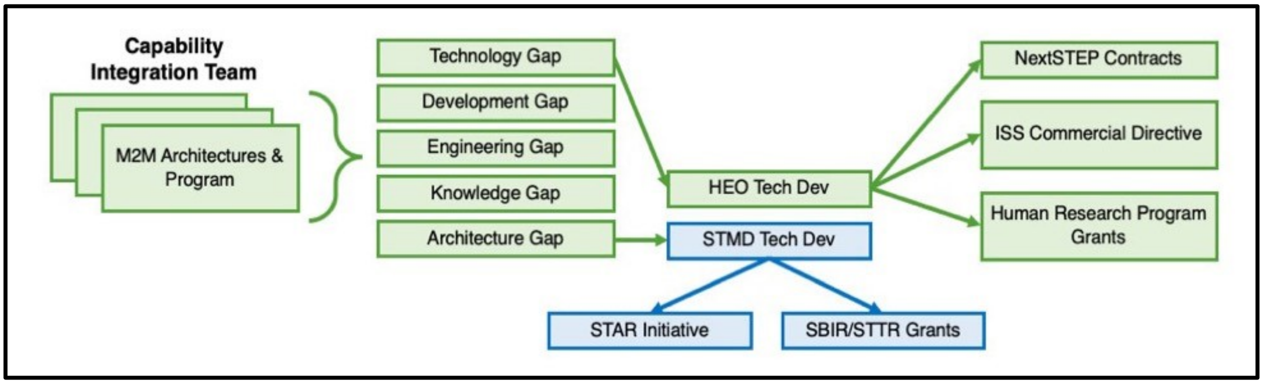


Figure 1. Flowchart of the Capabilities Integration Teams' agency wide impact

- M2M = Moon to Mars
- NextSTEP = Next Space Technologies for Exploration Partnerships
- SBIR = Small Business Innovation Research
- STAR = Strategic Technology Architecture Roundtable
- STMD = Science and Technology Mission Directorate
- STTR = Small Business Technology Transfer
- Tech Dev = Technology Development

3. DEFINITIONS

The following definitions are used within the context of this activity:

Capability: The ability to complete a task or meet an exploration objective through Architecture, Engineering, Development, Technology, or Operations for a given set of constraints and levels of risk.
Capability Area: A group of functions that performs a similar task (e.g. propulsion, robotic systems, power and energy storage).

Capability Gap: The inability to complete a task or meet an exploration objective. The gap may be the result of no existing capability, lack of proficiency or sufficiency in an existing capability solution, or the need to replace an existing capability solution to prevent a future gap (*see page 5 for the capability gap types and corresponding definitions*).

Architecture: A set of functional capabilities, their translation into elements, their interrelations and operations. The architecture enables the implementation of various mission scenarios that achieve a set of given goals and objectives.

Demonstrate: To exhibit the safe operation or use of a device, process, capability or system. Denotes the occurrence of an action or an event that satisfies all or part of an objective.

Enabling: System/architecture cannot function or achieve mission success without closing this gap; there may be alternatives such as different operational approaches or accepting more risk but usually at additional cost/resources.

Enhancing: Not strictly required to function or achieve mission success, but closing this gap (potentially in combination with other gaps) improves the architecture by adding functionality or resiliency.

Mission: A major activity required to accomplish an Agency goal or to effectively pursue a scientific, technological, or engineering opportunity directly related to an Agency goal. Mission needs are independent of any particular system or technological solution.

Technology: A solution that arises from applying the disciplines of science to synthesize a device, process, or subsystem, to enable a specific capability.

Validate: Denote the confirmation that an end product or system satisfies its intended use when placed in its intended environment. Validation is proof that the product accomplishes its stakeholders' expectations and proves whether "the right system was done."

4. CAPABILITIES FRAMEWORK

As aforementioned, NASA and the CIT use a capability-driven approach. Figure 1 outlines the framework process of the CIT and via the Data Call, the CIT is able to collect data describing capability gaps and relevant information for each gap to support investment decisions as well as science and technology utilization planning. Some of the data collected includes: proposed closure approaches/activities (such as SBIR programs), closure milestones, test and validation platforms (locations), or technology demonstrations. A key feature of the framework is that closure approaches are not limited to new technology solutions alone. Rather, experts are asked to consider whether engineering development, architectural changes, or different operational approaches may close the gaps. These experts are also asked to describe the testing needs in order to demonstrate gap closure, including ground testing and the sequence of flight tests utilizing human spaceflight platforms such as the ISS or Gateway.

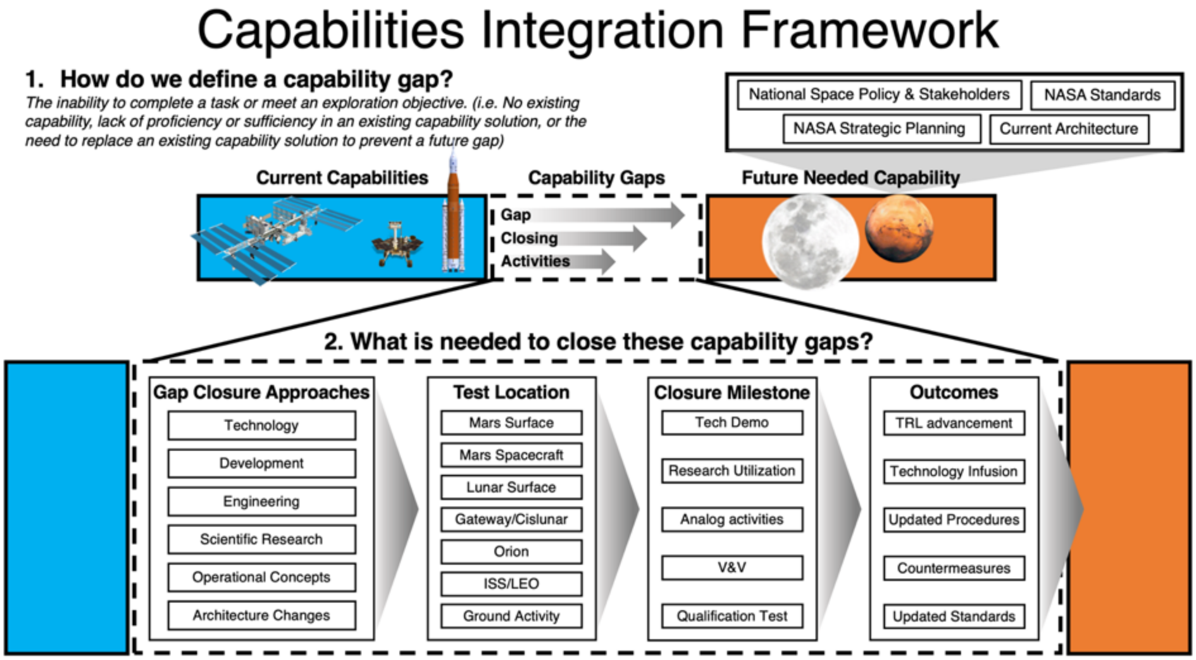


Figure 2. Capabilities Integration Framework

Once vetted and integrated by the CIT, the capabilities data is channeled to the architecture team and stakeholders to understand the current capability gaps and future capability needs for NASA's human exploration missions. This feedback loop between the CIT, architecture team, and stakeholders, is important in understanding which gaps may not be able to close for a given architecture, and the potential downstream impact(s), that this may have to the mission architecture, strategic planning, science and technology utilization, acquisition and planning, and programming budget and execution (PPBE) processes and activities.

5. CAPABILITY DATA CALL PROCESS

To collect the necessary capability data, the Capabilities Integration Team sends an annual request for data, or Data Call, to the technical discipline experts to understand and identify the maturing systems and advancing capabilities and technologies that are needed for the various elements within the Moon to Mars architecture. To inform this request, HEOMD's current mission architecture plans, open trades, and ground rules and assumptions (GR&A's) are provided. One of the primary goals for the Data Call is to validate proposed capability gap mappings for the current Moon to Mars architecture. Technical discipline experts within NASA who provide data to this call include Systems Capability Leadership Teams (SCLT's), STMD Principal Technologists (PT's), HEOMD technology program executives, NASA Engineering and Safety Center Technical Fellows, and other designated experts in unique areas like planetary protection and extravehicular activity. These experts are collectively referred to as the "capability leaders." It is vital for the Capabilities Integration Team to gather relevant data on the capability gaps from the capability leaders due to their in-depth knowledge of the state-of-the art (SoA) technologies and projected developments within their specific technical discipline. Within the data collection instrument, capability leaders are expected to provide gaps relevant to their area of expertise. Figure 2 shows a hierarchy to display the level of inputs provided by the capability leaders. Capability leaders can provide a range of gap inputs on various system levels, such as vehicle (e.g. Deep Space Transportation vehicle), system (e.g. propellant management system), subsystem (e.g. propellant storage), and/or component (e.g. propellant sensors/controllers). Similarly, gaps at the vehicle or mission level can be identified by mission architecture planners. When describing gaps, capability leaders are asked to describe the problem to be solved in quantitative terms to the extent possible, rather than specific technological solutions. Once the capability gaps are defined, there are a series of fields requested to provide additional information about the capability gap.

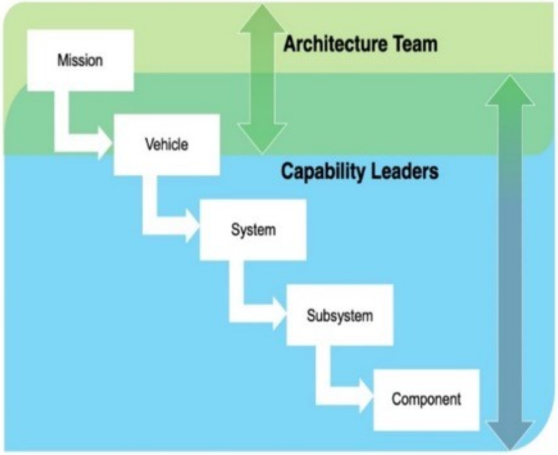


Figure 3. Role of NASA Capability Leaders and Architecture Teams in Capabilities Data Call

One of the many important fields for capability leaders to provide input in is the "gap type" field. This field provides capability leaders the opportunity to characterize the capability gap in terms of possible closure pathways for the given gap via new technology, development, engineering, acquisition of new knowledge/science, or architectural trade studies. Table 1 displays the gap types and definitions used by the CIT and the corresponding definitions. These definitions are consistent with the definitions used in NASA's Technology Readiness Assessment (TRA) report [4]. In order to differentiate between the types of high Technology Readiness Level (TRL) activities, the CIT added "Engineering" as a new gap type for the 2020 Data Call. An example of an engineering gap is the atmospheric trace contaminant control system (TCCS) on ISS. The TCCS is the primary system responsible for scrubbing the ISS for trace contaminants; ensuring the cabin atmosphere maintains habitable for humans and allowing for optimal system functionality. Atmospheric TCCS sorbents must be replaced due to obsolescence and to improve absorbent capabilities, particularly siloxanes. The TCCS process has been operating on ISS with minimal issues, except for the removal of siloxanes. This classifies as an engineering gap because the basic TCCS process does not need to be changed, but there needs to be an improvement to allow for new sorbents to be developed, or screened from commercially available off the shelf (COTS) systems, to use for human exploration.

Gap Type	Description
Technology Gap (T)	New and/or novel performance or function that has not been demonstrated (solutions to this gap type are generally TRL 1-4).
Development Gap (D)	At least one potential solution has been identified, but additional work is required to ensure feasibility of the new and/or novel performance or function in a specific operational application (solutions to this gap type are generally TRL 5-9).
Engineering Gap (E)	Performance or function is well accepted (not new or novel), but requires engineering development for a specific mission (solutions to this gap type are generally TRL 5-9).
Knowledge Gap (K)	Unknown data (e.g., chemical and physical properties) that will ultimately drive hardware requirements; these gaps typically require additional scientific research in order to close.
Architecture Gap (A)	Unknown mission parameters that will ultimately drive hardware requirements; further refinement of mission plans to clarify capability need.

Table 1. Capabilities Integration Team Gap types and descriptions

In addition to gap characterization, the capability leaders are asked to identify the current investments intended to close the gap, the maturity of those investments, the likelihood of fully closing a given capability gap with those investments and associated dependencies or linkages with other capability gaps. Additionally, it is important to note the testing platform requirements to prove gap closure, which vary from standard engineering qualification testing conducted on the ground to the flight tests conducted at the International Space Station, on or around the Moon, and Mars. Table 2 below details the additional fields within the data collection.

Title	Description
Capability Area / Capability gap title	*See Section 3 above for definitions.*
Gap Type	*See Table 1 for definitions.*
Current State of the Art Performance Metrics	Describes the current solutions associated with a given capability gap and the current performance metrics.
Impacts if gap is *not* closed	Describes what the impact will be if the capability gap is not closed.
Currently funded gap closing activities	Description of all the currently funded activities that will support closure of a capability gap.
TRL of currently funded gap closing activity	Lists the TRL of all activities listed for funded activities.
Projected Gap Closure	Details if the gap closing activities are successful, will they result in complete closure of a given capability gap.
Testing and Demonstration Platform	Indicates the primary location (closest to Earth) where possible solutions *must* be tested and where the closure *must* be demonstrated.
Validation Platform	Indicates the primary location (closest to Earth) where solutions *must* be validated to prove the gap has been closed.
Platforms Enhanced or Enabled	Indicates which platforms the closure of this gap directly enhances or enables (*see section 3 for definition of enhanced and enabled*).
Elements Enabled or Enhanced	Indicates which elements are enhanced or enabled due to the closure of a given capability gap.

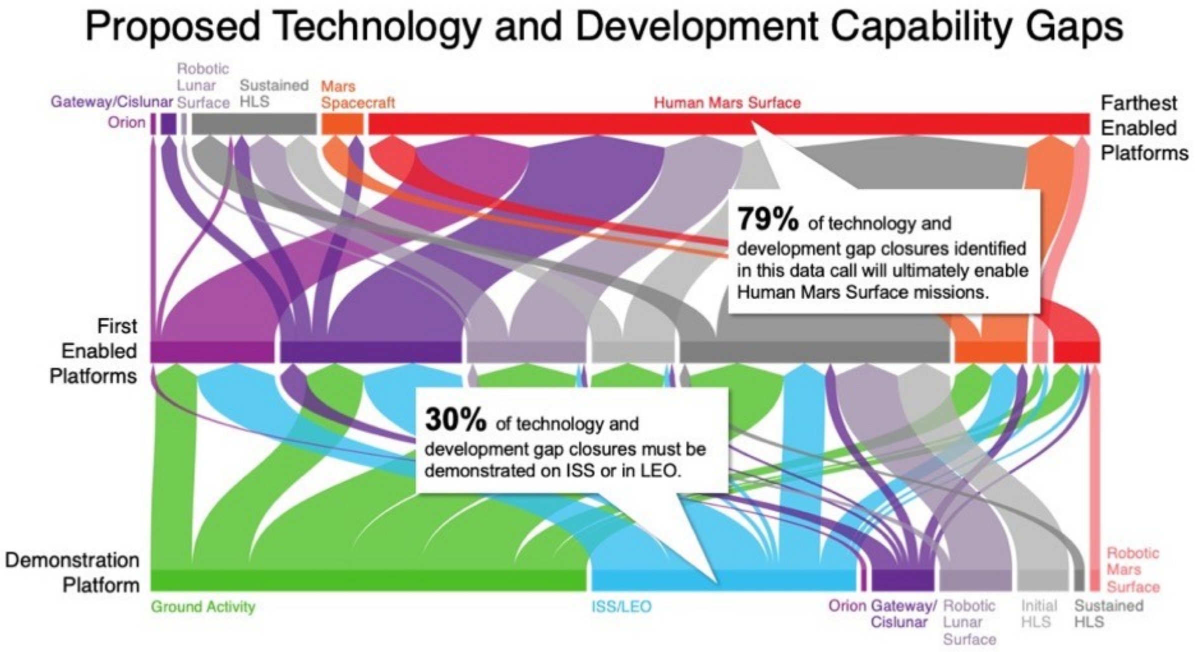
Table 2. CIT Data Call fields and associated descriptions

The human spaceflight architecture team defines NASA's high-level human spaceflight mission requirements. NASA's architecture team spans agency-wide with participants who range in technical disciplines of engineering, science, fiscal analysis, and mission planning. Due to their overall understanding of the "start-to-end" mission plan, the architecture team provides valuable confirmation of the capability gaps' applicability to the overall mission based on the current mission architecture. In Figure 2 above, the architecture team is responsible for verifying that the capability gaps provided in the Data Call align with the mission (e.g. Artemis and Mars exploration [3]) and vehicle requirements. In addition, the architecture team may provide additional missing gaps not identified by the capability leaders, given their depth of knowledge of the architecture elements and associated assumptions. The architecture team is usually involved in this towards the end of the Data Call process (as well as the beginning) once all the capability leaders' gaps have been assessed to determine quality, consistency, and initial applicability. Ideally, iteration facilitated by the CIT between the architecture team and capabilities leaders would result in a capabilities gap list concurred to by all parties involved.

As the CIT processes and analyzes the submitted data, it is important to note that not all the capability gaps submitted are accepted. Gaps that do not meet the minimum level of acceptance are labeled as "deferred gaps" and are held back for discussion and improvement during future data calls. Capability gaps are deferred for the following reasons: i.) capability gap description did not explain what the gap was, nor the impact of the gap if it was not addressed/closed, ii.) specified a technological implementation without describing the problem that needs to be solved, iii.) the input was not a gap at all (e.g. listed elements, requirements instead of addressing the actual gap), and iv.) duplicate entries, which are nominally combined into a single gap

6. DATA CALL RESULTS AND USES

HLS = Human Landing System



79% of technology and development gap closures identified in this data call will ultimately enable Human Mars Surface missions.

30% of technology and development gap closures must be demonstrated on ISS or in LEO.

Figure 4. 2019 mapping of demonstration platforms to enabled platforms

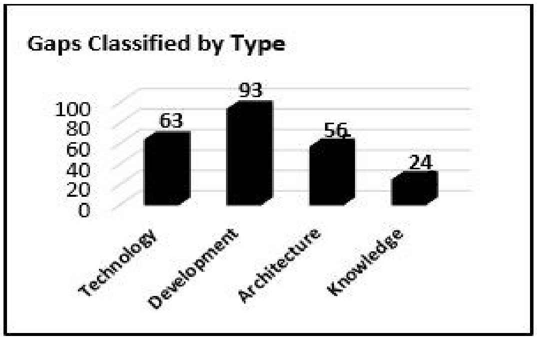


Figure 5. Results from the 2019 Data Call

Boggs et al previously described preliminary results from the 2019 capability data call, which included all proposed capability gaps associated with a range of architectural options that were under consideration by NASA for the Artemis campaign. With the recent publication of NASA's Artemis Plan [5] and other papers containing more details on capability needs associated with the campaign [6], further refinement of the gap list was possible. The capability gap list resulting from the 2019 Capabilities Data Call had 236 capability gaps after all integration activities were completed. Of the 236 capability gaps, 93, or 39%, of the overall capability gaps were classified as development gaps, indicating a need for TRL advancement rather than invention of new technologies to close the gaps (Figure 5). In fact, only 63 of the gaps, or 27%, were designated as technology gaps with solutions in the TRL 1-3 range. The remaining gaps included 56 (15%) Architecture gaps requiring further refinement of mission plans to clarify the capability needs, and the remaining 24 (10%) were Knowledge gaps – largely in the areas of human health and planetary protection, requiring scientific research for closure. In contrast, as shown in Figure 6, the 2020 data call yielded over 300 capability gaps, with nearly equal portions designated as Technology and Development gaps. The number of technology gaps increased by 58 gaps, or 92%, due to the increased fidelity of human spaceflight architectures associated with human exploration of the Moon and Mars, as well as due to increased participation of capability leaders in key areas like propulsion. It is also important to note that the capability gap data includes items that are not strictly enabling for the exploration campaign. Many of the included gaps reflect capabilities that could enhance missions with impacts such as reduced logistics or increased interoperability with partners.

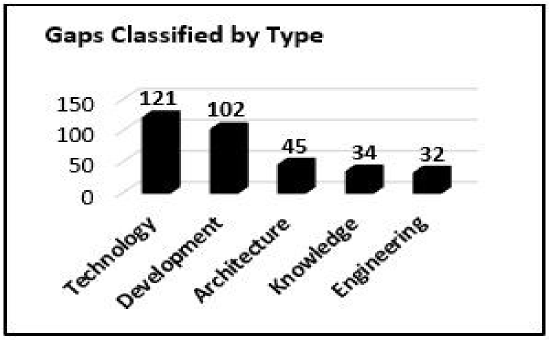


Figure 6. Results from the 2020 Data Call

Roughly 20% of habitation systems' development gaps were enhancements that reduced sparing requirements. In addition, 35% of the accepted capability gaps pertaining to the communications and navigation technical area enhanced the ability to provide high quality video.

Figure 4 traces technology and development capability gap closure from the required demonstration platform through the first platform enabled by that demonstration to the ultimate platform enabled by closure of the gap. The width of the lines corresponds to the number of gaps to be closed. In reviewing closure paths, it becomes clear that all of the current proposed platforms in NASA's plans as of now – ISS, Orion, Gateway, and Lunar Surface Assets – are required to enable the eventual human exploration of Mars. It is also worth noting that 43% of these gaps can be closed on the ground and 30% of these gaps must be demonstrated on ISS or other potential LEO platforms. Of the technology and development gaps identified through this process, 79% relate to capabilities that ultimately enable human Mars surface missions. The tracking of gaps from demonstration platform through to the first enabled platform and then on to further enabled platforms demonstrates the progression of capability development across mission phases, as well as the benefit of leveraging existing and nearer term platforms to enable future exploration missions. For instance, a majority of the gap closing activities identified in this effort can be closed via ground testing and/or on a LEO platform such as ISS. Characterization of gaps by type and element enabled or enhanced can provide useful insight to inform budget and acquisition processes. For example, as illustrated in Figure 7 technology program investments can be related to the campaign elements that may need those technologies. In the case of HEOMD's technology projects, a tendency towards supporting near term technology needs and higher TRL investments, consistent with agency guidance can be illustrated in this way. However, as illustrated by the overlapping arrow origins, many of these investments support multiple elements across the campaign.

Additionally, the CIT mapped the habitation systems capability gaps to the lunar and Mars validation platforms. This mapping highlighted the critical interdependencies and capability similarities within those platforms, as well as the gap closure pathways, or capability closure opportunities, for the first to last enabled platforms within the current architecture. Table 3 shows the platforms where the capability gaps needs to be validated in order to be closed, or proven to function properly verse the highest platform where a gap needs to be closed. As shown, ISS/Low Earth Orbit (LEO) is the platform where the majority of habitation systems capability gap closures need to be validated (129 gaps), followed by the initial Human Landing System (HLS) (57 gaps) and the Human Mars platform (17 gaps). This aligns with the findings found from Figure 4, in that the progression of capability gap closures benefit from leveraging existing and nearer term platforms.

Also, the highest platform where the habitation systems capability gaps needs to be closed is the Human Mars platform (57 gaps), followed by the Sustained HLS (52 gaps) and the Mars Craft platform (50 gaps).

This type of analyses is useful to stakeholders and decision makers at various levels, as the analysis provides additional insight on the interdependent closure pathways for HEO, which can lead to providing critical insight into everything from GR&A's to campaign costing.

The 2021 IEEE conference paper titled "Architecture Robustness in NASA's Moon to Mars Capability Development" [7] will specifically discuss the results in depth.

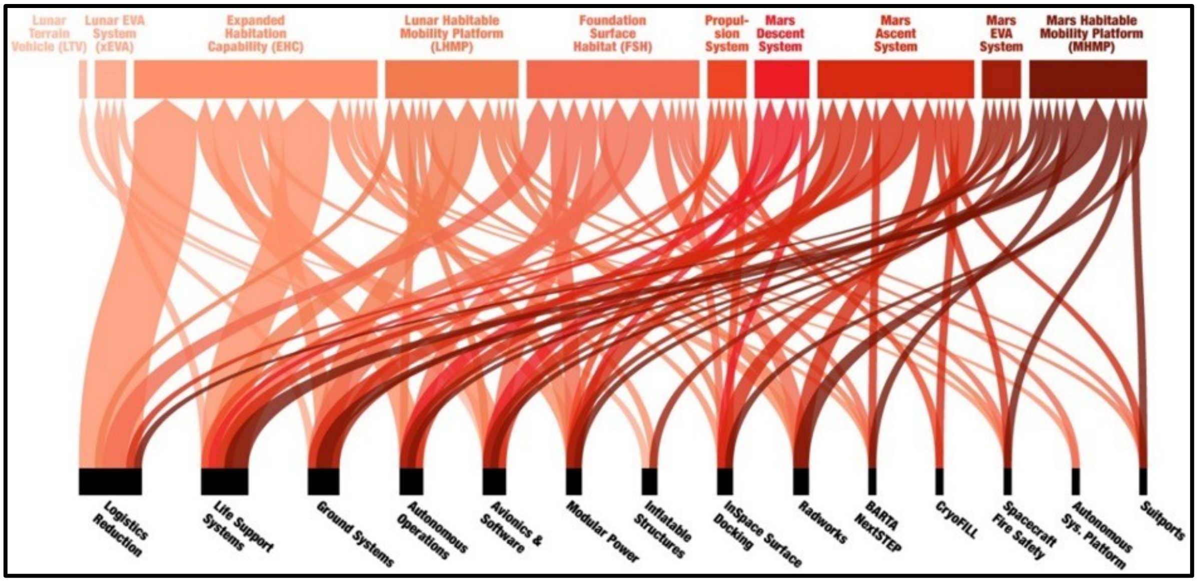
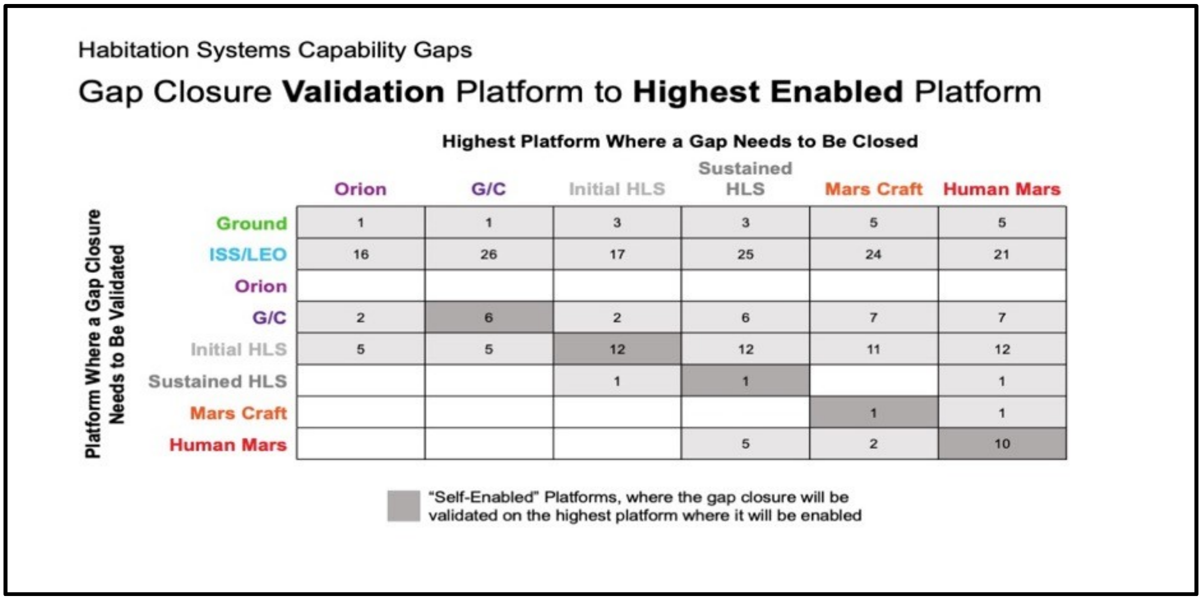


Figure 7. 2019 Elements enabled by proposed HEOMD Technology projects



Habitation Systems Capability Gaps

Gap Closure **Validation** Platform to **Highest Enabled** Platform

Highest Platform Where a Gap Needs to Be Closed

Platform Where a Gap Closure Needs to Be Validated	Orion	G/C	Initial HLS	Sustained HLS	Mars Craft	Human Mars
Ground	1	1	3	3	5	5
ISS/LEO	16	26	17	25	24	21
Orion						
G/C	2	▨ 6	2	6	7	7
Initial HLS	5	5	▨ 12	12	11	12
Sustained HLS			1	▨ 1		1
Mars Craft					▨ 1	1
Human Mars				5	2	▨ 10

▨ "Self-Enabled" Platforms, where the gap closure will be validated on the highest platform where it will be enabled

Table 3. Mapping of habitations systems capability gaps to lunar and Mars platforms

7. CONCLUSION/FORWARD WORK

The Capabilities Integration Team serves a key role in understanding, identifying, facilitating, and communicating the capabilities needed for the Artemis program and the Moon to Mars architecture. The results from the Data Calls are used to shape technology and development investment strategies, and are incorporated into missions to the lunar surface and Mars. The data collected, specifically for the technology gaps, has been used to support HEOMD and STMD technology development, which in turn, has allowed those mission directorates to align activities to address or close key technology capability gaps. The data and analysis provided from the Capabilities Integration Data Call has been used to support NASA's HEOMD PPBE processes, as well as STMD Strategic Technology Plans (STP). After completing the 2020 Data Call, the Capabilities Integration Team will provide recommendations to the appropriate stakeholders and decision makers, and begin preparation for the 2021 Data Call.

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