Implementing NASA's Capability-Driven Approach: Insight into NASA's Processes for Maturing Exploration Systems.

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NASA is engaged in transforming human spaceflight. The Agency is shifting from an exploration-based program with human activities focused on low Earth orbit (LEO) and targeted robotic missions in deep space to a more sustainable and integrated pioneering approach. Through pioneering, NASA seeks to address national goals to develop the capacity for people to work, learn, operate, live, and thrive safely beyond the Earth for extended periods of time. However, pioneering space involves more than the daunting technical challenges of transportation, maintaining health, and enabling crew productivity for long durations in remote, hostile, and alien environments. This shift also requires a change in operating processes for NASA. The Agency can no longer afford to engineer systems for specific missions and destinations and instead must focus on common capabilities that enable a range of destinations and missions.

NASA has codified a capability driven approach, which provides flexible guidance for the development and maturation of common capabilities necessary for human pioneers beyond LEO. This approach has been included in NASA policy and is captured in the Agency's strategic goals. It is currently being implemented across NASA's centers and programs. Throughout 2014, NASA engaged in an Agency-wide process to define and refine exploration-related capabilities and associated gaps, focusing only on those that are critical for human exploration beyond LEO. NASA identified 12 common capabilities ranging from Environmental Control and Life Support Systems to Robotics, and established Agency-wide teams or working groups comprised of subject matter experts that are responsible for the maturation of these exploration capabilities. These teams, called the System Maturation Teams (SMTs) help formulate, guide and resolve performance gaps associated with the identified exploration capabilities.

The SMTs are defining performance parameters and goals for each of the 12 capabilities, developing maturation plans and roadmaps for the identified performance gaps, specifying the interfaces between the various capabilities, and ensuring that the capabilities mature and integrate to enable future pioneering missions. By managing system development through the SMTs instead of traditional NASA programs and projects, the Agency is shifting from mission-driven development to a more flexible, capability-driven development.

The process NASA uses to establish, integrate, prioritize, and manage the SMTs and associated capabilities is iterative. NASA relies on the Human Exploration and Operation Mission Directorate's SMT Integration Team within Advanced Exploration Systems to coordinate and facilitate the SMT process. The SMT Integration team conducts regular reviews and coordination meetings among the SMTs and has developed a number of tools to help the Agency implement capability driven processes. The SMT Integration team is uniquely positioned to help the Agency coordinate the SMTs and other processes that are making the capability-driven approach a reality.

This paper will introduce the SMTs and the 12 key capabilities they represent. The role of the SMTs will be discussed with respect to Agency-wide processes to shift from mission-focused exploration to a capability-driven pioneering approach. Specific examples will be given to highlight systems development and testing within the SMTs. These examples will also show how NASA is using current investments in the International Space Station and future investments to develop and demonstrate capabilities. The paper will conclude by describing next steps and a process for soliciting feedback from the space exploration community to refine NASA's process for developing common exploration capabilities.

I. Introduction

ON April 15, 2010, in a speech at the National Aeronautics and Space Administration's (NASA) Kennedy Space Center (KSC), President Obama stated:

> Fifty years after the creation of NASA, our goal is no longer just a destination to reach. Our goal is the capacity for people to work and learn and operate and live safely beyond the Earth for extended periods of time, ultimately in ways that are more sustainable and even indefinite. And in fulfilling this task, we will not only extend humanity's reach in space—we will strengthen America's leadership here on Earth.[i]

Adding form to this vision, the National Space Policy of the United States directs NASA to meet broad space-related goals, including expanding international cooperation and pursuing human and robotic activities.[ii] The National Space Policy also provides a set of specific guidelines that will serve to guide human space exploration activities over the next several decades. Specifically it notes NASA should:

- Set far-reaching exploration milestones. By 2025, begin crewed missions beyond the moon, including sending humans to an asteroid. By the mid-2030s, send humans to orbit Mars and return them safely to Earth
- Continue the operation of the International Space Station (ISS)
- Seek partnerships with the private sector
- Implement a new space technology development and test program
- Conduct R&D [research and development] in support of next-generation launch systems
- Maintain a sustained robotic presence in the solar system
- Continue a strong program of space science

NASA has established a set of strategic directives to guide effort in meeting these national goals over the next several decades. This paper identifies how NASA's strategic guidance is implemented and introduces some of the structures and processes NASA is using to achieve the nations objectives. At the top level the agency's specific goals and objectives are captured in the NASA Strategic Plan.[iii] The Strategic Plan is reflected in NASA's human exploration strategy, which has been previously described through the capability-driven framework and more explicitly through the pioneering space initiative. To realize this strategy NASA has leveraged expertise across NASA through System Maturation Teams and exploring the trade space of human exploration architectures with the Evolvable Mars Campaign. The remainder of this paper discusses the interplay and implementation of each of these elements as the agency matures systems for human spaceflight.

II. The Capability-Driven Framework

NASA established the Human Exploration Framework Team (HEFT) in 2010 to analyze exploration and technology concepts and provide inputs to the agency's senior leadership on the key components of a safe, sustainable, affordable and credible future human space exploration endeavor. The team's work helps provide context for the next stage of NASA's diverse portfolio of activities and a basis for ongoing architecture analysis and program planning.

HEFT's analysis focused on affordability, cost, performance, schedule, technology, and partnership considerations, while also identifying capabilities and destinations for future exploration as we move out, step by step, into the solar system.

HEFT found that the most robust path for NASA in human space flight is a capability-driven framework (CDF) where evolving capabilities would enable increasingly complex human exploration missions over time. The CDF also provides increased flexibility, greater cost-effectiveness, and sustainability. This approach will open up many potential destinations for human spaceflight throughout the solar system, including the moon, near-Earth asteroids, and Mars.

The CDF, shown in Figure 1, describes an exploration path that follows incremental steps to build, test, refine, and qualify critical capabilities that will lead to affordable flight elements and deep space capability, eventually enabling crewed planetary exploration to destinations beyond the Earth-moon system, such as the surface of Mars. In the CDF, the four initial priorities are:

1. Development of a human-rated Space Launch System (SLS), or heavy lift rocket
2. Development of a Multi-Purpose Crew Vehicle (Orion)
3. Enable commercial crew and cargo services to low Earth orbit (LEO), including the International Space Station (ISS)
4. Pursue mission-focused technologies to support expanded exploration capabilities in the future.

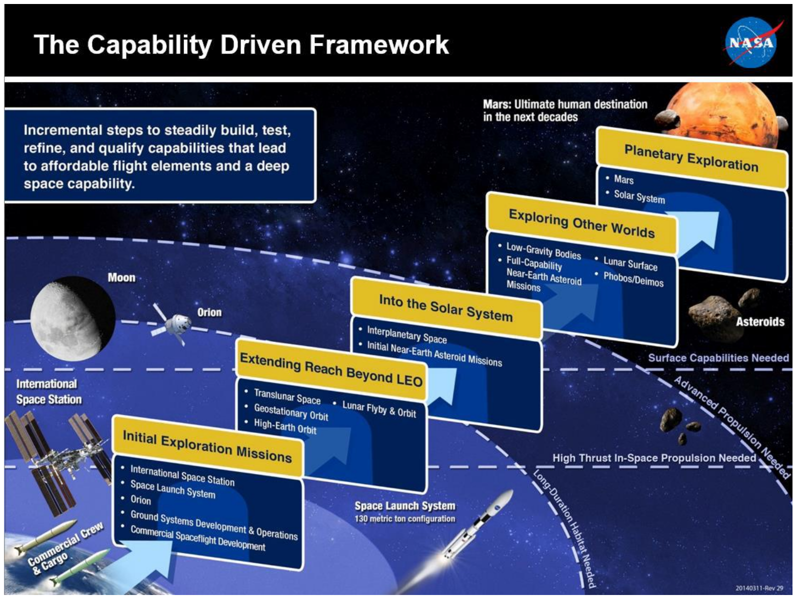


Figure 1. NASA's Capability-Driven Framework (CDF) for Human Space Exploration

The CDF path begins with initial exploration missions to establish the first steps, including use of the ISS and validation of transportation systems like the SLS and Orion crew vehicle. These initial steps are followed by missions in the Earth-moon system that extend our reach beyond LEO, to such destinations as cislunar space and high Earth orbit (HEO). This phase is followed stepwise beyond these near-Earth destinations further into the solar system, and eventually to Mars and its moons. All of the phases within the path are “capability-driven” in that each phase focuses on incrementally building, testing, and validating critical capabilities required to eventually field long-duration crewed missions to the Mars system. The CDF serves as a foundation for all future analyses.

III. NASA’s Pioneering Space Strategy

NASA’s Pioneering Space strategy provides a narrative on how capabilities outlined in the CDF will be used to conduct human missions to the Mars system during the 2030s. NASA has defined Pioneering Space as the sustainable sequence of activities—science missions, technology development, capability demonstrations, and human spaceflight—to expand human presence and robotic missions farther into the solar system with the horizon goal of humans reaching and remaining on the surface of Mars.

NASA believes the Pioneering Space strategy strikes a balance between progress toward horizon goals including human missions to Mars; near-term benefits; and long-term flexibility to budgetary changes, political priorities, scientific discoveries, and evolving partnerships. This strategy guides investment in specific capabilities, which enable a sustainable, affordable, programmatically-sound, and technically-feasible architecture for human missions to Mars.

Pioneering Space represents a natural evolution of NASA’s prior decades of space exploration. NASA’s human spaceflight program has already demonstrated the capability for Earth-reliant human exploration, culminating with the ISS, where astronauts and supplies can be ferried between the ISS and Earth within hours. Our partner space agencies with ISS, and now with commercial spaceflight ventures, reflect a blossoming worldwide human spaceflight capability for LEO access. Meanwhile, robotic science missions are bridging the gap between exploration and pioneering by scouting resources and characterizing potential destinations for humans at far more distant locations in our solar system. To fully realize the Pioneering Space strategy, NASA is taking programmatic steps to enable focused and adaptable capability development that spans multiple projects and programs and create the toolset necessary for human missions to Mars.

IV. System Maturation Teams

A key piece to the Pioneering Space strategy is input from System Maturation Teams (SMTs). The SMTs bring together subject matter experts from across the agency. These experts have been involved in advancing technology readiness and maturing systems for NASA since the beginning of NASA's Constellation program and have been involved in a variety of human spaceflight architecture studies. The SMTs provide NASA's Human Exploration and Operations Mission Directorate (HEOMD) with expertise to develop and mature systems needed for human exploration using the CDF approach. SMTs can provide integrated capability investment decisions with traceability to human exploration needs.

NASA established 12 SMTs, each focused on one or more capability areas. The subject matter experts that compose each SMT are responsible for understanding their capabilities across all elements within an evolving human spaceflight architecture. The SMTs are supported by multi-disciplinary teams in crosscutting capability areas, which are established as needed to address challenges that span multiple SMTs like dormancy (the length of time a system can remain idle between uses) and avionics. By using this approach, NASA facilitates continued coordination and development of functional capabilities that span multiple projects and programs.

Each SMT defined the scope of their capability area by determining specific functions and identifying performance gaps in relation to the current state of the art. These gaps define a capability advancement over the current state of the art along with mission criticality and mission need date. For example, the Environmental Control and Life Support System (ECLSS) SMT investigates four capability areas: atmospheric conditioning; environmental monitoring; pressure management; and waste management. Within these functions the ECLSS SMT identified performance gaps that need to be resolved in order to enable Mars missions. The full list of SMTs and their areas of focus are listed in the Table 1.

Table 1. List of System Maturation Teams (SMTs) and their Capability Areas of Focus

System Maturation Team	Capability Areas
Autonomous Mission Operations (AMO)	Autonomous Mission Operations
Crew Health and Performance - Radiation (CHP)	Medical Diagnosis and Prognosis
	Behavioral Health and Performance
	Human Physiology
	Human Factors and Habitability
Communications and Navigation	Communications
	Navigation
	Internetworking
Environmental Control and Life Support Systems and Evironmental Monitoring (ECLSS-EM)	Atmospheric Conditioning
	Environmental Monitoring
	Pressure Management
	Waste Management
Entry, Descent, and Landing (EDL)	Earth EDL
	Mars EDL
Extravehicular Activity (EVA)	Launch, Entry, and Abort (LEA)
	Exploration Pressure Garments
	Exploration Portable Life Support Systems (PLSS)
	Exploration EVA Avionics
	Exploration EVA Tools
	Exploration EVA Architecture
	EVA Integration
Fire Safety	Fire Safety
In-Situ Resource Utilization (ISRU)	Resource Location
	Resource Acquisition
	Resource Processing

	Civil Engineering
Power and Energy Storage	Solar Power Generation
	Nuclear Power Generation
	Energy Storage
	Power/Energy Support Systems
Propulsion	Earth-to-Orbit
	High Thrust In-Space
	Low Thrust In-Space
Human-Robotic Mission Operations	Robotics
Thermal (including cryo)	Active Thermal Control
	Cryogenic Systems Management
	Thermal Protection Systems

Using this structure to determine performance gap information, the SMTs developed white papers designed to articulate the state of the art and the capability areas requiring closure to support human missions to Mars. The papers are also designed to describe dependencies between SMTs, effectively linking the 12 papers into a coherent narrative. The whitepapers also describe how capabilities are developed and matured for each destination therefore utilizing the CDF. Other NASA groups working on the Pioneering Space strategy rely on the data within these whitepapers to bound and inform architecture studies.

The SMTs have specific objectives designed to support NASA's processes by leveraging expert inputs. For example, each SMT identifies capability needs and roadmaps for each mission described in human exploration spaceflight studies (like the Evolvable Mars Campaign study described later in this paper). SMT experts also guide the technology maturation of their respective systems, provide capability development status and budget input, aid in the development of budgets, and support various HEOMD study activities like the Future Capability Teams. Finally, SMTs should make recommendations on how to integrate capability developments that leverage the ISS, cislunar space, and ground testing. Figure 2 illustrates how the SMTs are integrated across different NASA organizations and stakeholders.

Each SMT has a lead or co-leads. The lead or co-leads identify the team and expertise needed to develop and guide an agenda designed to provide NASA decision-makers with consistent inputs on capability development and maturation activities. SMTs are encouraged to include key industry stakeholders in a single capability area. The SMT are identified in Table 2.

SMTs interact with each other via a technical forum, the System Advancement Coordination Group (SACG). SACG representation includes each SMT lead, Discipline team point of contact (POC), program representatives from the Human Resource Program (HRP), HEOMD Division representatives from the Advanced Exploration Systems Division (AESD), mission directorate representatives from the Space Technology Mission Directorate (STMD), SMT Integration Team and any key stakeholders across all capability areas and programs. Products from each of the SMTs are delivered to the SACG, and any actions or requests are fed to the SMTs through the SAGC. In addition, any guidance from architecture study teams are provided to SMTs through the SACG.

When successful, the SMTs will have met the agency goals to establish forums of subject matter experts and a means to coordinate their recommendations across all directorates, enabling steady progress toward exploration mission capabilities.

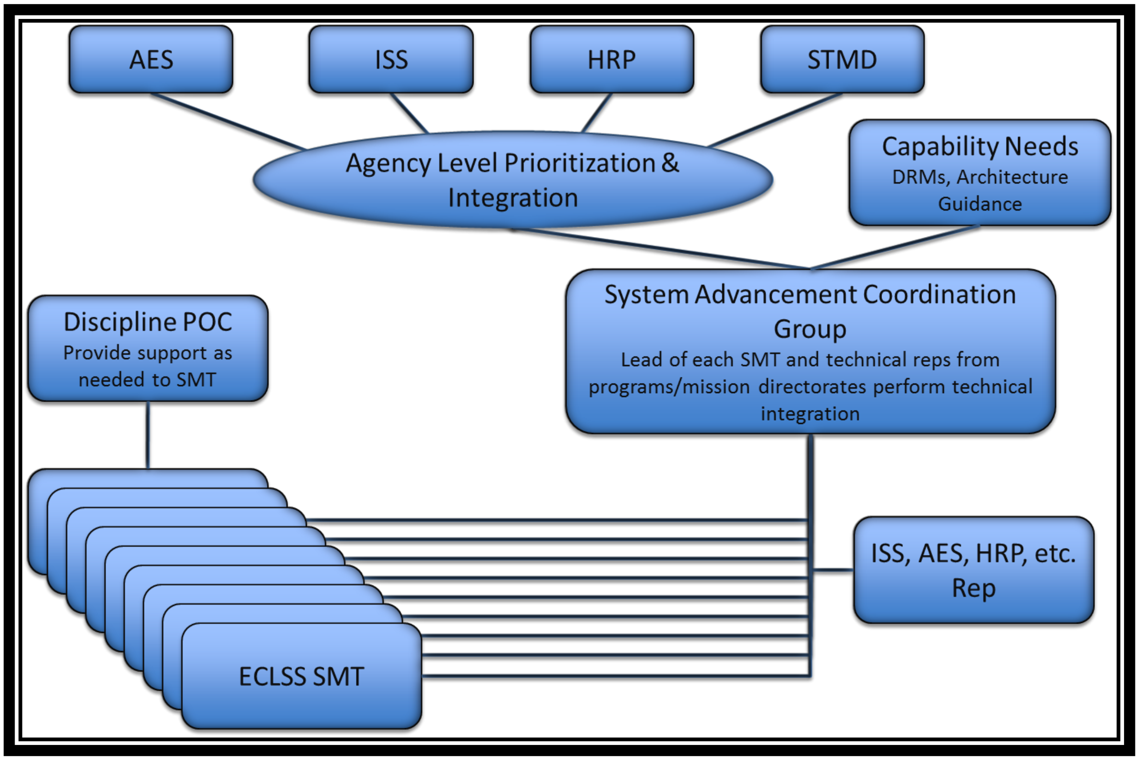


Figure 2. System Maturation Team Organizational Structure

Table 2. System Maturation and Discipline Teams

System Maturation Team
Autonomous Mission Operations (AMO)
Communication and Navigation (Comm/Nav)
Crew Health & Protection – Radiation (CHP)
ECLSS-EM (incl Environmental Monitoring)
Entry, Descent and Landing (EDL)
EVA
Fire Safety
Human-Robotic Mission Operations
In-Situ Resource Utilization (ISRU)
Power and Energy Storage
Propulsion
Thermal (including cryo)
Discipline Team - Crosscutting
Avionics
Structures, Mechanisms, Materials and Processes (SMMP)
Strategic Knowledge Gap (SKG) Measurement Instruments and Sensors (science instruments)

V. Evolvable Mars Campaign Study

The Evolvable Mas Campaign (EMC) is an ongoing study built upon the Pioneering Space strategy. The EMC objective is to identify potential options and key decision points to enable sustainable crewed Mars missions in the mid-2030s timeframe. The EMC illustrates a flexible strategy that utilizes the CDF and data from the SMTs. The EMC is adaptive to scientific discovery and ever-changing programmatic environments. The EMC study is intended to inform the HEOMD, the Science Mission Directorate (SMD) and the Space Technology Mission Directorate (STMD) on near-term key decision options and investment priorities for advancing NASA's journey to Mars.

Although the EMC indicates an order of progression, potential paths to Mars do not necessarily explore the same interim destinations, nor accomplish identical objectives at those destinations. The intent of the EMC is to inform capability development and an assessment of options without prescribing a path to Mars. The EMC is designed to provide a range of capabilities and identify challenges associated with potential destinations; hence, it is "evolvable." Beyond the bounding date for Mars vicinity and Mars surface missions—2033 for crew in Mars orbit and 2039 for the first crew on Mars surface—specific dates have not been assigned to the missions associated with the EMC. Future work will explore a range of assumed dates to assess viability from a technical and programmatic perspective.

The EMC follows three primary phases of missions consistent with the Pioneering Space strategy. These phases will consist of missions with increasing duration and complexity, and greater capability. The initial phase, "Earth Reliant," consists of mission durations of 6 to 12 months with a return to Earth accomplished within hours (for example, as would be the case from the ISS). The second phase, the Proving Ground, includes mission durations of 1 to 12 months that require days for Earth return (for example, missions in cislunar space). It is expected that primary demonstration, testing, and validation of Mars-required capabilities would be accomplished within deep space during this second phase. This second phase also includes robotic pathfinder missions that further develop enabling capabilities. The third and final phase, "Earth Independent," includes mission durations on the order of two to three years and Earth return requiring months. See Figure 3 for an overview of the three human exploration "Path to Mars" phases.

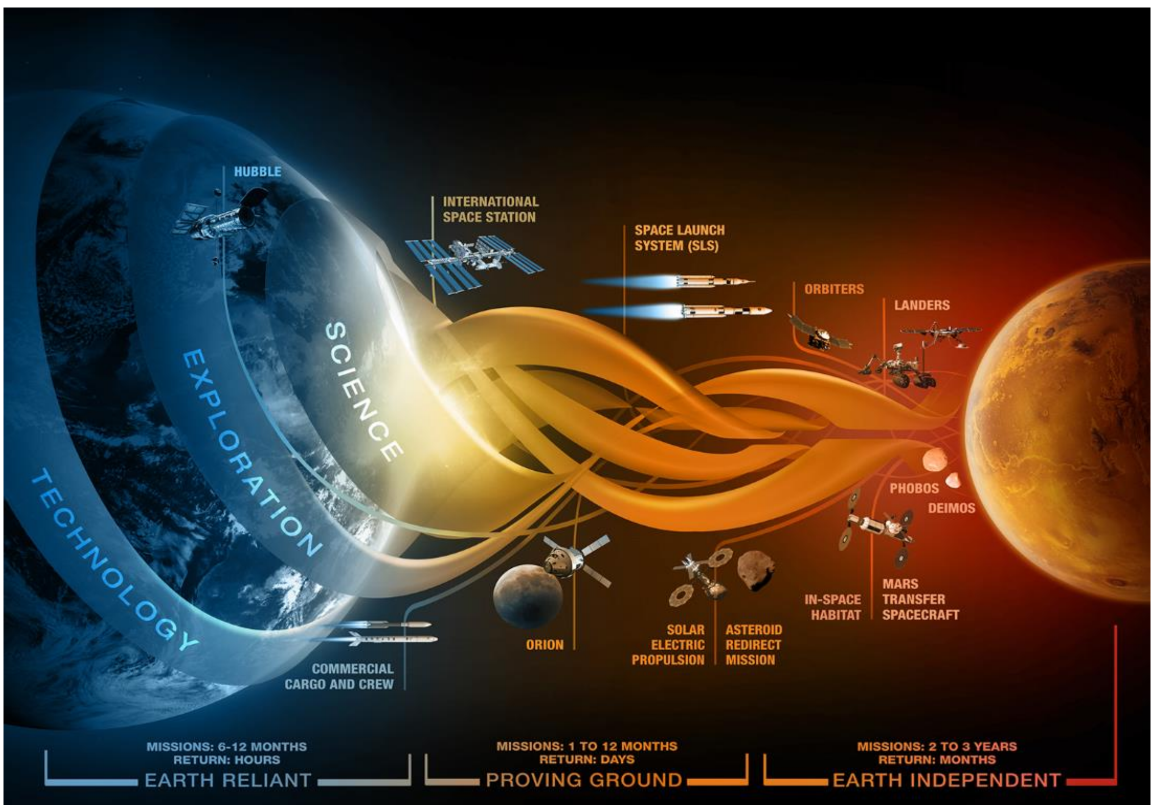


Figure 3. Path to Mars Phases

The EMC differs from other exploration architecture "point solutions" like the often-cited Design Reference Architecture 5.0. Instead the EMC is a philosophy based on a set of ground rules and constraints applied to all EMC trade studies and analyses:

- Use ISS to the greatest extent possible.

- The first crewed mission to the Mars system would be conducted during the 2030s decade and would lay the foundation for further crewed missions to the Mars vicinity.
- Assume Lunar Distant Retrograde Orbit (LDRO) as the location for aggregation of Mars mission elements
- Capabilities and technologies required for Mars missions will be demonstrated, tested, and validated within a Proving Ground environment.
- An Initial Cislunar habitat (ICH) will be emplaced at LDRO to serve as a facility for deep-space testing in support of exploration capabilities and technologies, extending the initial work carried out on ISS. The ICH is a crew-tended habitat that comprises elements that will eventually be used during Mars missions.
- The SLS is used for delivery of cargo and crew to multiple exploration destinations and the Orion vehicle is used for crew transport.
- At least one SLS-based crew mission will be conducted per year within the Proving Ground.
- The Asteroid Redirect Crewed Mission (ARCM) will be conducted in approximately 2025, with the robotically-retrieved asteroid or boulder returned to the LDRO-vicinity in approximately 2024.
- A crew of four will be sent to the Mars system by the mid-2030s; the specific location is TBD and could be to Mars orbit, one or both of Mars' moons, or to the surface of Mars (multiple potential Mars missions are under consideration).
- Solar Electric Propulsion (SEP) in-space transportation system is under consideration for use during all deep space missions (pre-deliver cargo to Mars prior to crew arrival).
- Crewed habitation elements (Mars transit habitat) will be "refurbishable" and reusable over multiple missions.

The EMC outlines a cadence of missions that align with the CDF and the Pioneering Space strategy. The EMC describes an exploration path that follows incremental steps to build, test, refine, and qualify critical capabilities, eventually enabling crewed planetary exploration to the surface of Mars.[iv] The capabilities needed to address the Mars challenges are identified and categorized into the following focus areas: Transportation (Crew and Cargo to and from Deep Space, and In-Space), Staying Healthy (Short and Long Duration Habitation, EVA, and Crew Health), and Working in Space (Destination Systems). The EMC also identifies capability performance metrics for twenty elements across multiple destinations within these areas. Many of the capabilities require test and demonstration aboard the ISS or in the Proving Ground before they feed into EMC missions. The evolvable nature of the EMC allows NASA to invest in critical capabilities to enable near term missions such as ISS test and demonstrations, Asteroid Redirect Missions, and robotic precursors, while still making progress toward human missions to Mars. For instance, NASA is developing EVA pressure garments to support microgravity missions in cis-lunar space. For surface missions, NASA will leverage these investments, augmenting with a new lower torso and vehicle interfaces, to increase performance. Figure 4 represents this process with exploration capabilities evolving through the Proving Ground to enable human missions to Mars.

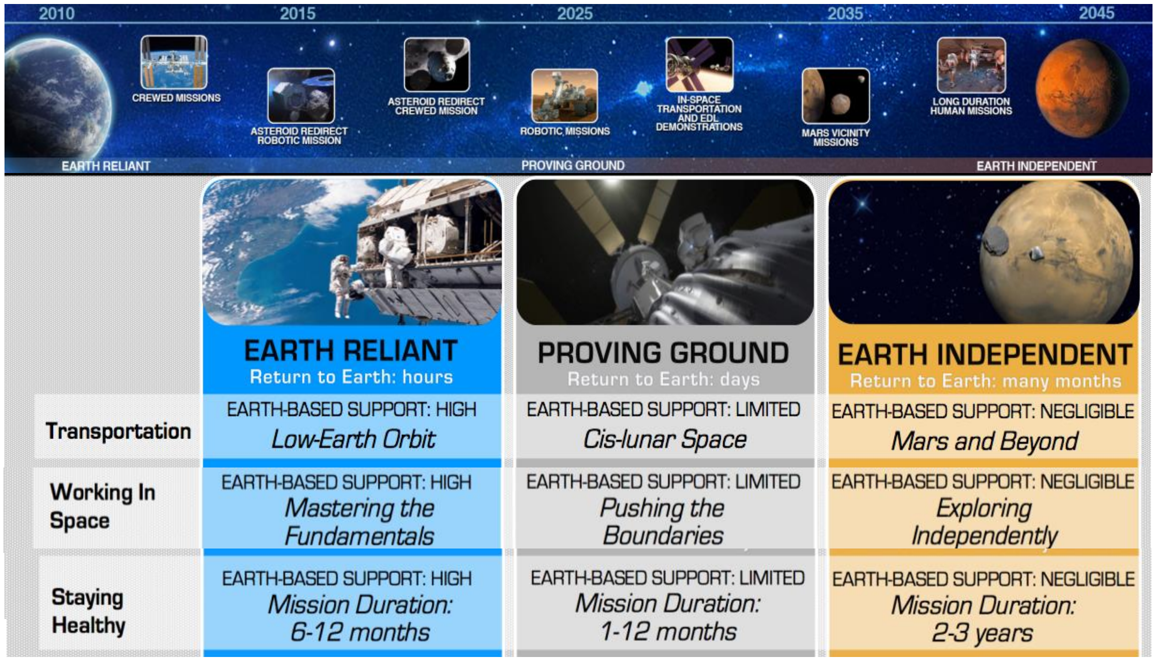


Figure 4. Evolving Capabilities within the EMC

VI. SMT Study Analysis

A. SMT Performance Metrics Reviewed by EMC Study Leads

The SMTs assess the needs of the EMC elements and missions, and then characterize the performance necessary to achieve the capability advancements required to address the Mars challenges. To ensure consistency between the EMC performance metrics and the SMT performance characteristics, the SMTs present their performance gaps, associated performance characteristics, capability mission need, and capability testing location to the EMC architecture element leads for review and validation. The dialog exchanges take place during Technical Interchange Forums (TIFs).

Each TIF lasts 60-120 minutes and is an active discussion between the EMC architecture leads, SMTs, and EMC senior leadership. This forum is an opportunity for the SMTs to provide context not included in the white papers or in the performance characteristic dataset. The discussions are valuable because they highlight areas of disconnect between the teams and identify potential risk areas.

B. SMT Identification of Capability Development Environments

Three distinct environments exist for addressing SMT capability gaps and conducting associated gap closing activities: ground; LEO on the ISS; and cislunar space. Each of these environments provide unique characteristics for developing and testing various aspects of SMT capabilities. Gap closing activities within each of these environments are defined tasks with cost, phasing, and duration information to ensure identified gaps are met.

Ground based environments typically provide the first stage in the development of new capabilities where concepts are tested in a laboratory or a field site, which may include planetary analog sites depending on the capability being tested. Ground based activities are readily accessible by researchers to prove concepts or test specific aspects of a capability; however, ground based environments don't provide all of the characteristics needed to simulate a deep space environment, such as micro or low gravity and radiation exposure. Space-based locations such as the ISS and cislunar space will be employed for that stage of capability development.

The ISS provides a space-based laboratory for testing long duration system performance in a microgravity and vacuum environment. It also allows demonstrations of exploration operations techniques and the ability to improve reliability and performance of critical systems to meet the challenging requirements of deep space exploration missions. With crew availability and access to recurrent logistics support from Earth, capability development can be evaluated and adapted as new aspects are learned during testing.

Similar to the ISS, the cislunar environment also provides access to microgravity and vacuum environments. In addition, cislunar locations beyond the Van Allen belts also provide unique characteristics to demonstrate capabilities for managing the risks of the deep space environment, including the ability to study deep space radiation effects on living systems, avionics, and shielding materials. The combined effects of microgravity and a radiation environment also can be studied along with associated countermeasures for mitigating the effects. Additionally, the cislunar environment enables testing of required space operations capabilities, such as operational modes during dormant periods that would rely heavily on robotic systems to maintain a vehicle without a crew being present.

Each SMT identified activities that will be needed to address their defined capability gaps, along with the appropriate environment for conducting those activities. Figure 5 describes how gaps fit into the SMT process.

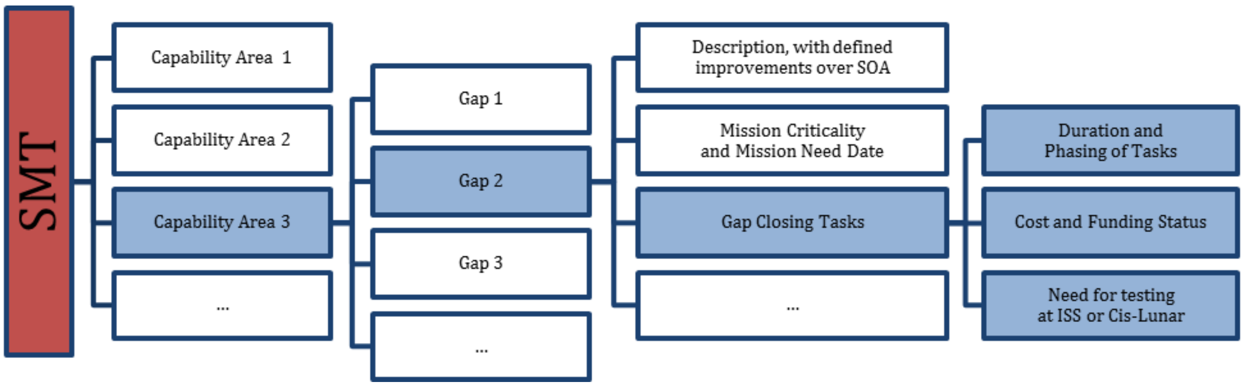


Figure 5. SMT Gap Closing Process

C. Capability Ranking Assessment

In an environment where budgets are limited, capability investments that are most critical to the mission(s) must be determined. Because every capability development cannot be funded simultaneously, those capabilities must be ranked to ensure that the initial portfolio provides the most return on investment. In the CDF, early investments in key capabilities ensure faster progress toward human exploration in space.

In order to rank the capabilities defined by the SMTs, the SMT Integration team took the approach presented in Figure 6, which describes the process, required data, and its source (in brackets beside the data). The process starts with collecting the required data from the SMTs and EMC Subject Matter Experts (SMEs). The capability areas, gaps, and their descriptions were provided in the SMT white papers. Additional data was provided for each gap, including the following development needs, which can be used as filters on the data to look at specific types of gaps if desired:

- Does this gap need to start in the next 5 years?
- Does this gap need to be tested or demonstrated on ISS?
- Does this gap need to be tested or demonstrated in cislunar space?

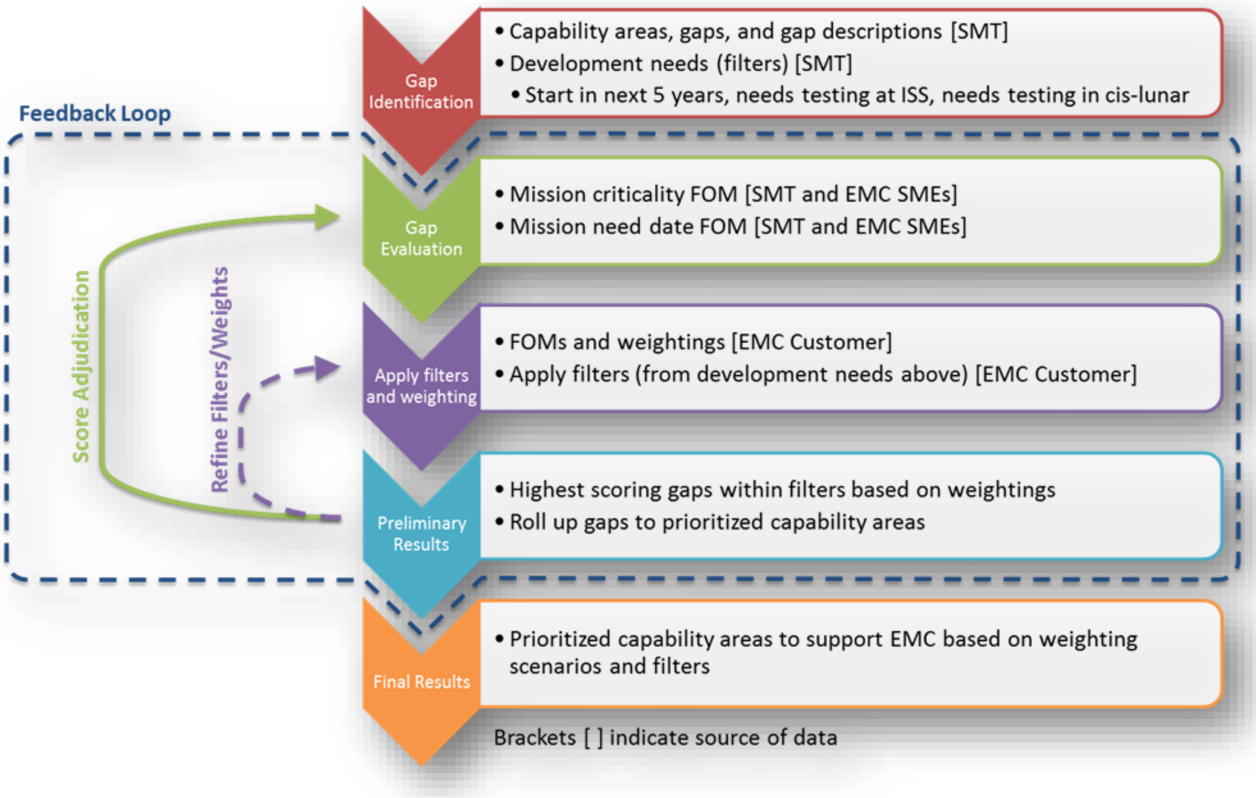


Figure 6. SMT Capability Ranking Process

To evaluate the gaps, two Figures of Merit (FOM) were used to query the SMTs and EMC SMEs. The first FOM is mission criticality, which asks the question: How critical is closing the identified gap to successfully performing the applicable mission(s)? The scoring for this FOM is below, where the score value is the correct response to completing the following sentence:

- Without closing the identified gap,
  - 5: the mission(s) cannot be performed
  - 4: the mission(s) would have **major** reductions to its value and **major** increases to its cost and risk
  - 1: the mission(s) would have **minor** reductions to its value and **minor** increases to its cost and risk

Scores of 2-3 serve as compromises between a score of 1 or 4. The second FOM is mission need date, which identifies the first mission in which the capability is needed. First need date is defined as the launch date of the first mission for which the gap must be closed. This date is translated to a 1-5 score using the conversion in Table 3. These two FOM scores are assigned to each gap identified by the SMTs.

Table 3. First Need Date FOM Definition

Date Range	Score
$\leq$ 2015	5
2016-2020	4
2021-2025	3
2026-2030	2
2031+	1

To then rank the capabilities, an aggregate score for each gap is calculated as

$$Gap\ Score = \sum_{i=1}^{2} Weight_i FOM_i \tag{1}$$

FOM_i is the mean of the scores provided for a given FOM by the SMTs and EMC SMEs. The two values for $Weight_i$ are provided by the customer, and define that customer's value on criticality to any given mission versus the need to support near term missions. The filters are then applied by removing the gaps that do not fit within the development need identified by the SMT. For instance, if the customer wanted to only prioritize gaps that must be tested and demonstrated on ISS, all gaps that did not fit this development need would be removed from the ranked set. It is also possible that no filters are applied to look at all gaps equally.

To convert the gap scores to represent the ranking of capability areas, the highest scoring gap is used to score a capability area. If filters are used, the highest scoring gap that meets the filter is used to score the capability area. At this point, the results can then be used to discuss discrepancies that are impacting the score with the SMTs and EMC SMEs to improve the accuracy of the scores. Also, the customer can begin to understand the impact of their weights and filters on the results.

As an exercise, a scenario that explores the sensitivity to customer weighting was run. The FOM weightings were varied from 100 percent mission criticality to 100 percent mission need date. No filters were applied in this scenario. The capability areas were grouped into three tiers based on the multiple weighting scenarios, outlined below:

- **Tier 1:** Capability area consistently scores highly across all weighting scenarios
- **Tier 2:** Capability area scores high in some scenarios but low in others and is highly dependent on weighting scenario
- **Tier 3:** Capability area scores low across all weighting scenarios

The results of this analysis are presented in Figure 7. The results show the capability areas that are likely to be highly critical to near term missions in Tier 1, and the capability areas that are either critical to later missions or that serve as less critical advancements for near term missions are in Tier 2. Tier 3 are capability areas that do not show up in the top half of the unfiltered results, but could be prioritized based on the filters that are applied.

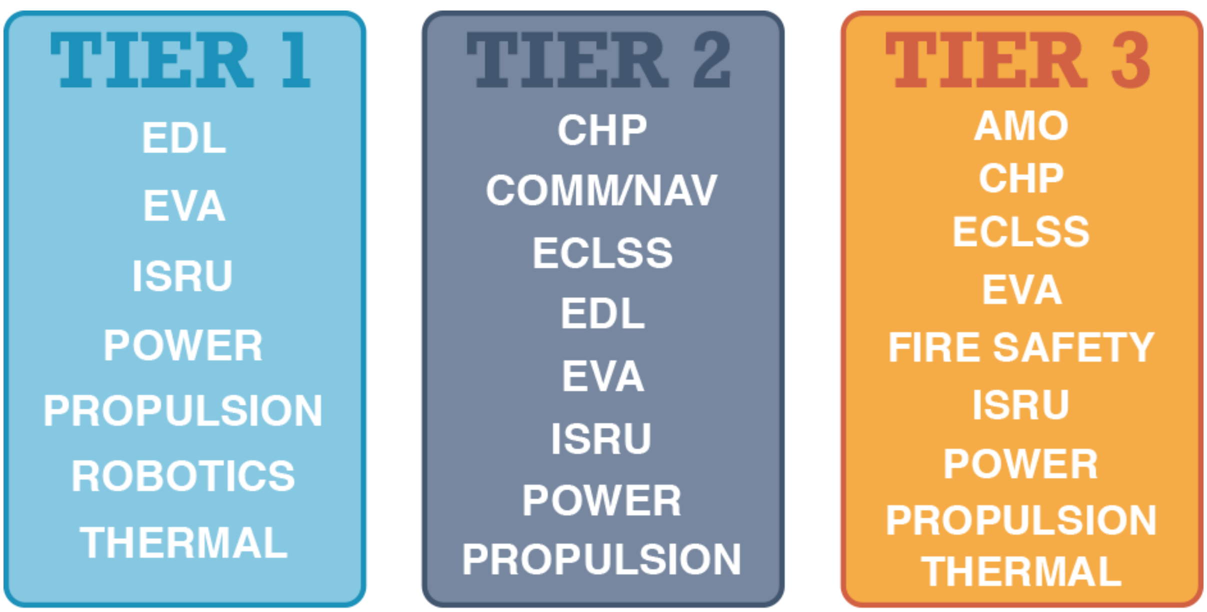


Figure 7. Multiple Weighting Scenario Results

This process has some limitations and caveats that must also be discussed. The data collection is continually evolving as the understanding of the gaps and capability areas evolve. Also, the mission definition in the EMC is constantly changing with trades and new ideas come to the table, which affects the FOM values. This is where the importance of the feedback loops presented in Figure 6 keep this process relevant. The FOM set is also limited in this analysis. Ideally, FOM sets consist of 5-10 independent FOMs. Using the two FOMs and filters captures the impact of the capability investments on missions within the capability driven framework, but other metrics such as cost, schedule, and political viability must be taken into consideration by the decision maker before selecting programs to fund.

VII. Key Findings

A. Summary of Near-Term Capability Investments

With the understanding that NASA is developing an evolvable campaign to define the next investments to achieve its goals, the data and processes described in this paper have been used to inform the near-term, mission critical investments for NASA. Figure 8 graphically represents how the entire set of SMT gaps ("All Gaps") is reduced to the subset of interest ("Near-Term, Mission Critical Gaps"). The near-term, mission critical gaps are defined using the data provided by the SMT and EMC SMEs for mission criticality, mission need date, and testing and development needs for each gap. First, the "SMT Mission Critical Gaps" are identified as only those that the SMTs scored a "5" for the mission criticality FOM. Second, an even weighting on mission criticality and mission need date FOMs is used in conjunction with filters to emphasize investments in the next five years and utilization of ISS following the ranking process described in Section VI. The overlap between the capability areas that are prioritized in this process and the SMT mission critical gaps produces the data set that comprises the near-term, mission critical gaps.

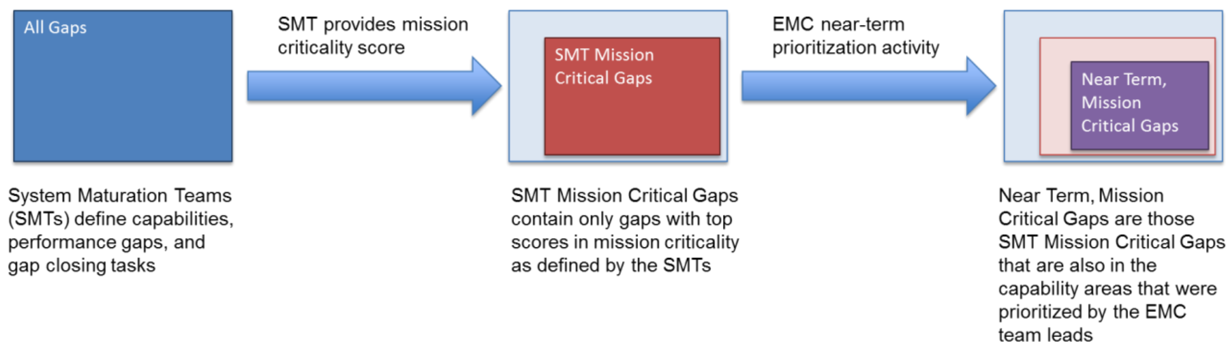
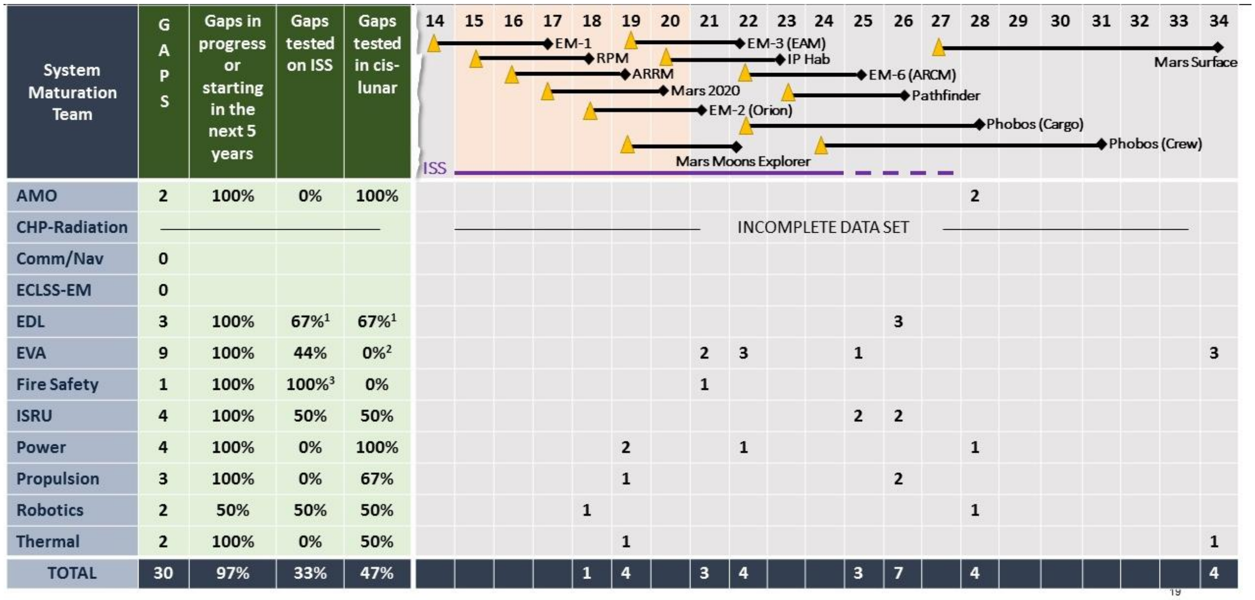


Figure 8. Process used to Identify Near-term, Mission Critical Gaps

Of the initial set of 134 gaps identified by the SMTs, a total of 30 near-term, mission critical gaps were generated through this process. These gaps are summarized in Figure 9, organized in alphabetical order by SMT and the mission need date. The total number of gaps in this final data set for each SMT are identified in the first four data columns (in green) along with the percentage of those that need to start closure in the next five years (or have already started), need to be tested on ISS, and need to be tested in cislunar space. Note that these may not add up to 100 percent because some gaps are tested in both locations, or can be tested on the ground. The timeline to the right of that data shows the number of the gaps needed for each mission defined by its notional launch date above. The row for CHP-Radiation is incomplete because the data set for that SMT was insufficient to perform the data analysis as described. Of the 30 near-term, mission critical gaps, 29 are in progress or must start in the next five years, 10 must be tested on ISS, and 14 must be tested in cislunar space.



System Maturation Team	GAPS	Gaps in progress or starting in the next 5 years	Gaps tested on ISS	Gaps tested in cis-lunar	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
AMO	2	100%	0%	100%															2						
CHP-Radiation												INCOMPLETE DATA SET													
Comm/Nav	0																								
ECLSS-EM	0																								
EDL	3	100%	67%[1]	67%[1]													3								
EVA	9	100%	44%	0%[2]								2	3			1									3
Fire Safety	1	100%	100%[3]	0%								1													
ISRU	4	100%	50%	50%												2	2								
Power	4	100%	0%	100%						2			1						1						
Propulsion	3	100%	0%	67%						1							2								
Robotics	2	50%	50%	50%					1										1						
Thermal	2	100%	0%	50%						1															1
TOTAL	30	97%	33%	47%					1	4		3	4			3	7		4						4

[1]Tested with return velocity greater than LEO [2]33% need to be tested in Cis-lunar if testing does not occur on ISS [3]100% need to be tested on ISS resupply vehicle

Figure 9. Overview of near-term mission critical gaps

Table 4 presents a summary of the mission need for each of the 30 near-term, mission critical gaps. These results show that the investments in capabilities that close gaps for early missions reduce the number of mission critical gaps that must be developed for the Mars surface and Phobos missions. The Pathfinder, ARRM, and Resource Prospector missions, which are intended to advance capabilities in transportation, EDL, and ISRU, close gaps in those areas that are applicable to the Mars missions. Orion, ICH, and ARCM advance capabilities necessary to support humans living and working in space. After these initial investments are made, fewer gaps need to be closed to specifically support the Phobos and Mars surface missions than if all of those gaps needed to be addressed at once, which is the foundation of the capability driven framework.

Table 4. Summary of Mission Needs for the Near-term Mission Critical Gaps

Mission	Number of Gaps Closed	Percent of Total Gaps
Pathfinder	7	23.3
ARRM	4	13.3
EM-3 (EAM)	4	13.3
Phobos (Cargo)	4	13.3
Mars Surface	4	13.3
EM-2 (Orion)	3	10.0
EM-6 (ARCM)	3	10.0
Resource Prospector	1	3.3

VIII. Summary

The capability driven framework has been developed as NASA's approach to meeting the nation's goals and objectives for human spaceflight exploration in a dynamic policy and budget environment. The framework institutes a way to develop capabilities for near term missions and then build on the performance of those capabilities to enable future missions. This approach also provides a cost effective way to develop needed capabilities and make additional small investments to improve the performance and enable future missions that go to greater and greater distances in the solar system. This paper chronicles how NASA is utilizing SMTs and EMC architecture SMEs to perform analyses that utilize the CDF. The analysis provides information regarding capability investments. Identification of a human exploration mission manifest and the support capabilities needed to enable the missions are also presented in this paper. The SMTs are utilizing the capability driven framework by identifying capability development opportunities based on near-term mission availability. Then closing performance gaps for Mars surface missions by building on the maturation of systems during near-term missions within a variety of space environments. This approach provides guidance to systems developers and provides efficient investments for maturing these systems and shows the application of the CDF.

Acknowledgement
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Acronyms

AESD	Advanced Exploration Systems Division	ISRU	In-Situ Resource Utilization
AMA	Analytical Mechanics Associates	ISS	International Space Station
AMO	Autonomous Mission Operations	KSC	Kennedy Space Center
ARCM	Asteroid Redirect Crew Mission	LDRO	Lunar Distant Retrograde Orbit
ARRM	Asteroid Redirect Robotic Mission	LEA	Launch, Entry and Abort
CDF	Capability Driven Framework	LEO	Low Earth Orbit
CHP	Crew Health and Performance	NASA	National Aeronautics and Space Administration
DRM	Design Reference Mission	PLSS	Portable Life Support System
ECLSS	Environmental Control and Life Support System	POC	Point of Contact
EDL	Entry Descent and Landing	SACG	System Advancement Coordination Group
EM	Exploration Mission	SEP	Solar Electric Propulsion
EMC	Evolvable Mas Campaign	SKG	Strategic Knowledge Gap
EVA	Extra Vehicular Activity		
FOM	Figure of Merit	SLS	Space Launch System
HEFT	Human Exploration Framework Team	SMD	Science Mission Directorate
HEO	Human Exploration and Operations	SMT	System Maturation Team
HEOMD	Human Exploration and Operations Mission Directorate	STMD	Space Technology Mission Directorate
HRP	Human Research Program	TBD	To Be Determined
ICH	Initial Cislunar Habitat	TIF	Technical Interchange Forum

References

[i] The White House, Office of the Press Secretary, “Space Exploration in the 21st Century,” 2010. URL http://www.nasa.gov/news/ media/trans/ obama_ksc_trans.html
ii The White House, Office of the President, “National Space Policy of the United States of America,” 2010. URL http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf.
iii National Aeronautics & Space Administration, Office of the Administrator, “NASA Strategic Plan” 2014, URL http://science.nasa.gov/media/medialibrary/2014/04/18/FY2014_NASA_StrategicPlan_508c.pdf
[iv] Bobskill, M.R., Lupisella, M.L., Mueller, R.P., Sibille, L., Vangen, S., and Williams-Byrd, J., “Preparing for Mars: Evolvable Mars Campaign ‘Proving Ground’ Approach”, presented at the IEEE Aerospace Conference, Big Sky, Montana, March 7 – 14, 2015.