SYSTEM MATURATION TEAM ASSESSMENT of ISRU for NASA's EVOLVABLE MARS CAMPAIGN.

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NASA Capability Driven Approach to Human Exploration of Space: On April 15, 2010, the US President gave a speech at NASA's Kennedy Space Center stating that NASA's goal was no longer just to reach a destination, but to develop "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"[1]. Later that year, NASA established the Human Exploration Framework Team (HEFT) 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. HEFT determined that the most robust path for human exploration of space was a capability-driven framework (CDF) where evolving capabilities would enable increasingly complex human exploration missions over time in phases. The CDF path begins with initial exploration missions to establish the first steps in human exploration beyond low Earth orbit (LEO), including the use of the International Space Station (ISS) and validation of transportation systems like the Space Launch System (SLS) and Orion crew vehicle. These initial steps are than followed by missions to extend human exploration beyond low Earth orbit (LEO), to such destinations as high Earth orbit (HEO) and cis-lunar space. Once these capabilities have been demonstrated and mastered at these near-Earth destinations, missions further into the solar system, and eventually to Mars and its moons are performed. All of the steps in this path are "capability-driven" in that each step focuses on incrementally building, testing, and validating critical capabilities required to eventually field long-duration crewed missions to the Mars system and surface.

The new approach taken by NASA in human space exploration reflects a change in philosophy from focusing on what is needed to reach a single destination, to what is needed to reach multiple destinations over time. Not only that, the new approach also needs to consider flexibility in the timing and sequence of when destinations are reached due to changes in budget, political priorities, scientific discoveries, evolving partnerships, and lessons learned from earlier exploration steps. This new "Pioneering Space" strategy strikes a balance between progress toward achieving the overarching horizon goal of human missions to the Mars surface with near-term benefits to guide investment and timing in development and demonstration of mission critical capabilities.

As part of the Pioneering Space strategy, NASA established the Evolvable Mars Campaign (EMC) as outlined in NASA's Journey to Mars [2]. The EMC is an on-going study to identify potential options and key decisions points to enable sustainable crewed Mars missions in the mid-2030s timeframe. The EMC involves three primary phases that consist of missions with increasing duration, complexity, and capability. The three phases, are Earth Reliant, Proving Ground, and Earth Independent. It is expected that demonstration, testing, and validation of Mars-required capabilities would be accomplished primarily in the second phase, which involves crewed missions consisting of 6 to 12 months in cis-lunar space and beyond as well as robotic precursor missions to surface destinations. As part of the EMC, NASA has identified enabling technologies for all destinations and phases associated with Transportation, Staying Healthy, and Working in Space. The EMC further divides human Mars surface activities into three phases: Emplacement, Consolidation, and Utilization, with growing capabilities and independence with each phase.

NASA System Maturation Teams: In June of 2013, NASA established System Maturation Teams (SMT) to bring together subject matter experts from across the agency involved in maturing systems and advancing technology readiness for human exploration. The purpose of the teams were to provide guidance and planning on how to develop the critical capabilities identified for human exploration in this new sustainable capability-driven architecture approach, and to provide recommendations on investment decisions that could be traceable to human exploration needs. NASA established 12 SMTs to perform the following, of which *In Situ* Resource Utilization (ISRU) was one:

- Define the scope and functions of the capability
- Define performance measurements, metrics, and needs
- Define the state of the art, and identify performance and capability gaps
- Define ISRU capabilities needed in the EMC and progression from Earth-reliant to Earth Independent
- Develop maturation plans and roadmaps for flexible pathways to Mars
- Define interfaces between the various capabilities
- Prioritize ISRU capabilities in support of the EMC
- Define Proving Ground satisfaction criteria
- Ensure that capabilities mature and integrate to enable future pioneering missions

The extended abstract format does not allow for complete documentation of all the work performed by the ISRU SMT to complete the products associated with all the tasks above. Figure 1 below depicts the top-level ISRU capabilities identified to support a notional series of missions considered for the EMC. Each ISRU capability needed for eventual human Mars surface exploration is tied to earlier demonstrations missions with development start dates identified. For each of these capabilities, development and gap closing tasks were identified along with associated costs and schedules.

Findings and Recommendations: Incorporation of ISRU capabilities into human missions will enable sustainable, longer-duration exploration and pioneering of space. ISRU capability and system testing on Earth in conjunction with other exploration systems that interact or benefit from ISRU products could significantly reduce the risk and increase the benefits of future missions with ISRU. It is important that Proving Ground missions are aimed at understanding and demonstrating extraction of resources in space (Moon, Mars, asteroids, Phobos) leading to the goal of Earth independence. While ISRU production of oxygen for human Mars ascent has been baselined, Mars soil processing for water extraction will significantly enhance and enable Earth Independence. Also, lunar oxygen production (75 to 80% of chemical propulsion mass) and lunar volatile/ice extraction may be architecture driving capabilities for long-term cis-lunar and Mars exploration. The stabilization and elimination of crew trash/waste in space and on the Mars surface is a volume, logistic, and planetary protection issue that could be turned into a benefit through processing into gases and propellant. Lastly, with the advent of additive manufacturing and significant logistics mass and delivery delays associated with human Mars missions, in space manufacturing with eventual feedstock from *in situ* resources is required for Earth Independence. In the next 5 years, work should focus on gaps in capabilities associated with resource prospecting (Moon, Mars, NEA), Mars oxygen ptoduction from the atmosphere, Mars oxygen/fuel production, lunar/Mars soil excavation and processing for water, and trash processing into propellants. Early testing on the ISS for trash processing, NEA material prospecting and processing, and space manufacturing under long durations of micro-g are important for asteroid and Phobos/Mars missions. To minimize cost and risk, closer development and integration of ISRU with ECLSS (including trash management), power, and propulsion is highly recommended.

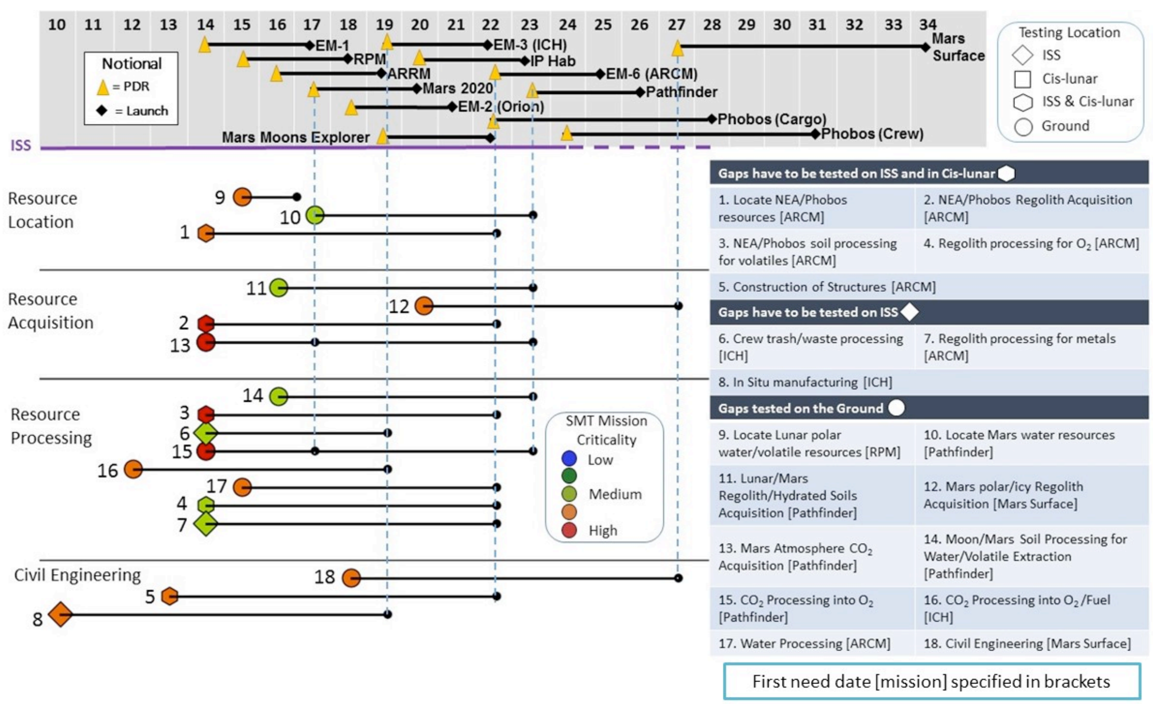

Figure 1. ISRU Capabilities and Development Durations for *Notional* Missions in the EMC

References:

[1] Linne, D. L., Sanders, G.B., and Taminger, K. M. (2015) AIAA 2015-1650.

[2] NP-2015-08-2018-HQ, "NASA's Journey to Mars – Pioneering Next Steps in Space Exploration", NASA, Oct. 2015.