Acta Astronautica 111 (2015) 29–36

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

The Asteroid Redirect Mission and sustainable human exploration ☆

Michele Gates [a,*], Steve Stich [b], Mark McDonald [b], Brian Muirhead [c], Dan Mazanek [d], Paul Abell [b], Pedro Lopez [b]

[a] NASA Headquarters, USA
[b] NASA Johnson Space Center, USA
[c] NASA Jet Propulsion Laboratory, USA
[d] NASA Langley Research Center, USA

ARTICLE INFO

Article history:
Received 13 October 2014
Received in revised form
29 January 2015
Accepted 30 January 2015
Available online 12 February 2015

Keywords:
Asteroid Redirect Mission
Human Space Exploration
Human exploration

ABSTRACT

We present the importance of the Asteroid Redirect Mission (ARM) in the context of the Global Exploration Roadmap and NASA's strategy for sustainable human exploration. We also provide status toward baseline of the ARM, including evolution of concept development based on internal NASA analysis and risk reduction, as well as external inputs received. This includes development of mission concept options, key trade studies, and analysis of drivers for both the robotic and crewed mission segments.

Published by Elsevier Ltd. on behalf of IAA.

1. Introduction

The Asteroid Redirect Mission will utilize critical exploration technologies and capabilities under development within NASA that enable many future human exploration missions. This work provides the current internal reference concepts for the robotic and crewed missions, including vehicle and system options and trades. Applicability to future deep space human mission is also discussed. The crewed mission in the mid-2020's will include the Space Launch System (SLS) heavy-lift crew launch vehicle; Orion multi-purpose crew vehicle; advanced technologies and systems for rendezvous and extra vehicular activities (EVA); the International Docking System; and crewed/robotic vehicle integrated stack operations [1]. The preceding robotic mission will demonstrate high power, long life solar electric propulsion (SEP) for future deep space exploration cargo delivery and interaction with low gravity, non-cooperative targets [1].

2. Overall mission description

The ARM robotic mission will 'capture' and redirect a cohesive asteroidal mass to a stable, crew-accessible lunar distant retrograde orbit (DRO) [2]. The asteroid mass is primarily dependent upon the capture system's capabilities and orbital mechanics drivers, such as the launch date and velocity change required to rendezvous with the Near Earth Asteroid (NEA) and return the captured material to Earth. One approach, capture option A, for this robotic mission is to rendezvous with a small 4–10 m mean diameter NEA with a mass up to ~1000 metric tons. The target asteroid will be captured and redirected from its native orbit to a lunar DRO. Capture option B is to rendezvous with a larger NEA (100+ meter diameter) and collect a boulder, typically 2–4 m in

☆ This paper was presented during the 65th IAC in Toronto.

* Corresponding author.
E-mail addresses: michele.m.gates@nasa.gov (M. Gates), j.s.stich@nasa.gov (S. Stich), mark.a.mcdonald@nasa.gov (M. McDonald), brian.k.muirhead@nasa.gov (B. Muirhead), daniel.d.mazanek@nasa.gov (D. Mazanek), paul.a.abell@nasa.gov (P. Abell), pedro.lopez-1@nasa.gov (P. Lopez).

http://dx.doi.org/10.1016/j.actaastro.2015.01.025
0094-5765/ Published by Elsevier Ltd. on behalf of IAA.

size, and return the boulder to the same DRO orbit. Both options can demonstrate basic techniques for slow push planetary defense operations.

Once the asteroidal mass is returned to the proper orbit in cis-lunar space, the ARM crewed mission will be launched. The Orion spacecraft serves as the crewed transportation vehicle, habitat, and airlock for the reference mission concept. Potential partnerships may provide for additional capability. In the reference concept, Orion will be launched into cis-lunar space on the SLS, allowing it to rendezvous and dock with the robotic spacecraft to demonstrate early human exploration capabilities including longer duration operations in deep space, rendezvous and proximity operations, life support, and EVA capabilities. Two EVAs, each 4 h in duration, are currently envisioned to explore, select, collect, and secure samples via a variety of sample collection options being examined.

3. Robotic mission concepts and trades

NASA's ARM robotic mission (ARRM) concept includes a conceptual design used for mission pre-formulation and analysis, as well as a number of study contracts to examine additive and alternative concepts [3].

The conceptual design for the spacecraft, Asteroid Redirect Vehicle (ARV) in this work, features a modular design with simple interfaces for ease of design, development, and testing by different organizations. There are three modules notionally shown in Fig. 1: a solar electric module (SEPM), a mission module (MM), and a capture module (CM).

In this conceptual configuration, power and propulsion are provided by the SEPM and the MM provides all of the other spacecraft bus functions. The SEPM and MM are very similar for both mission options. The CM implementation is dependent upon the mission capture option selected, and may include unique hardware and software required for capturing the NEA or boulder. The CM includes the capture system and may include the sensor suite. NASA is investigating the implementation of a common sensor suite for the robotic mission and crewed mission. The sensors will facilitate automated rendezvous and docking/capture (AR&D) for both the robotic and crewed segments. The goal is to eliminate the cost of multiple sensor developments and qualification programs. The proposed sensor suite specification consists of one or more visible wavelength cameras, a three-dimensional Lidar, and a long-wavelength infrared camera for robustness and situational awareness [2].

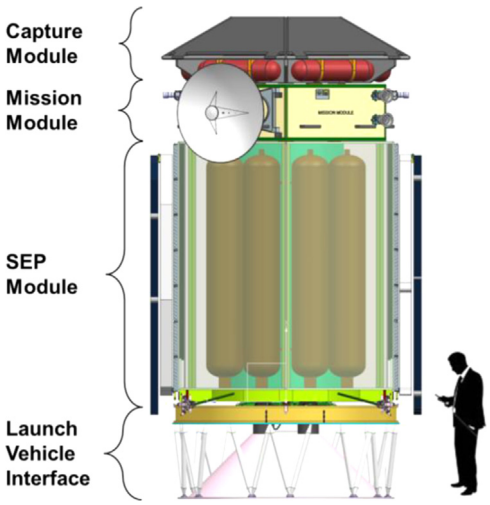

Fig. 1. Asteroid Redirect Vehicle (ARV) modules.

The SEPM provides 50 kW power at the solar arrays for the beginning of the mission and 40 kW into the solar electric propulsion system. This system features significant advances in solar array, thruster, and power processer technology sponsored by NASA's Space Technology Mission Directorate (STMD) to enable a total impulse capability greater than 30 times current deep space and commercial capabilities. The MM is comprised of the avionics, sensors and software required to control the spacecraft during all phases of mission operations.

A number of trade studies have been conducted to arrive at the current conceptual design. Such analyses included studies of the solar electric propulsion elements such as the solar array, thrusters, and power processors. This has led to the working reference of 50 kW solar arrays, and four 12.5 kW magnetically shielded Hall thrusters (three active and one cold spare). A trade study is underway for the primary voltage. We are examining both 300 V and 150 V from the solar array and evaluating the extensibility benefits to future higher power missions vs. development risk and use for other applications.

Another important trade study has been the SEP module structure and tankage. The reference module can carry 10 t of Xe and is scalable up to 16 t to support extensibility to future deep space missions. The thrust level of three Hall thrusters normally operating is 1.5 N at an Isp of 3000 s. Primary considerations have been the type, size, shape, and number of tanks. Examination of a wide range of options yielded a configuration that minimizes tank development cost and risk by using a currently manufactured design of seamless composite overwrapped tank in the approximate size of 0.23 m (30 in.) by 3 m (10 ft) long. The SEPM core structure features a 3 m composite central load carrying cylinder that would support 4–8 tanks depending on the desired load. For the 10 t load five tanks would be used. Nominal dry mass of the spacecraft is about 4500 kg.

3.1. Mission capture options

Capture option A focuses on redirecting an asteroid of up to 10 m mean diameter and 1000 t mass to a stable lunar orbit. NEAs accessible for the mission are, in general, located in very Earth-like orbits in which the velocity change (ΔV) required to redirect it to the desired lunar DRO is less than $\sim$2 km/s. In capture option B, to reach currently known asteroid targets during current potential launch dates, the mission concept is focused on acquiring and returning a 2–4 m mean diameter boulder with the capture system sized to capture a boulder with a mass up to 70 metric tons. Figs. 2 and 3 provide notional depictions of option A and option B, respectively.

For both options, high-power and high specific impulse solar electric propulsion is the key enabling technology

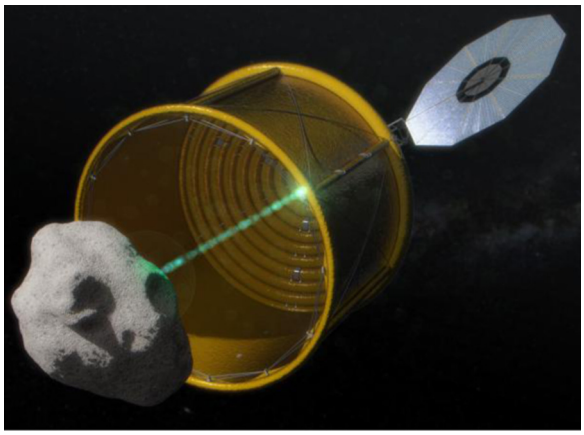

Fig. 2. Robotic mission option A—small asteroid capture option (Credit: NASA/JPL).

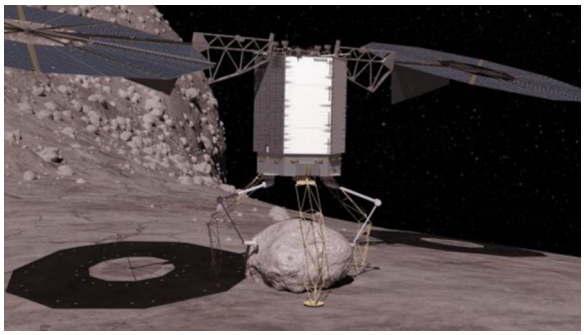

Fig. 3. Robotic mission option B—robotic boulder capture option (Credit: NASA/AMA, Inc.).

needed for providing the required ΔV with a reasonable propellant expenditure.

For capture option A, the capture system is designed to encapsulate the entire small NEA and is capable of handling a wide variety of possible NEA properties ranging from a weak rubble pile to monolithic rock. For this option, the capture mechanism is a large deployable structure with a high-strength bag that can capture a small NEA with a mass of up to ~1000 t and a rotation period of greater than 2 min. During the capture phase for option A, the ARV matches the spin state of the object, maneuvers so that the NEA is inside the open bag, and then uses cinch lines to pull the bag closed and hold the spacecraft against the asteroid.

For capture option B, the CM performs the following key functions: 1) asteroid and boulder characterization; 2) onboard asteroid- and boulder-relative navigation; 3) asteroid surface interaction; (4) boulder capture; 5) boulder restraint during the return flight; and 6) enhanced support of crew extra-vehicular activity (EVA). Conceptual refinement of option B is focused on a hybrid option that includes two 7-degree of freedom arms, each with an end-effector tool, and a contact and restraint subsystem (CRS). The microspine end effector gripper uses hundreds of fishhook-like spines to opportunistically grab the surface features of the boulder during capture. The CRS attenuates the contact forces during the ARV's descent to the NEA's surface, stabilizes it while on the surface, and provides a mechanical push-off during ascent from the surface. This approach avoids directly pluming the surface of the NEA with the ARV's reaction control subsystem to minimize contamination of the spacecraft's solar arrays and other sensitive components. The CRS design consists of a set of three arms with three or four degrees of freedom. Each CRS arm has a contact pad at its tip. The contact pads allow the collection of surface regolith that provide geological/geographical context sample in addition to the captured boulder. EVA support may include robotic preparation of the work site prior to crew arrival and between EVAs, and possible robotic collection and caching of boulder surface and sub-surface samples for crew retrieval and return to Earth [4].

4. Crewed mission concept

The Asteroid Redirect Crewed Mission (ARCM) consists of three primary segments: launch, Earth departure and DRO transit; rendezvous with the ARV and human exploration operations; and DRO departure, deorbit preparation, and crew return [5]. The current reference ARCM concept utilizes the SLS booster in the Block 1 configuration (70 metric ton lift capability to low Earth orbit) for initial ascent to Earth parking orbit. The assumed SLS configuration for the reference ARCM concept includes the interim Cryogenic Propulsion Stage (iCPS) and the Orion vehicle with a crew of two [6]. This reduced crew size will yield mass and volume savings to accommodate additional hardware to accomplish the crewed mission objectives. Initial analysis of a representative launch epoch has shown that approximately two launch opportunities would exist in a given month where the trajectory, communications coverage, and eclipse constraints are acceptable for conducting this mission. The current reference conceptual crewed mission will last approximately 26 days, as shown in Table 1. A four crew concept option is also being studied, which could utilize an early deep space habitat, and other system component prototypes.

4.1. Launch, Earth departure and DRO transit

Upon launch, the crew will be the first to travel to cis-lunar space in over 50 years. In fact, this crew will travel further from the Earth than in history. Before Orion departs Earth parking orbit, initial on-orbit checkout operations will occur. This will include, but is not limited to, communications configuration/ checkout and solar array deployment, and will occur in the first flight orbit of the mission.

The necessary ΔV for conducting the trans-lunar injection (TLI) will be obtained through the SLS-provided iCPS and Orion. Transit includes a Lunar Gravity Assist (LGA) maneuver prior to entering the lunar DRO. The transit time is estimated to be 9 days with crew activities consisting of cabin and extravehicular activity (EVA) preparations, cabin depressurization to 10.2 psi, rendezvous and docking preparations, EVA task ‘dry runs’, potential deep-space science activities and media and outreach events. EVA preparations include transforming the vehicle and their Modified Advanced Crew Escape Suits (MACES) from the launch configuration to one that can support EVA.

The crew will arrive at the DRO in which the robotic SEP ARV and redirected asteroid are located. In the reference

Table 1
Example ARCM operational timeline.

Flight Day	Event
1	Launch, ascent, trans-lunar injection
2–5	Outbound trans-lunar cruise. depressurize to 10.2 psi, suit checkout/EVA dry run, rendezvous/docking preparations
5	Lunar Gravity Assist and lunar close approach
5–7	Lunar to DRO cruise
8	Rendezvous and docking
9	EVA 1
10	Suit refurbishment, EVA 2 prep
11	EVA 2
12	Contingency margin, housekeeping, departure prep
13	Undock and depart
13–19	DRO to lunar cruise
19	Lunar Gravity Assist maneuver
20–26	Inbound trans-lunar cruise, cabin stow, repressurize to 14.7 psi
26	Entry, crew recovery

concept, the current DRO is ~71,000 km above the surface of the Moon along the Earth–Moon line and 90° off the Earth–Moon line, it varies from ~70,000 to ~80,000 km.

4.2. Rendezvous with ARV and crewed operations

By the eighth mission day, Orion will reach the DRO insertion point approximately 10 km away from the ARV. The ARV will hold its pre-docking attitude non-propulsively throughout Orion's final approach. Prior to Orion contact, the ARV will be ground-commanded to free drift mode and the Orion will transition to free drift at first contact. Orion will then initiate the final docking operations utilizing a system compliant with the International Docking System Standard. Once mated, the ARV will maintain the docked attitude with augmentation from Orion as needed.

Orion and the ARV will remain docked in the lunar DRO for approximately four days with undocking occurring on the 5th day. Over the course of the docked period, two 2-person, 4-h EVAs will be conducted utilizing lightweight exploration space suits. The day between EVAs will be spent reconfiguring/servicing the suits. This servicing and checkout of the suits will recharge suit consumables (including batteries and carbon dioxide removal), clean the suit interior, replace biomedical sensors, and allow checkout of Portable Life Support System (PLSS) components in preparation for the second EVA. After suit donning, in-suit pre-breathe, and a cabin depressurization to vacuum, the crew will commence EVA by opening the Orion hatch, deploying a boom from the Orion hatchway across to the ARV, and translating across the ARV to reach the capture system where additional EVA tools and translation aids were stowed/launched on the ARV.

These EVAs will constitute the first-ever contextual observation and sample collection of asteroid material by humans operating in space. Throughout the EVAs, the crew will interact with Johnson Space Center's Mission Control Center (MCC) over a ~3 s round-trip communications delay.

Upon completion of the EVAs, asteroid samples will be labeled and contained within a sample return container for return to Earth in the Orion vehicle. The EVA crew will stow tools and translation aids on the ARV for use by future crews and then ingress Orion for cabin repressurization, suit doffing, and preparations for undocking from the ARV.

Fig. 4. Image of Orion docking with the ARV.

A day after the final EVA will be reserved for contingency schedule margin, generic Orion/ARV housekeeping, lower priority science and outreach activities, and preparation for ARV departure. EVA capability will be maintained in the event of a contingency during undocking operations. On the day of undocking, the integrated stack will be commanded into free drift until physical separation is achieved. As during rendezvous and docking operations, range and range rate information will be collected until vehicles are no longer operating in proximity. The ARV will then be configured for extended quiescent operations for a potential future visit by Orion, commercial, or an international vehicle (Fig. 4).

4.3. DRO departure, deorbit prep, and crew return

After the Orion undocks from the ARV, the crew will enter an ~11-day return from the lunar DRO including another LGA. During this journey, the crew can complete potential deep-space and lunar science activities, media

and outreach events, and cabin reconfiguration for return and re-entry, including repressurization to 14.7 psi.

The returning Orion will complete a targeted skip entry for splashdown off the coast of California with all deorbit, entry, landing, and recovery operations as determined by the Orion Program. In order to maintain the integrity of the collected asteroid samples they will remain in a sealed sample containment kit until Orion is transferred to a post-flight handling facility. The kit will then be transported to a sample curation facility for processing, study, and analysis in an inert environment.

5. Sustainable exploration strategy

The Global Exploration Roadmap provides an integrated international strategy for space exploration [7]. In this strategy, missions to the lunar vicinity, including ARM, are clearly depicted as an important step toward future collaborative human missions to Mars. Collaboration with international and commercial partnerships is a key element of maintaining an affordable path for NASA.

NASA's approach for sustainable exploration builds from important research and operations conducted on the International Space Station (ISS) today in core areas that only the long duration missions on the ISS can provide such as human health and performance; long duration, reliable closed loop life support systems; development of commercial service capabilities; and extending learning opportunities in space to include broader commercial and research markets.

NASA has articulated a strategy for sustainable human exploration as described in Fig. 5 which includes the three regimes of Earth-dependent, the 'proving ground', and Earth-independent, which includes missions to Mars that are largely independent of any rescue or resupply from Earth [8].

Current NASA studies are focused on split mission concepts to the Martian moons which utilize chemical and advanced SEP to preposition supplies. ARM includes SEP in the proving ground, as well as other technologies and capabilities required for crewed missions to Mars vicinity and Mars surface [9]. The use of common systems and flexible architecture options, which allow international and commercial partners to choose their roles, will lower the overall cost to NASA.

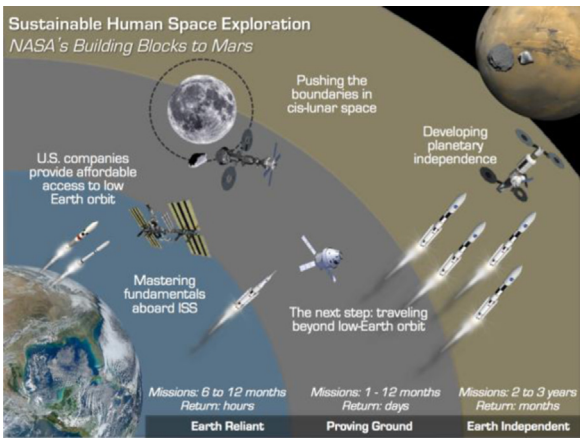

Fig. 5. Regimes in Sustainable Human Space Exploration.

In this approach, continued long duration missions to ISS and in the proving ground of the lunar vicinity allow for maintaining flexibility toward the development of partnerships, selection of systems, and determination of detailed manifests for specific missions to Mars. The early proving ground missions provide systems and technology testing and operational experience beyond the 'Earth Dependent' domain of the International Space Station (ISS). Risk reduction in the proving ground, with returns to Earth possible within a few days, complement the important long duration human system risk reduction on the ISS.

6. Arm contributions to sustainable exploration

ARM is a logical early step beyond LEO in the proving ground toward NASA's horizon goal of sending humans to Mars. As an early step, ARM can be accomplished prior to the availability of additional capabilities such as longer duration life support. In addition, ARM offers a reasonable risk posture by allowing early crew returns within consumables limits, even with contingency operations that require the use of Orion auxiliary thrusters.

There are many aspects of this crewed mission in the mid-2020's that will build capabilities and reduce risk for Mars missions [10]. This paper explores moving large objects through interplanetary space using solar electric propulsion (SEP); integrated crewed/robotic vehicle stack operations in deep-space orbits, e.g. integrated attitude control and solar alignment during multi hour EVAs; in-space systems for astronaut extra-vehicular activity; sample selection, handling, and containment; lean implementation of SEP vehicle design and development using simple interfaces, streamlined processes, and common AR&D systems; and broad scope robotic/crewed integration, including crewed system hardware deliveries to and integration and test with robotic spacecraft, and joint robotic spacecraft and crewed mission operations. A few key areas are described below.

6.1. Pre-emplacement at Mars with SEP

The use of advanced SEP on ARM to maneuver the target asteroid through a trajectory similar to interplanetary transit will be the pathfinder demonstration in the use of advanced SEP for moving large objects in such applications. NASA's examination of the split mission Mars approach utilizes advanced SEP busses directly derived from the ARM SEP bus to preposition propulsion stages and habitats into Mars Orbit. The NASA Evolvable Mars Campaign Study is evaluating several variants for combining chemical and SEP propulsion strategies and the use of single and split habitat strategies to enable Mars vicinity and future Mars surface missions [11].

SEP offers the advantage of very high efficiency propulsion. The disadvantage of SEP is that SEP engines operate at very low thrust levels. Thus, SEP provides a very cost-effective and mass-efficient approach for moving large elements through space along with the disadvantage that SEP trajectories are inherently of longer duration than higher thrust chemical trajectories. Conversely, traditional chemical propulsion stages have relatively low efficiency but much higher thrust. Thus, chemical propulsion

provides higher mass solutions which increase launch costs but result in much shorter duration trajectories.

Hybrid propulsion architectures are proposed to utilize each propulsion technology for mission purposes best suited for the technology. Crewed mission segments inherently call for mission durations to be as short as possible. Reducing mission duration limits crew exposure to deep-space radiation, reduces the quantity of crew consumables such as food, and limits the crew's risk due to systems failures. Therefore, in hybrid architectures, chemical propulsion systems are favored for mission segments requiring delivery of astronauts. Conversely, mission segments targeting the delivery of uncrewed cargo favor the use of SEP due to its higher efficiency. Hybrid architecture studies seek to explore the appropriate balance of functionality delivered by SEP versus that which is delivered with the crew. The objective is usually to limit the mass of the crew delivery segment. Lower mass on this segment is a direct driver for the required size of the chemical propulsion stages and factors directly back to overall launch costs.

There are many possible hybrid architectures being evaluated in the Evolvable Mars Campaign study. One example is discussed below to demonstrate that the ARM SEP bus directly contributes to future potential Mars missions.

6.2. Phobos base mission conceptual architecture

The notional Phobos based mission discussed herein is comprised of four SLS launches to implement the crewed mission to Phobos [12]. The first two SEP cargo launches are depicted on the left-hand side of Fig. 6. These cargo launches utilize 100–200 kW SEP vehicles to pre-deploy a Phobos habitat to the surface of the Martian moon and to pre-deploy chemical propulsion stages to Mars orbit. The next two launches deliver a chemical propulsion stage to high Earth orbit and the Orion spacecraft carrying a crew of four astronauts. In this scenario, the SEP vehicles are a second generation SEP cargo directly derived from the ARV. The proposed ARV increases the state-of-the-art power level to 40 kW; roughly a factor of three power increase compared to current systems. Current SEP systems also have relatively small Xenon fuel loads. The proposed ARV carries significantly more fuel and as a result delivers more than 30 times the total impulse compared to today's state of the art SEP systems.

The ARV is a stepping stone to higher power SEP systems. The conceptual ARV has tanks, fuel load, primary structure, and avionics compatible with a future Mars-class 100–200 kW bus. In addition, through a Broad Agency Announcement, NASA has selected four studies now under contract to examine use of commercially available spacecraft.

With this strategy, the 40 kW ARV can utilize a block upgrade approach to replace the original solar arrays with higher power arrays to achieve 100–200 kW power levels. Similarly, in the block upgrade approach additional electric thrusters can be added to utilize the higher available power to provide higher thrust.

In this Phobos mission concept, the upgraded SEP vehicle would deliver a Mars class habitat to the Mars system. This habitat also has components derived from the Asteroid Redirect Mission. The Common Automated Rendezvous and Docking Sensor suite will be utilized to approach the Phobos target landing site and could be augmented to provide hazard avoidance for landing. The capture option B robotic capture concept also provides specific technologies applicable to a Phobos mission. The operational strategies and experience, the landing, and surface contact systems would all apply to the Phobos mission.

On the second SEP launch, the SEP vehicle is used to deliver propulsion stages and preposition them in Mars orbit. The Orion spacecraft and crew rendezvous with a large chemical stage and then utilize a high-thrust

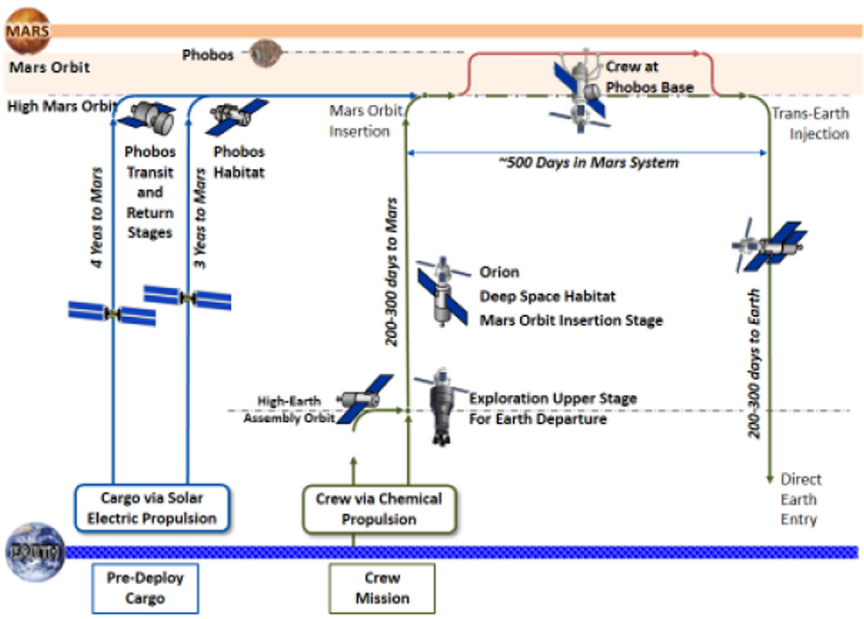

Fig. 6. Architecture characteristics of a Notional Phobos Mission.

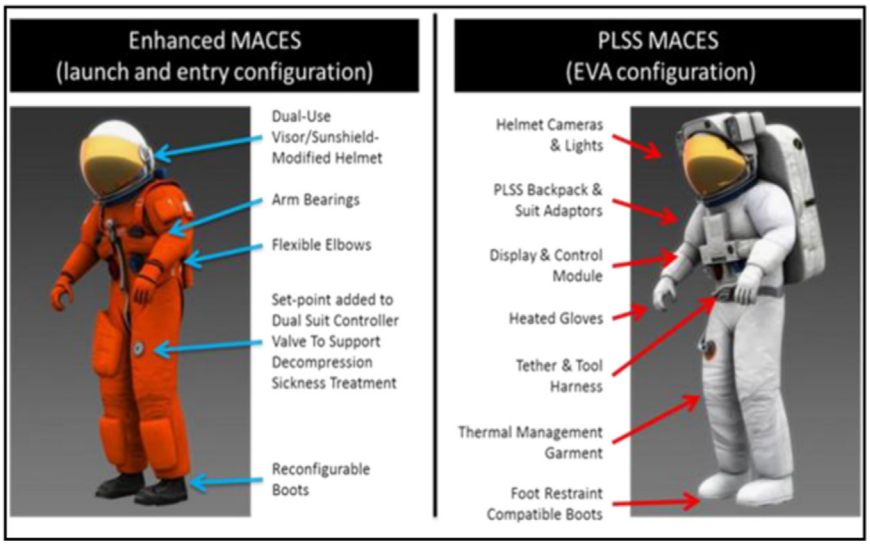

Fig. 7. MACES configurations.

trajectory to Mars Orbit using chemical propulsion. Orion and its crew then rendezvous with a pre-positioned habitat to perform the Phobos mission and subsequently rendezvous with the propulsion stages for return to Earth.

This type of hybrid architecture utilizes SEP to reduce launch costs and the mass of the integrated stack for crew transit by pre-positioning the Phobos habitat and propulsion stages.

6.3. Integrated crewed/robotic vehicle operations

The ARCM will provide a 'first ever' opportunity for integrated crewed/robotic vehicle stack operations in deep space. Human spaceflight has several examples of crewed/robotic vehicle interaction in LEO, such as the Space Shuttle Hubble Repair missions. Crew/robotic vehicle interactions in deep space present new challenges. The automated rendezvous sensor suite required to perform docking must operate without the assistance of Global Positioning Satellites for navigation and must operate more quickly than Deep Space Network tracking can accommodate. The rendezvous sensor suite can provide a common suite that can be used to support multiple future exploration missions, including the Phobos mission just discussed. Once docked, the crewed vehicle and robotic vehicle will have to operate as an integrated stack.

6.4. Advanced EVA Systems

Advanced EVA systems under development support multiple Global Exploration Roadmap scenarios. The MACES can serve as the Orion Launch and Entry Suit for all Orion flights. The MACES suit (Fig. 7) would also operate as a contingency EVA suit on umbilicals. Improvements to the MACES design currently being tested increase EVA mobility in and allow the MACES to interface with a Portable Life Support System (PLSS). The improved MACES design also supports other future missions using the Orion spacecraft.

6.5. Sample selection, handling and containment

The main purpose of the EVAs in ARCM is to collect samples of the returned asteroidal material. Currently two EVAs are envisioned to two different locations on the returned asteroidal material. Currently, approximately 1 h in each would be reserved for sample identification, collection, and containment. In the reference ARCM, the crew translates from the Orion capsule to the robotic vehicle to set up their work site and prepare for sampling operations. Once the crew has removed any obstacles presented by the capture mechanism, they will conduct preliminary characterization and photo documentation prior to assessing the best locations from which to collect samples. Ideally the crew will first obtain contingency samples of rocky materials and some loose surface regolith, as well as a sample of the capture mechanism for reference. Then, more detailed sample collection activities would focus on obtaining surface rocks and regolith materials, chips or fragments from larger rocks, and samples from depth (i.e., cores). All of these samples will be sealed in their own separate collection devices and then stowed in a larger container for return to Earth. Core tubes and other samples may be put in a separate stowage container and kept at ambient conditions (i.e., frozen temperatures, vacuum, etc.). All of these items would be secured and kept sealed until transported inside the proper curatorial facilities at NASA Johnson Space Center.

The proposed ARCM sampling and containment operations would be the first time that astronauts have collected and returned extraterrestrial samples to Earth since Apollo. In terms of the specific activities for sample collection and containment, the ARCM mission will help pave the way for future sample and collection activities for other Solar System destinations (e.g., asteroids, Mars, the moons of Mars, etc.). New procedures would be developed for identifying samples based on their textural and mineralogical characteristics through a variety of remote sensing and in situ instruments. Involvement and support of ground-based science teams would be invaluable for educating the astronauts on the best

samples to obtain for further study. Newly developed tools and instruments will minimize the contamination of samples and allow much more sensitive measurements of pristine materials to be obtained once they are inside the laboratory. As the scientific community's understanding of solar system materials has evolved, there is increased recognition that some extraterrestrial samples are best returned inside well-sealed and climate controlled containment devices [13]. This is not only to protect the crew from contamination, but also to preserve the scientific integrity of the samples. This is especially crucial for samples from organic and volatile-rich objects, which are of interest from both a scientific and human exploration perspective.

7. Conclusions

We have presented the current development status for ARM robotic and crewed mission concepts, including robotic mission modular design, SEP system trades and technical performance references, capture options and system design drivers, and crewed mission concepts and conceptual design.

We have also presented the contributions of the ARM conceptual design to sustainable human exploration, and in particular, to a Mars split-mission approach. A variety of options for these split missions employ the strategy of utilizing SEP to pre-position cargo in Mars orbit for supporting human missions to Mars and demonstrate the need for a mission such as ARM to advance SEP technology to levels that can support mission to the Mars system. The applicability of technologies, systems, and operations used for ARM include the ability to pre-position architecture elements using SEP; operate integrated crewed/robotic vehicle stacks in deep space; validate systems and operations at the surface of low-gravity bodies; advance EVA systems; and verify sample selection, handling, and containment procedures critical to future deep-space missions. The successful verification of these technologies, systems, and operations by the Asteroid Redirect Mission will provide a critical step in NASA's journey towards sustainable human exploration of the solar system.

References

[1] Asteroid Initiative Opportunities Forum, Update on Asteroid Redirect Mission, ⟨http://www.nasa.gov/ asteroidforum⟩.
[2] Muirhead, B., Asteroid Redirect Robotic Mission Overview, presentation to the Small Bodies Assessment Group, ⟨http://www.lpi.usra.edu/sbag/meetings/jul2014/presentations/1030_Wed_Muirhead_ARM_OptionA.pdf⟩, July 2014.
[3] Asteroid Redirect Mission Broad Agency Announcement, ⟨http://go.nasa.gov/1jiPXs⟩, March 2014.
[4] Belbin, S. P., Merrill, R. G., Boulder capture system design options for the asteroid robotic redirect mission alternate approach trade study, in: Proceedings of the AIAA SPACE 2014 Conference and Exposition, San Diego, CA, August 2014.
[5] Stich, S. Asteroid Redirect Robotic Mission Overview, presentation to the Small Bodies Assessment Group, ⟨http://www.lpi.usra.edu/sbag/meetings/jul2014/presentations/1030_Wed_Stitch_ARM_Crewed_Mission.pdf⟩, July 2014.
[6] NASA Fact Sheet, ⟨http://www.nasa.gov/sites/ default/files/files/SLS-Fact-Sheet_aug2014-finalv3.pdf⟩, August 2014.
[7] Global Exploration Roadmap, ⟨http://www.nasa.gov/sites/default/files/files/GER-2013_Small.pdf⟩, August 2013.
[8] Pioneering Space: NASA's Next Steps on the Path to Mars, ⟨http://www.nasa.gov/sites/default/files/files/Pioneering-space-final-052914b.pdf⟩, May 2014.
[9] Crusan, J., Presentation to the NASA Advisory Council Human Exploration and Operations Committee, ⟨http://www.nasa.gov/sites/default/files/files/20140623-Crusan-NAC-Final.pdf⟩, June 2014.
[10] McDonald, M. A., et al., Extensibility of Human Asteroid Mission to Mars and Other Destinations, in: Proceedings of the AIAA SpaceOps 2014 13th International Conference on Space Operations, May 2014.
[11] Troutman, P., The Evolvable Mars Campaign: The Moons of Mars as a Destination, ⟨http://www.lpi.usra.edu/sbag/meetings/jul2014/presentations/1115_Thu_Troutman_Mars_moons.pdf⟩, July 2014.
[12] Price, H., et al., Human Missions to Mars Orbit, Phobos, and Mars Surface Using 100-kWe-Class Solar Electric Propulsion, in: Proceedings of the AIAA Space 2014 Conference, AIAA paper 2014-1967009, August 2014.
[13] Private communication, Curation and Planning Team for Extraterrestrial Materials (CAPTEM) Task Force findings, January 2014.