NASA's Asteroid Redirect Mission Concept Development Summary

Michele Gates
NASA Headquarters
300 E Street, S.W.
Washington DC 20546
202-358-1048
Michele.M.Gates@nasa.gov

Dan Mazanek
NASA Langley Research Center
1 North Dryden Street
Hampton, VA 23681
757-864-1739
Daniel.D.Mazanek@nasa.gov

Brian Muirhead
Jet Propulsion Laboratory
4800 Oak Grove Lane
Pasadena, CA 91109
818-393-1013
Brian.K.Muirhead@jpl.nasa.gov

Steve Stich
NASA Johnson Space Center
2101 NASA Parkway
Houston, TX 77058
281-483-8038
J.S.Stich@nasa.gov

Bo Naasz
NASA Goddard Space Flight Center
8800 Greenbelt Road
Greenbelt, MD 20771
301-286-3819
Bo.J.Naasz@nasa.gov

Paul Chodas
Jet Propulsion Laboratory
4800 Oak Grove Lane
Pasadena, CA 91109
818-354-7795
Paul.W.Chodas@nasa.gov

Mark McDonald
NASA Johnson Space Center
2101 NASA Parkway
Houston, TX 77058
281-483-4376
Mark.A.Mcdonald@nasa.gov

Jim Reuter
NASA Marshall Space Flight Center
Huntsville, AL 35812
256-544-5763
Jim.L.Reuter@nasa.gov

Abstract—**This paper summarizes key findings of Asteroid Redirect Mission pre-formulation concept development efforts, including mission architecture and design drivers, flight system concepts and trades, advanced solar electric propulsion component and system options, and asteroid capture option trades and risk reduction efforts. This paper also provides a summary of concept development findings with a focus on extensibility to future mission applications and risk reduction and early testing of astronaut extra-vehicular activities.**

TABLE OF CONTENTS

1. INTRODUCTION

Building on the International Space Station, the Commercial Crew Program, the Space Launch System, and Orion, as well as a suite of complementary robotic Mars exploration and Space Technology Programs, NASA will continue to expand human presence into the solar system forging a path towards future Mars surface missions[1]. A key component of this exploration strategy is to perform early, affordable missions that test and prove key capabilities required for long-duration, deep space exploration while continuing human health and performance research on the International Space Station. The Asteroid Redirect Mission (ARM) is a compelling combination of robotic and crewed missions which substantially contributes to advancing technologies, techniques and operational capabilities required for human missions to Mars.

The ARM will identify, robotically capture, and redirect a small near-Earth asteroid (NEA) or a multi-ton boulder from the surface of a larger NEA to a stable orbit around the moon, where astronauts will explore it in the 2020's, returning with samples. ARM is one of the first steps beyond low-Earth Orbit into the "Proving Ground" of cis-lunar space, representing NASA's efforts to prove essential deep-space capabilities (technologies, systems, and operations) required to safely send humans progressively farther out into the solar system. Through ARM, NASA will utilize a number of key capabilities that will be needed for future exploration purposes, as well as providing other broader benefits. This includes advanced solar electric propulsion, capture and control of non-cooperative objects, rendezvous and docking systems, deep space trajectory and navigation methods, advanced extra-vehicular activity (EVA) technologies and techniques, and sample collection and containment. This mission will also provide demonstration of basic asteroid deflection techniques that will inform future planetary defense approaches.

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 meter mean diameter NEA with a mass up to ~1,000 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 meters in size, and return the boulder to the same DRO orbit. Figures 1 and 2 provide notional depictions of capture options A and B.

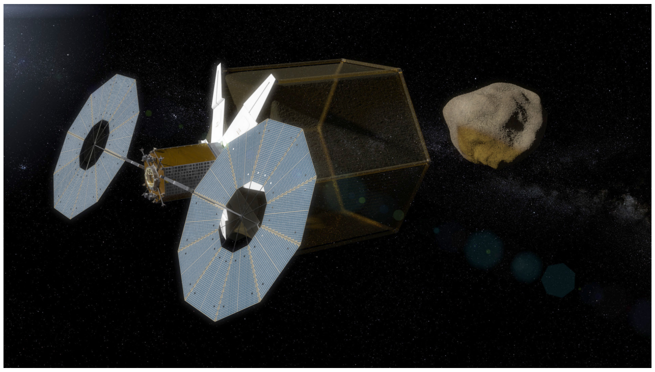

Figure 1: Robotic Mission Option A – small asteroid capture option (Credit: NASA/JPL).

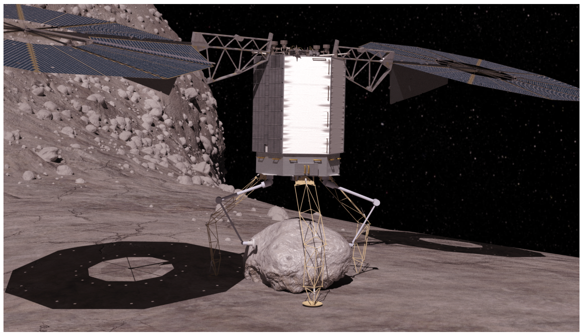

Figure 2: Robotic Mission Option B – robotic boulder capture option (Credit: NASA/AMA, Inc.).

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[3]. 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 Space Launch System (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 four hours in duration, are currently envisioned to explore, select, collect, and secure samples via a variety of sample collection options being examined. Figure 3 shows a conceptual depiction of an EVA with a notional capture system for robotic mission capture option A.

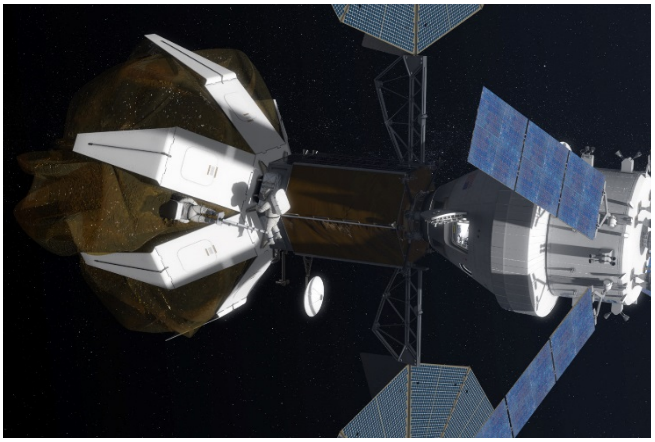

Fig. 3: Conceptual EVA for capture option A (Credit: NASA/AMA, Inc.).

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.

3. Robotic Mission Concepts and Trades

NASA's Asteroid Redirect Robotic Mission (ARRM) concept includes an internal conceptual design used for mission pre-formulation and analysis, as well as a number of study contracts to examine additive and alternative concepts. The conceptual design for the spacecraft, Asteroid Redirect Vehicle (ARV), features a modular design with simple interfaces for ease of design, development, and testing by different organizations. There are three modules: a Solar Electric Propulsion 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 command, control, and communications 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 rendezvous and approach sensor suite. NASA is investigating the implementation of a common sensor suite to facilitate automated rendezvous and docking/capture (AR&D/C) 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[4].

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. The reference 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 examining 300 V, 150 V, and 100V from the solar array, evaluating the extensibility benefits to future higher power missions as compared to development risk and use for other applications.

Another important trade study has been the SEP module structure and tankage. The reference SEP module can carry 10 tons of Xe and is scalable up to 16 tons to support extensibility to future deep space missions. 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 meter (30 in.) by 3 meter (10 ft) long. The SEPM core structure features a 3 meter composite central load carrying cylinder that would support 4-8 tanks depending on the desired load. For the 10 ton load, five tanks would be used.

The capture approach is very different for the two mission options. Capture option A focuses on capturing an entire asteroid of up to 10 meters mean diameter and 1,000 tons of mass and redirecting it to a stable lunar orbit. Candidate targets for this mission option must follow very Earth-like orbits so that the velocity change (ΔV) required to redirect it to the desired lunar DRO is less than ~ 2 km/s. Capture option B focuses on acquiring a boulder from an asteroid hundreds of meters in diameter, and returning the boulder to the desired DRO. The size and mass of the boulder that can be successfully returned depend on the orbit of the asteroid; for currently known asteroid targets and currently planned launch dates, the boulder can have a mean diameter of 2-4 meters and a mass of up to 70 metric tons. For both options, high-power and high specific impulse solar electric propulsion is the key enabling technology needed for providing the required ΔV with a reasonable propellant expenditure.

For capture option A, the capture system is designed to encapsulate an entire small asteroid and is capable of handling a wide variety of possible asteroid physical 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 envelope a small NEA with a maximum dimension of 15 meters, a mass of up to ~1,000 t and a rotation period of as short as 2 minutes. During the capture phase for option A, the ARV matches the spin state of the object, deploys the capture mechanism, translates forward to bring the asteroid inside the open bag, and then uses cinch lines pull the bag closed and hold the asteroid securely against the spacecraft.

For capture option B, the CM performs the following key functions: 1) asteroid and boulder high resolution mapping and characterization; 2) onboard asteroid- and boulder-relative navigation; 3) asteroid surface interaction; 4) boulder capture; and 5) boulder restraint during the return flight. 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)[5]. The microspine end effector gripper uses hundreds of fishhook-like spines to grab the natural surface features of the boulder during capture[6]. 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 legs with four degrees of freedom, each. 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[7].

Both ARM robotic mission options provide excellent opportunities to demonstrate basic operational techniques of "slow push/pull" deflection methods for planetary defense, that don't require direct contact with the body, such as Ion Beam Deflection (IBD), Gravity Tractor (GT) or Enhanced Gravity Tractor (EGT). These methods are relevant for smaller asteroid impact threats with warning times of many years, to include gravitational keyhole avoidance, or trim maneuvers following a rapid "impulsive" techniques such as a kinetic impactor[8]. Option A is currently focusing on demonstrating the IBD technique to produce a measurable deflection of the small asteroid target[9]. IBD uses a beam of quasi-neutral plasma from the electric propulsion system to impinge upon the asteroid's surface to create a force and/or a torque on the target. Option B is currently focusing on demonstrating EGT operations by using the combined mass of the spacecraft and captured boulder to gravitationally deflect the host asteroid, which will actually be in the potentially hazardous size range[10].

4. Asteroid Target Identification

Discovery and orbit determination of new potential NEA candidates for ARM is an on-going process provided by a world-wide network of discovery teams supported and coordinated by NASA's Near Earth Object Observation Program (NEOOP). The vast majority of these discoveries are made by ground-based optical telescopes using very large format charged couple device (CCD) imagers and highly automated image processing to detect the orbital movement of NEAs. Discovery and tracking of NEAs is required but it not sufficient for providing a valid ARM candidate. Detailed characterization of a candidate NEA is needed also required to determine whether the asteroid's physical parameters are within the design envelope for the ARM robotic mission. High-quality remote characterization using ground-based and space-based assets are needed, with ground-based radar observations, when possible on a potential candidate, being particularly helpful for determining size, shape, spin state, and the presence of boulders. The Goldstone radar facility, a key asset for ground based radar observation, is shown in Figure 4. Additional ground-based facilities, such as the NASA-funded Infrared Telescope Facility (IRTF) in Mauna Kea, Hawaii, can provide more details on the NEA's spectral type, reflectivity and expected composition (see Figure 5).

The Spitzer Space Telescope, depicted in Figure 6, has been used to remotely observe two Option A targets, 2009 BD and 2011 MD, which were not observed by radar when within range in 2009 and 2011. Spitzer tried to observe 2009 BD in October 2013, but it was too small to be detected. The non-observation allows an upper bound of approximately 7 meters to be placed on the size of that candidate target. 2011 MD was observed by Spitzer in February 2014, and it was successfully detected, constraining its size to be between 4-10 meters. A third candidate, 2013 EC20 was characterized by radar in 2013, and determined to be in the 2-4 meter size range.

Figure 4: 70-m dish (DSS-14) radar facility in Goldstone, California (Credit: NASA/JPL-Caltech).

Figure 5: Subaru, Keck, and NASA IRTF facilities on Mauna Kea's summit, shown left-to-right (Credit: NASA).

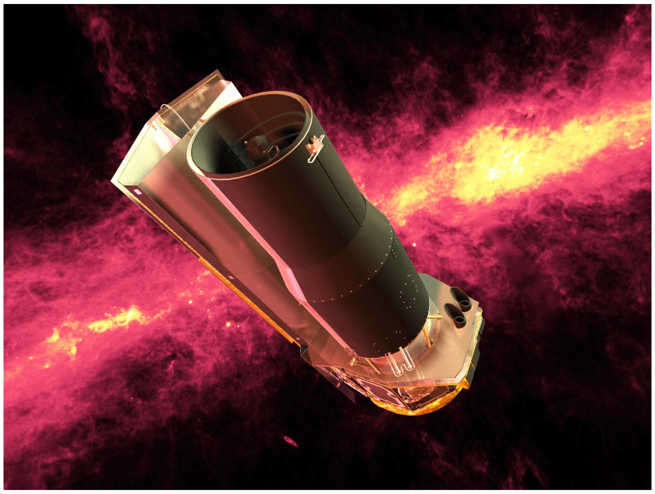

Figure 6: Artist's rendering of Spitzer Space Telescope (Credit: NASA/JPL-Caltech).

Of course, in-situ reconnaissance from a precursor mission can provide much more detailed and precise information than can remote observations. This is particularly important for Option B, where a priori evidence of boulders is required to reduce mission risk. Of the four large asteroids that have been or are planned to be visited by robotic spacecraft (Eros, Itokawa, Bennu, and 1999 JU_3), three could be potential targets for the ARRM mission. NASA's Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer (OSIRIS-REx) spacecraft will visit Bennu in 2018, and the Japan Aerospace Exploration Agency's (JAXA's) Hayabusa 2 spacecraft will rendezvous with 1999 JU3 also in 2018. Both spacecraft will provide detailed characterization of the boulder distribution on their target asteroids. Another Option B candidate, 2008 EV5, has been characterized by ground-based radar well enough to infer the existence of suitably sized boulders. Based on ground-based reconnaissance, all of these NEAs except for Itokawa are carbonaceous (C-type) asteroids and are believed to be water/volatile-rich[11].

5. Robotic Capture Risk Reduction

NASA's internal risk reduction activities for capture options A and B in 2014 are detailed herein. In addition, four contracts to examine augmentations and alternatives to the internal concepts via six month concept development studies are ongoing and scheduled to complete by early calendar year 2015.

For robotic mission capture option A, internal risk reduction includes test of a high fidelity one-fifth scale model of the concept evolved through analyses in 2013 and early 2014. The model is a 3 meter diameter x 2 meter long, inflatable structure that supports the capture bag. Design features include mechanical initial deployment of 6 arms with inflatable booms at the end of the arms that deploy and control the bag material. The testbed system is fully operational in 1 g to include deployment and capture, and enables tests of deployment/inflation, "docking" to the asteroid, and bag closure, with force measurements. This testing is scheduled to complete by end of 2014.

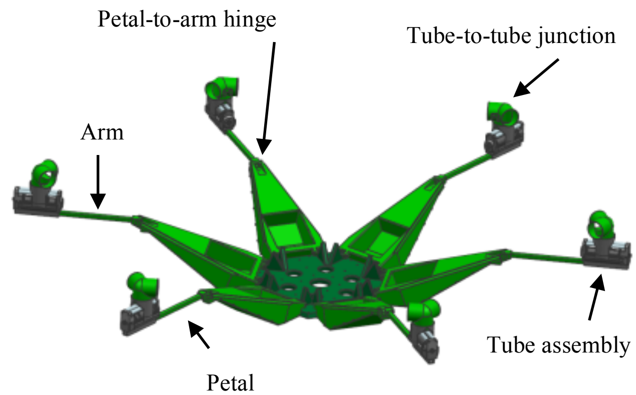

Figure 7: Robotic Mission Capture Option A Conceptual Internal Capture Mechanism

Figure 8 One-fifth scale testbed in initial deployed configuration before the inflation of the bag support tubes

Capture option A offers advantages in terms of a relatively simple deployment, proximity operations and capture that is analyzable and testable. This testbed now includes force sensing between the bag and the asteroid. Figure 7 shows a schematic representation of the one-fifth testbed showing the arms and inflatable tube assembly. Figure 8 shows the actual test hardware.

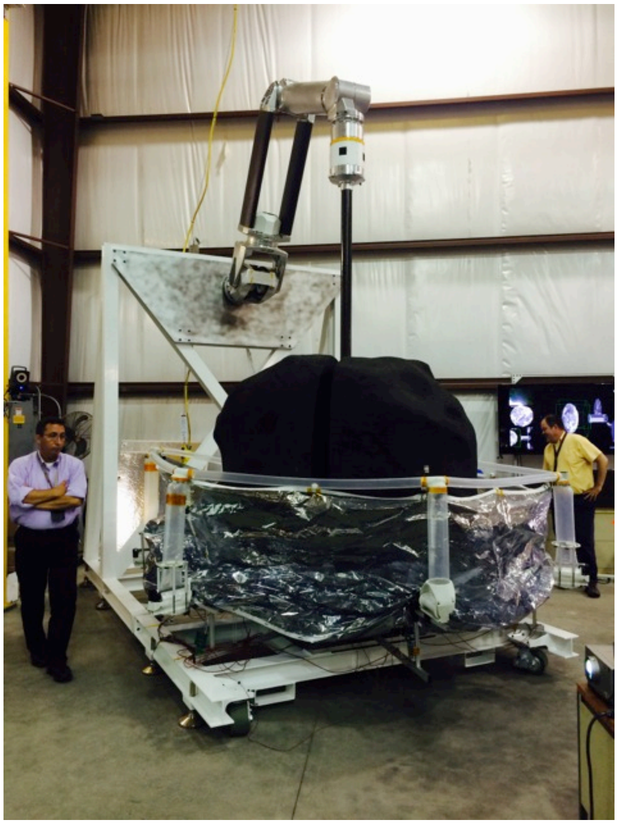

Figure 9: One-fifth scale testbed bag partially deployed with asteroid on robotic arm with force sensor measurement

Figure 9 shows the partially deployed configuration with a simulated asteroid inside. The robotic arm supporting the "asteroid" enables 6 DOF motion and force sensing. Figure 10 shows the bag closed on the asteroid. This testbed is being further upgraded with an updated petal design, a new bag design including a "trampoline" bottom that provides accommodation for the irregular shape of the asteroid and control of contact forces and damping. This new configuration is expected to be in test by mid November 2014.

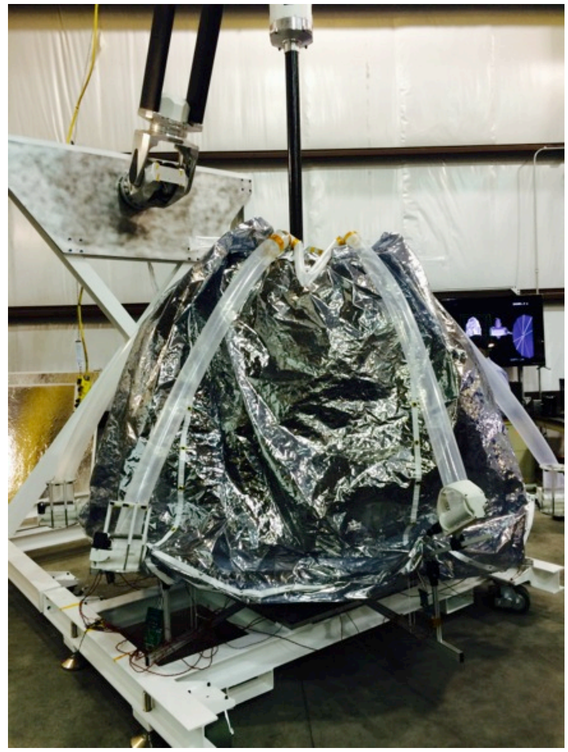

Figure 10: Closed bag with asteroid inside.

The conceptual flight design is being updated based on the testbed work. The stowed configuration provides a complete enclosure of the soft goods. Figure 11 depicts the cruise configuration of Option A before deployment of the capture bag. Figure 12 shows the deployed configuration with the current concept for the bag design using a transparent material such a reinforced Kapton.

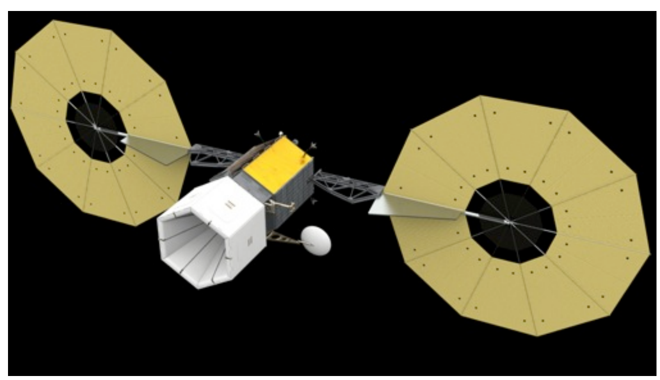

Figure 11: Cruise configuration for Option A

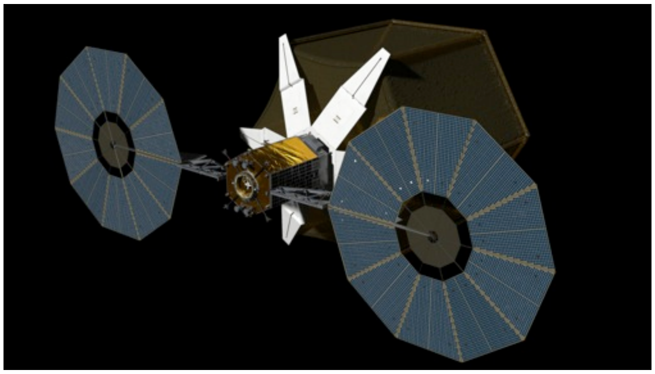

Figure 12: Deployed Option A capture system

For robotic capture mission option B, internal risk reduction includes several analysis and test areas to reduce engineering and technology development risks: system dynamics simulations; boulder capture with a microspine tool; spacecraft "landing" and ascent in a micro-gravity environment; boulder restraint; and closed-loop terrain-relative guidance, navigation, and control. These are also scheduled to complete prior to December 2014.

Figure 13 displays a conceptual boulder collection phase for option B, including descent (top) using closed-loop terrain-relative navigation, surface operations and capture (middle), and ascent (bottom). Analysis of spacecraft and system dynamics during descent, contact/soft landing, and ascent are underway in several high-fidelity simulations, including: Automated Dynamic Analysis of Mechanical Systems (ADAMS) analysis to understand the dynamics in the system and how loads are distributed during landing and ascent; and control-structure interaction analysis to demonstrate vehicle control during ascent.

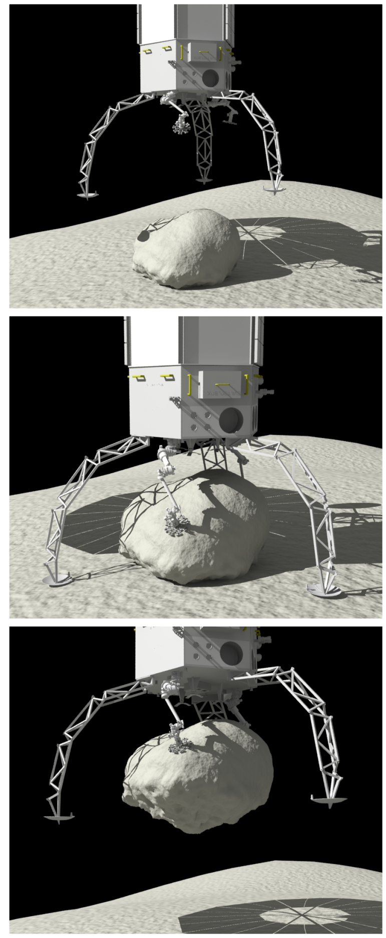

Figure 13: Notional descent, surface operations, and ascent phases for capture option B.

Robotic capture risk reduction includes testing of 7 degree of freedom (DOF) boulder capture using systems already under development for satellite servicing applications, which would be leveraged for capture option B. Tests include an early prototype end effector, as shown in Figure 14, and with a newly fabricated larger, all-metal version of the tool.

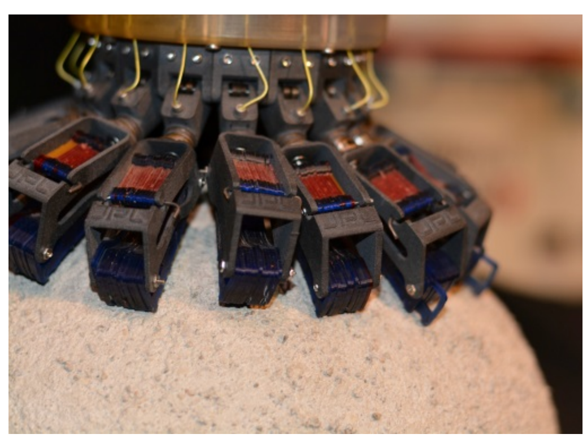

Figure 14: Capture option B risk reduction end effector

These tests use industrial robots and boulder mockups of varying compositions and shapes to better characterize the performance of the tool, and its ability to support loads associated with removal of large amounts of mass from the surface of the parent asteroid. In the option B conceptual internal design, the CRS includes three contact/restraint 'legs' as illustrated in Figures 13 and 15. To better understand the sources and level of technical risk in contact/soft landing and boulder capture, testing of full scale prototypes on a flat surface is being employed.

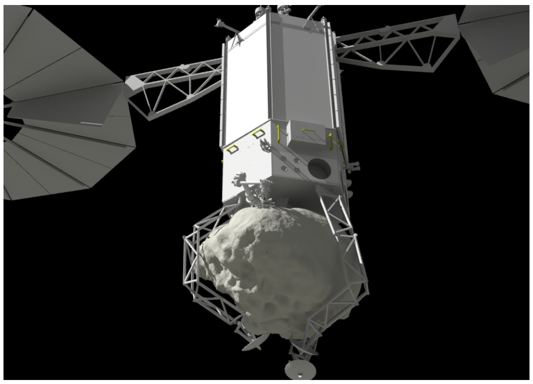

Figure 15: Conceptual Design Features of Capture Option B Contact/Restraint Legs.

To examine risk in relative navigation, testing of integrated sensors and algorithms is underway to validate the candidate approach. Imaging of a subscale mockup of a boulder with an example light detection and ranging (LIDAR) sensor has been completed and resulting imagery, as well as calibrated synthetic visible and LIDAR imagery is being processed in flight-like terrain-relative navigation (TRN) algorithms. Resulting measurement models are then passed into linear covariance analysis to demonstrate that the system can achieve the required landing accuracy over the desired sample collection site.

6. Crewed Mission Concept Results

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[3]. 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[12]. 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 26-27 days. Figure 16 provides a notional graphic of major phases of the crewed mission reference trajectory.

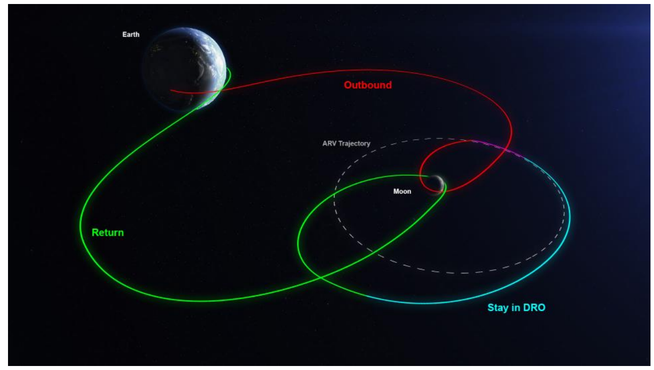

Figure 16: Reference Trajectory Graphic for the Crewed Mission.

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 any human has traveled in the history of spaceflight. In the reference concept, the current DRO is ~ 71,000 km above the surface of the Moon. The reference mission design utilizes lunar gravity assist for both the inbound and outbound trajectories. The current reference crewed mission concept of operations and associated system modifications are described below.

Before Orion departs Earth parking orbit, initial on-orbit checkout operations will occur. This will include spacecraft on-orbit configuration, key systems check out, and solar array deployment during the first orbit of the mission prior to the trans-lunar injection by the upper stage. 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.

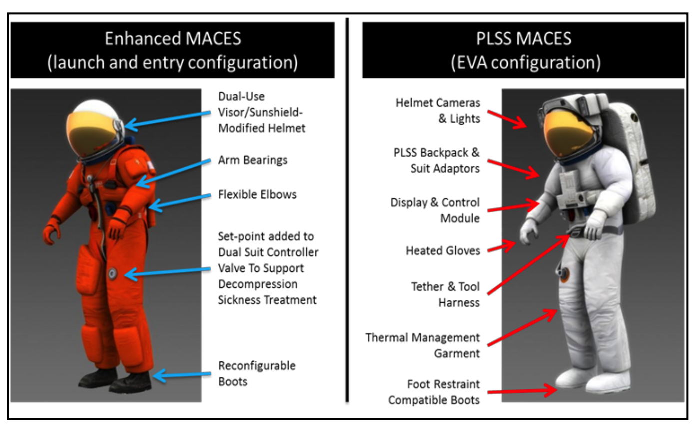

Figure 17: Modified Crew Escape Suit configurations

EVA preparations include transforming the vehicle and their Modified Advanced Crew Escape Suits (MACES) from the launch configuration to one that can support EVA. Figure 17 provides enhancements of the MACES configuration for launch and entry and for EVA.

The crew will arrive at the DRO in which the robotic SEP ARV and redirected asteroid are located. 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. A common docking system compliant to the international docking system standard completed critical design review in June 2014 and will support both the Orion and the ARM robotic vehicle with some slight modifications for the deep space cis-lunar environment. Figure 18 shows the passive side of this docking system.

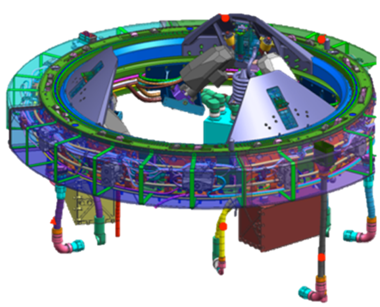

Figure 18: International Docking System Standard Common Docking System Passive Side

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-hour EVA's will be conducted utilizing lightweight exploration space suits based on the MACES concept. The day between EVAs will be spent reconfiguring/servicing the suits. The crew will commence EVA by donning their suits, depressing the cabin, and opening the Orion hatch. After hatch opening the crew will deploy a boom from the Orion hatchway across to the ARV, and translate across the ARV to reach the capture system where additional EVA tools and translation aids will be previously stowed and launched on the ARV. A next generation backpack primary life support system (PLSS), also shown in Figure 4, is in development as a common life support system for human space flight. The current PLSS prototype, shown in Figure 19, is currently in early interface testing with the MACES and is in early human in-the loop tests with an air environment.

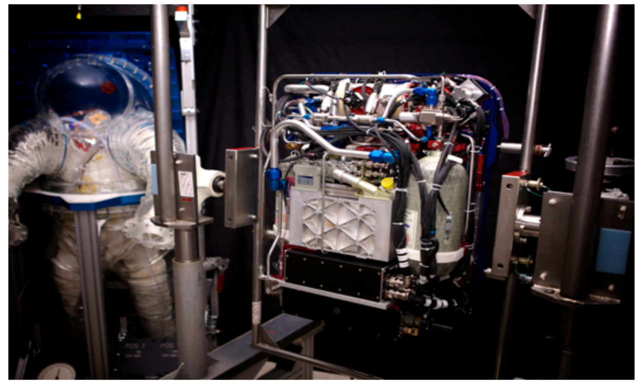

Figure 19: Next Generation Portable Life Support System Prototype

These EVAs will constitute the first-ever contextual observation and sample collection of asteroid material by humans operating in space. Upon completion, asteroid samples will be labelled 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.

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 Orion undocking. 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 potential future use, such as a visit by another Orion, commercial, or an international vehicle.

After the Orion undocks from the ARV, the crew will begin an ~11-day return from the lunar DRO including another lunar gravity assist maneuver to set up the earth return trajectory. 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. 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 the sample curation facility at the Johnson Space Center for processing, study, and analysis in an inert environment.

Crew Mission Concept Evolution

The Asteroid Redirect Crewed Mission concept continues to evolve as the team matures technology approaches, operational concepts, and performs more detailed trajectory analyses. For example, the evolution of understanding of technical feasibility of use of the MACES for the in-space EVAs for a mission such as ARM has taken place through a systematic rapid prototype and test approach. Through testing in the laboratory, zero-g and active response gravity offload system, the initial feasibility of the baseline Orion MACES was established as a viable option in the spring of 2013, resulting in follow-on neutral buoyancy testing to confirm these results In summer of 2013, crew, engineering, and operations personnel performed initial testing of the same configuration inside in NASA's Neutral Buoyancy Laboratory (NBL), including the NBL Interface, ability to weigh-out the suit, and the subject's ability to use the suit underwater. Further testing in durations increasing from two to four hours increased task complexity while improvements were made to the suit including the integration and use of extravehicular mobility unit (EMU) gloves and a drink bag. These tests determined a need for improved stability and define the work envelope.

Through fall 2013 and spring 2014, enhancement to the MACES and NBL tests included use of a new liquid cooling garment, mobility enhancements for the shoulder, EMU boots to enhance lower body positioning along with the addition of a PLSS mockup and body restraint tether. Increasingly difficult tasks in the NBL were attempted included an evaluation of mobility enhancements, improved worksite stability, use of standard ISS and prototype ARM EVA tools and testing on higher fidelity capsule mockups with a variety of tools. The addition on mission representative tasks, such as basic sample collection and handling culminated in two full four hour simulations of the ARM EVAs. Figure 20 shows NBL testing of translation with two crew members in MACES and testing of sampling task mobility and dexterity.

Figure 20: Testing of the MACES in the Neutral Buoyancy Laboratory

The detailed concept for Automated Rendezvous and Docking sensors has evolved significantly as well. Both the Robotic Vehicle and the Orion vehicle require rendezvous sensors to complete their respective mission phases. The Robotic Vehicle must rendezvous with the target asteroid. For Option A, the vehicle must rendezvous with the small asteroid for capture. For Option B, the vehicle must rendezvous with the large parent asteroid, characterize boulders, and descend on the larger asteroid for boulder capture. The Orion vehicle must rendezvous with the robotic vehicle for the crew segment. A detailed study was performed to determine if a common suite of sensors could be developed that would satisfy the needs of multiple missions to reduce development costs. The results of this study concluded that a common suite could in fact satisfy the needs of all three scenarios: Robotic Option A Rendezvous and Capture, Robotic Option B Rendezvous and Boulder Capture, and Orion Automated Rendezvous and Docking. This common sensor suite includes a 3D LIDAR, a medium resolution camera and a high resolution camera. The study also indicated the benefit of an infrared camera for increased robustness and situational awareness. The AR&D Sensor team is continuing to refine and evaluate common sensor approaches and pursue risk mitigation testing to further mature this aspect of the mission concept[13].

Finally, NASA is also pursuing other related studies which will inform and influence continued updates to the Asteroid Redirect Mission Concept. For example, NASA is continuing to assess various approaches for the ultimate goal of human exploration of Mars. The Evolvable Mars Campaign Study is looking at approaches for evolving from the Asteroid Redirect Mission technologies and operations concept to Human Mars Missions. In addition, the Habitation and Logistics Study is looking at approaches for adding habitat and logistics capabilities to cis-lunar proving ground missions such as the Asteroid Redirect Crewed Mission. The possibility of merging Evolvable Mars Campaign Study results, the proving ground Habitation and Logistics Study results, and the existing ARM concept could potentially provide greater opportunity for more science, more exploration objectives, more partnership and more collaboration opportunities by increasing deep space mission duration, additional capabilities, and increasing crew size. NASA will continue to assess evolvable approaches and adding appropriate capabilities to step beyond low earth orbit into the proving ground of cis-lunar space and further as stepping stones to eventual human exploration of Mars[14].

7. SUMMARY

This paper provides a brief summary of the current status for ARM robotic and crewed mission concepts, including robotic mission modular design, capture options, major system design drivers, and crewed mission conceptual design.

ARM is a compelling combination of robotic and crewed missions which will substantially contribute to advancing technologies, techniques, and operational capabilities required for human missions to Mars. It is a key component of NASA's exploration strategy to perform early, affordable missions that test and prove the key capabilities required for long duration, deep space exploration. Substantial progress has been achieved in developing the ARM pre-formulation concept. The two key alternative robotic missions are described and key risk mitigation activities are discussed. A number of trade studies have been completed to arrive at the current robotic spacecraft conceptual design based on a solar electric propulsion system concept that significantly advances the state-of-the-art for solar arrays, thrusters, and power processing technologies. Discovery and orbit determination of new NEA candidates is ongoing in support of the development of the robotic concept options. Crewed mission concepts are being developed in parallel with the robotic mission including advancements in EVA suit technology and techniques, as well as automated rendezvous sensors that can support both the crewed and robotic mission segments. NASA will continue to develop the ARM in the context of how it provides an evolvable approach and adds appropriate capabilities to step beyond low earth orbit into the proving ground of cis-lunar space and further as stepping stones to eventual human exploration of Mars.

References

[1] "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.

[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, Jul. 2014.

[3] 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, Jul. 2014.

[4] "Asteroid Redirect Mission Broad Agency Announcement," http://go.nasa.gov/1jiPXs, Mar. 2014.

[5] Roberts, Brian, and Joe Pellegrino, "Robotic Servicing Technology Development," AIAA 2013-5339, *AIAA Space 2013*, San Diego, CA, 10-12 September 2013.

[6] Parness, A., et al., "Gravity-independent Rock-climbing Robot and a Sample Acquisition Tool with Microspine Grippers," Journal of Field Robotics 30, No. 6, p. 897-915, 2013.

[7] Belbin, S. P., and Merrill, R. G., "Boulder Capture System Design Options for the Asteroid Robotic Redirect Mission Alternate Approach Trade Study," AIAA SPACE 2014 Conference and Exposition, San Diego, CA, August 2014.

[8] "Natural Impact Event Interagency Deliberate Planning Exercise After Action Report," http://neo.jpl.nasa.gov/neo/pdc_paper.html, December 2008.

[9] Bombardelli, C., et al., "The ion beam shepherd: A new concept for asteroid deflection," Acta Astronautica, Vol. 90, Issue 1, September 2013, Pages 98–102.

[10] Mazanek, D. D., et al, "Asteroid Redirect Robotic Mission: Robotic Boulder Capture Option Overview," AIAA SPACE 2014 Conference and Exposition, San Diego, CA, August 2014.

[11] Rivkin et al, *Asteroids III*, 2002.

[12] NASA Fact Sheet, http://www.nasa.gov/sites/default/files/files/SLS-Fact-Sheet_aug2014-finalv3.pdf, Aug. 2014.

[13] Hinkel, H., "Rendezvous and Docking Strategy for the Crewed Segment of the Asteroid Redirect Mission," presented at AIAA Space Ops 2014, Pasadena, CA, May 2014.

[14] Gerstenmaier, W., "NASA's Human Exploration and Operations Mission Directorate: An Overview of Current Programs," IAC-14.B3.1.1, 65th International Astronautical Congress, Toronto CA,September 2014.

Biographies

Michele Gates currently serves as the Program Director for NASA's Asteroid Redirect Mission. She received a B.S., M.S. and PhD in Aerospace Engineering from the University of Maryland at College Park in 1991, 1992, and 1997. She has been with NASA for more than 20 years.

Bo Naasz received a B.S. and M.S. in Aerospace Engineering from Virginia Tech in 2000 and 2002. He has been with Goddard Space Flight Center for 12 years, and currently serves as the Systems Engineering Manager for the Satellite Servicing Capabilities Office.

Brian Muirhead has worked on numerous spacecraft and technology projects since joining JPL in 1977, including the Galileo mission to Jupiter, and the Shuttle Imaging Radar-C. He was responsible for the design, development, test, and launch of the Mars Pathfinder spacecraft that landed successfully on Mars on July 4, 1997. He was Project Manager of the Deep Impact Project from formulation through CDR in 2002. He worked as the Chief Engineer of the Mars Science Laboratory until August 2004 when he became Chief Engineer of JPL. In February, 2007 Brian was named Chief Architect and Program Systems Engineer for the Constellation Program, which included responsibility for the architecture for a new human exploration spaceflight system to the Moon and beyond. He returned to JPL as the Chief Engineer at the Executive Council level in December, 2009. Brian is also currently the pre-project manager for the conceptual design of the cross Agency study of the Asteroid Redirect Robotic Mission (ARRM). He received his BS in Mechanical Engineering from the University of New Mexico in 1977 and an MS in Aeronautical Engineering from Caltech in 1982. He is the recipient of two of NASA's Outstanding Leadership Medals for his work on Mars Pathfinder and Constellation. He is the author of "High Velocity Leadership" (Harper Business, 1999), and "Going to Mars" (Simon and Schuster, 2004, with Garfield and Judy Reeves-Stevens).

Dan Mazanek is a Senior Space Systems Engineer and Near-Earth Object mission lead analyst at NASA's Langley Research Center. He graduated with a B.S. degree in Aerospace Engineering from Virginia Tech in 1989 and has over 25 years of experience in space mission conceptual design and architecture formulation. He has led multiple study efforts to investigate sending humans beyond low-Earth orbit and serves as the Near-Earth Asteroid Destination Lead for NASA's Human Spaceflight Architecture Team. He is currently leading the Robotic Boulder Capture Option formulation effort for the Asteroid Redirect Mission. He currently resides in Williamsburg, Virginia, with his wife Deborah, and their three children, Sarah, Kyle, and Lauren.

Jim Reuter is a senior executive at NASA's Marshall Space Flight Center. He has been with NASA for more than 30 years where he has served multiple leadership roles in nearly every NASA human space flight development during that time, including Space Shuttle, the International Space Station, Commercial Crew, Constellation, and Exploration Systems development.

Steve Stich currently serves as the Director of Exploration Integration and Science at the Johnson Space Center and is the Crewed Mission Lead for the Asteroid Redirect Mission. He received a B.S. in Aerospace Engineering from Texas A&M University in 1987 and has served in a variety of operations, engineering, and programmatic positions within NASA over the last 27 years.

Mark McDonald currently serves as the Exploration Mission Development Lead at the Johnson Space Center (JSC). He received a B.S. in Electrical Engineering from Texas A&M University in 1987 and an M.S. in Aerospace Engineering from the University of Southern California in 1990. He served as a flight controller for the Galileo Spacecraft at the Jet Propulsion Laboratory prior to transferring to JSC in 1990. At JSC, Mr. McDonald was the Integrated Design Team Chairman for the International Space Station and has been Project Manager for numerous flight projects.

Paul Chodas is a senior scientist at the Jet Propulsion Laboratory where he has computed trajectories of asteroids and comets for over 30 years. He received a B. Math. from the University of Waterloo, Canada, in 1975 and an M.A.Sc. and Ph.D. in Aerospace Engineering from the University of Toronto in 1980 and 1986. He is the principal architect of JPL's small body software that determines orbits, computes trajectories, detects close approaches and calculates impact probabilities in support of JPL's small body database. Paul coined the term "keyhole" in connection with asteroid close approaches that can lead to later impacts, and is currently coordinating the search and characterization of candidate targets for the proposed Asteroid Redirect Mission.