Legacy of the Asteroid Redirect Robotic Mission (ARRM)

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NASA's proposed Asteroid Redirect Robotic Mission (ARRM) began with the recognition in a 2010 NASA study that emerging high-power solar electric propulsion technology could be used to rendezvous with, capture, and return an entire, very small (~10,000 kg), near Earth asteroid to the International Space Station. A 2011 workshop by the Keck Institute for Space Studies (KISS) extended this NASA study to asteroid masses of order 500,000 kg by returning them to cislunar space. Subsequent detailed NASA studies in 2013-2014 confirmed the feasibility of this concept. This led to the establishment of the Asteroid Redirect Mission program that consisted of a robotic mission to return multiple tons of asteroid material to cislunar space and a crewed mission to rendezvous with the robotic vehicle, perform two extra vehicular activities (EVAs), collect samples of the asteroid material, and return this material to Earth. Implementation of ARRM proceeded midway through Phase B before being cancelled in April 2017. Although ARRM was cancelled, it left a near-term legacy of positive impacts to the human spaceflight community, the planetary defense community, the deep space science community, and asteroid mining interests.

I.Introduction

THE idea to exploit the natural resources of asteroids is older than the space program [1]. Numerous studies have identified and evaluated the benefits and challenges of exploiting the natural resources of near-Earth asteroids (see for example [2-13]). These studies and others identify three generic approaches for mining asteroids: 1) Mine and process the material at the asteroid and return only the processed material; 2) Mine the asteroid and return the raw material for processing; 3) Return an entire small asteroid to a more convenient location for processing. For all of these approaches, transportation is a major challenge, both to rendezvous with the target asteroid, as well as to return the asteroid material (processed or unprocessed) to the desired point of use. To address the transportation problem, most conceptual studies of asteroid mining assumed the use of reaction mass that, in one form or another, is obtained from the asteroid itself.

This situation changed significantly beginning with a 2010 NASA study [14]. This study recognized that near-term advances in high-power solar electric propulsion (SEP) could make it feasible to capture and return an entire small near-Earth asteroid (NEA), with a diameter of about 2 m and a mass of roughly 10,000 kg, to the International Space Station, without using reaction mass obtained from the asteroid itself. This approach promised to greatly reduce the cost and complexity of returning large amounts (10's to 100's of tons) of asteroid material to cislunar space. The 2010 NASA study was followed by a feasibility study conducted at the Keck Institute for Space Studies (KISS) which investigated two options for asteroid retrieval [15]. The first option considered the capture and return to cislunar space of an entire small near-Earth asteroid with a diameter of approximately 8 m and a mass of order 500,000 kg. The other option examined the feasibility of extracting a boulder several meters in diameter from the surface of a larger NEA and returning this boulder to cislunar space. A key feature of both options was to create a high-value target in cislunar space for a human mission beyond low Earth orbit for the first time since 1972. NASA considered the KISS concept sufficiently interesting that it sponsored follow-on studies to investigate the feasibility in more detail. These studies,

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which focused primarily on the concept to capture and return an entire ~8-m diameter asteroid, confirmed the feasibility of this mission concept [16-24]. In the course of subsequent formulation studies, NASA ultimately decided that picking a multi-meter diameter boulder off a larger NEA would develop a broader range of technologies extensible to future human exploration of Mars and its moons [25]. This mission concept became known as the Asteroid Redirect Robotic Mission (ARRM). In parallel with this selection, NASA established the Asteroid Redirect Mission (ARM) Program consisting of two missions, ARRM and a joint human/robotic mission called the Asteroid Redirect Crewed Mission (ARCM). ARRM would use a robotic spacecraft with a high-power SEP system to rendezvous with a near-Earth asteroid, land on the surface, extract a 2-6 m diameter boulder from the surface, and return that boulder to cislunar space. ARCM would have an astronaut crew in the Orion vehicle rendezvous with and dock to the ARRM vehicle, conduct two extra vehicular activities (EVAs) to obtain samples of the boulder, and return those samples to Earth.

Implementation of ARRM was led by the Jet Propulsion Laboratory (JPL) from 2014 through mid. 2017 with major participation by Glenn Research Center, Goddard Space Flight Center, Langley Research Center, Johnson Space Center, and Kennedy Space Center. The ARRM Pre-Phase A/Phase A study was conducted from June 2014 through July 2016. Following a successful Key Decision Point-B review ARRM entered Phase B in August 2016. Approximately mid-way through Phase B, the ARRM activity was terminated by NASA in April 2017. Even though the mission will not be implemented, its existence impacted a significant range of NASA's interests. While its long-term legacy remains uncertain, the short-term legacy of the Asteroid Redirect Mission is highlighted briefly below.

II.ARRM Impacts

The ARM Project impacted a number of NASA interests including high-power solar electric propulsion, human spacecflight, deep space robotic missions, in situ resource utilization, and planetary defense.

A. High-Power Solar Electric Propulsion Technology

One of the most important aspects of ARRM would have been the development and demonstration of a high-power solar electric propulsion system in deep space that would serve as a risk-reduction stepping-stone toward the development of mulit-hundred kilowatt systems needed to support human missions to Mars. Numerous Mars mission concept studies spanning decades have identified the need for very high-power SEP systems (100's of kilowatts or greater). However, the highest power electric propulsion (EP) system flown in deep space to date is the 2.5-kW ion propulsion system on NASA's Dawn spacecraft. Building a multi-hundred kilowatt SEP system based on the Dawn experience would likely expose such a project to unacceptably high risk. Flight implementation of an intermediate step up in power would significantly mitigate this risk. Demonstration by ARRM of an electric propulsion system at a power level of 40 kW would by sixteen times the state of the art for deep space EP systems. Implementation of a hypothetical 200 kW EP system, such as might be needed for human Mars missions, would then only be a more manageable factor of five increase relative to the ARRM system. Thus, a 40-kW electric propulsion system for ARRM appeared to be a reasonable stepping-stone forward to higher power systems.

Throughout all of the early feasibility and formulation studies of the asteroid retrieval concept conducted by NASA, one thing remained constant, the robotic mission concept would use a 40-kW, Hall-thruster based SEP system. The fine details of this system changed over time. For example, the output voltage range for the solar array was the subject of significant trade studies and debate. The maximum thruster input power, the maximum thruster specific impulse, and the details of the throttle table all changed over time. But, the basic architecture which used a small number of high-power, high-specific impulse, magnetically-shielded Hall thrusters, with a total electric propulsion system imput power of ~40 kW, remained constant. This was driven primarily by the assertion in the 2010 study [14] that a solar array with an output power of about 50 kW at 1 AU represented the best balance between implementation risk and pushing light-weight, deployable, solar array technology to higher power levels.

NASA's initial feasibility study in 2013 [22] considered launch readiness dates as early as 2017. Budget realities would result in the launch readiness date slipping approximately one year per year. At the time ARRM was terminated in 2017, the project was targeting a launch readiness date at the end of 2021. For launch dates in 2021 or later, a case could be made that 50 kW no longer represented the best stepping stone to multi-hundred kilowatt solar arrays projected to be needed to support human missions to Mars and that the ARRM spacecraft, or whatever replaces ARRM should target a higher power solar array.

To support a launch readiness date at the end of 2021, NASA initiated the development of the required Hall thrusters along with their power processing units (PPUs) and xenon flow control assemblies (XCAs). A competitive procurement activity managed by GRC selected Aerojet Rocketdyne for this development with significant risk reduction activities performed in parallel at GRC and JPL. The high-power Hall thruster for ARRM was given the name HERMeS (Hall Effect Rocket with Magnetic Shielding). Development of the thruster, PPU, and XCA are documented in numerous technical papers, see for example [26-63].

B. Human Spaceflight

Prior to ARRM, NASA intended to send astronauts to a near-Earth asteroid in the mid 2020s. In studying this concept it became clear to NASA that there were numerous difficulties that had the potential to significantly increase the cost of such a mission. These difficulties included lack of abort modes, vulnerability to solar flares, long flight times, and lack of resupply opportunities [64]. The ability to bring NEA's to cislunar space suggested that with respect to cost, complexity, risk, duration and resupply it may be better to bring these objects to the astronauts rather than to send astronauts to a NEA, at least initially [64]. Such a mission would likely be significantly easier and less expensive than a mission to a NEA in its native orbit, but would still draw astronauts away from low-Earth orbit for the first time in more than 50 years. It would have transit times measured in days not months, abort-to-Earth times also measured in days not months, and it would put astronauts in contact with only the second extraterrestrial object in history (the Moon being the first).

A key feature of such a mission would be the experience NASA would gain from working out the requirements and procedures for a human crew to interact with a robotic spacecraft in deep space. Such experience would be valuable for potential future human missions to Mars, which almost certainly will involve a mix of interacting human and robotic vehicles.

A significant part of ARRM's near-term legacy on human spaceflight is the expanded recognition and understanding by the human spaceflight community of the benefits that high-power solar electric propulsion can provide for human missions to the Martian system [71-81]. Prior to ARRM the benefits of high-power SEP for such missions was widely recognized within the electric propulsion community, but not as widely recognized outside of that community. ARRM and the mission studies that supported it and its extensibility to potential human missions to Mars changed this. A notable example of this is the so-called SEP/Chem hybrid architecture that combines the best features of high-power SEP with high-thrust chemical propulsion to reduce the overall flight times to those comparable to all-chemical propulsion architectures, while significantly reducing the initial mass in low-Earth orbit [74]. Significantly, this approach also reduces the overall mission risk, since the SEP/Chem hybrid vehicle could take all of the supplies and propellant necessary for the complete round-trip mission eliminating the need for a rendezvous with pre-positioned assets in Mars orbit in order to return to Earth.

Further impacts of ARM on low-thrust trajectory design are discussed in references [82-89].

C. Deep Space Robotic Missions

It has long been recognized that solar electric propulsion has the effect of making every launch vehicle better. That is, SEP can enable missions from smaller launch vehicles that would be impossible otherwise. Strange and Landau [83] have carried this concept to an extreme level, combining a 150-kW ARRM-derived robotic vehicle with a Block 1a Space Launch System (SLS). The resulting performance is impressive as an example of what might be possible. Such a system is projected to be capable of delivering 12,200 kg to orbit around Jupiter in a flight time of just 3 years; 8,500 kg to orbit around Saturn in 5 years; 4,400 kg to orbit around Uranus in 9 years; or 4,500 kg to orbit around Neptune in 13 years.

The version of ARRM selected by NASA for implementation would have required autonomous precision landing on an airless body, grasping a non-cooperative object, i.e., a 2-6 m boulder, extracting this boulder from the surface, securing it to the spacecraft, departing from the asteroid surface, and returning the multi-ton boulder to cislunar space. Successful execution of this concept would have significantly advanced NASA's capabilities for autonomous operations in close proximity to airless bodies as indicated by the body of work described in Refs [90-115].

D. Systems Engineering

ARRM also attempted to streamline the way flight projects are implemented at NASA. Two of the key features of this approach were the use of model based systems engineering [116-118], and the development of a capability driven system [119]. In the model-based systems engineering approach, the objective was to make the model be the one source of truth for the system that was accessible to all parties engaged in the flight system development regardless of their physical location. The capability-driven approach was intended to control costs by implementing a system whose performance largely driven the by capabilities of key subsystems.

E. Asteroid Mining

ARRM had a significant impact on multiple aspects of potential future asteroid mining activities, see for example [120-126]. Multiple asteroid retrieval studies by NASA from 2010 through 2014 confirmed the feasibility of a high-power SEP-based robotic vehicle to retrieve entire small asteroids with masses that are > 50X the mass of the SEP propellant. Return of hundreds of tons of asteroid mass to cislunar space enables asteroid mining equipment to stay relatively close to Earth. It also makes products derived from asteroidal materials available for relatively near-term space development in cislunar space [64]. While it is debatable what the most valuable near-term use of asteroid material will be, its use as radiation shielding to protect astronauts from galactic cosmic rays seems like a good candidate. Such an application would require lots of material, 100's to 1000's of tons, but would require little processing of this material.

Ultimately, asteroid mining will have to rely on asteroid-drived propellants to avoid the high cost of lifting propellants from Earth. Most concepts assume the use of water extracted from the asteroid as the source of this propellant for use either in solar thermal rockets or in LOX/H2 systems. ARRM's legacy with high-power, magnetically-shielded Hall thrusters suggests another possible approach. Asteroids are extremely poor sources of the inert gases typically used with Hall thrusters. However, asteroids are believed to have a significant amount of magnesium (~10 to 15%) and sulfur (~2 to 5%). Hall thrusters have been successfully operated on magnesium in the laboratory [126]. While no one has yet operated a Hall thruster on sulfur, it has a lower melting temperature than magnesium and a significantly lower temperature for the same vapor pressure. These features suggest that Hall thruster operation on sulfur may be easier than on magnesium. The low atomic mass of sulfur would enable high Isp operation in direct-drive systems with moderate solar array voltages [125].

F. Planetary Defense

Prior to ARRM, SEP was recognized as enabling or enhancing for most planetary defense techniques including kinetic impactors and gravity tractors [127]. A variation on the gravity tractor [128] is the so-called "enhanced" gravity tractor (EGT) in which the gravitational coupling between the asteroid and the spacecraft is enhanced by the spacecraft acquiring mass from the asteroid prior to the initiation of tractoring [129-130]. The resulting higher coupling force in an enhanced gravity tractor system requires high-power SEP in order to provide the necessary thrust levels. ARRM, with its 40-kW SEP system would have been the first demonstration of a gravity tractor, and specifically would demonstrated the EGT technique on a 100-m class NEA.

During the ARRM development, however, it was recognized that a planetary defense technique sometimes referred to as ion beam deflection (IBD) would benefit significantly from the development of high-power SEP systems. This technique is under appreciated by the planetary defense community. Ion beam deflection works by directing a beam of high-energy ions into the surface of the threat object and transferring the momentum of the ions to the object through inelastic collisions [131-136]. This is conceptually similar to a kinetic impactor with the impinging ions taking the place of the impacting spacecraft, but with two important differences. First, an ion beam deflection system can be designed so that the ions impact the asteroid surface at speeds much greater than is practical for kinetic impactors. Second, the ions can impact in the direction most effective for deflection. Ion impact speeds of 70 km/s are readily achievable, which would be roughly four to five times the impact speed of a kinetic impactor spacecraft. The finite power levels for the IBD vehicle means the transfer of momentum is necessarily spread out over time, typically over a timescale of months to years.

NASA is mandated by Congress to discover and track all NEOs greater than 140 meters in diameter. At the completion of this survey, if nothing is found on a collision course with Earth, then the impact risk will be dominated by Tunguska-scale objects, i.e., objects that are tens of meters in diameter [137]. IBD is particularly well suited to the deflection of objects in the size range of 50 m to 100 m diameter. A high-power IBD vehicle (of order 100 kW) could likely deflect such objects in matter of months. For example, if asteroid hypothetical asteroid 2017 PDC (used in the 2017 Planetary Defense Conference exercise) was 100 m diameter with a density of 2 g/cm^3, it would take only two months of IBD operations for a 160-kW IBD vehicle to deflect it by one Earth radius, assuming that deflection operations began 3.6 years before impact [136].

III.Conclusion

NASA's ARM program, which consisted of a robotic mission (ARRM) and a crewed mission (ARCM) would have impacted a wide variety of NASA's interests including: the demonstration of high-power solar electric propulsion at 16x the power level of the current state-of-the art for deep space electric propulsion systems; demonstration of precision landing on an airless body; demonstration of the ability to grasp, extract, and control a large non-cooperative object on the surface of an asteroid; demonstration of a planetary defense technique known as an enhanced gravity tractor; demonstration of the ability to transport a multi-ton payload through deep space; demonstration of joint operations with crewed and robotic vehicles in deep space; the return to Earth of large quantities of C-type asteroid material; human exploration beyond low-Earth orbit for the first time in more than 50 years; and human exploration of only the second extraterrestrial body in history.

Work related to ARM created a near-term legacy that includes: appreciation by the human spaceflight community of the benefits of high-power solar electric propulsion for human missions beyond low-Earth orbit; development of the SEP/Chem hybrid approach for human missions concepts to Mars that provide the mass savings of EP missions with trip times comparable to all chemical propulsion missions; verification by multiple in depth studies of the feasibility of capturing and returning to cislunar space entire small near Earth asteroids; and emerging recognition by the planetary defense community of the potential benefits of high-power SEP for ion beam deflection of potentially hazardous asteroids in the size range of 50 to 100 m diameter.

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