<u>*DRAFT*</u>
July 30, 2014

Report of the Small Bodies Assessment Group Asteroid Redirect Mission Special Action Team

In January 2014, the Asteroid Redirect Mission (ARM) Robotic Concept Integration Team (RCIT) engaged the Small Bodies Assessment Group (SBAG) community by presenting a list of tasks for which input was requested. In response, a SBAG ARM Special Action Team (SAT) was assembled to address the task list items. This report addresses three general aspects of the task list that were requested to support assessments of the ARM robotic mission concepts in the topics of: science, planetary defense, and resource utilization.

Though this report provides input to aid assessments of the ARM robotic mission concepts, previous findings by SBAG that relate to ARM are also still valid. In particular, the finding from the SBAG 9 meeting in July 2013 as related to planetary science states: "*While the SBAG committee finds that there is great scientific value in sample return missions from asteroids such as OSIRIS-REx, ARRM has been defined as not being a science mission, nor is it a cost effective way to address science goals achievable through sample return. Candidate ARRM targets are limited and not well identified or characterized. Robotic sample return missions can return higher science value samples by selecting from a larger population of asteroids, and can be accomplished at significantly less cost (as evidenced by the OSIRIS-REx mission). Support of ARRM with planetary science resources is not appropriate.*" The SBAG ARM SAT continues to support this and other previous SBAG findings.

The SBAG ARM SAT consisted of:

Nancy Chabot, *Johns Hopkins University Applied Physics Laboratory (SBAG Chair and SAT Science Lead)*
Paul Abell, *NASA Johnson Space Center*
Dan Britt, *University of Central Florida*
John Dankanich, *NASA Marshall Space Flight Center (SAT Resource Utilization Lead)*
Josh Emery, *University of Tennessee*
Andrew Rivkin, *Johns Hopkins University Applied Physics Laboratory*
Dan Scheeres, *University of Colorado (SAT Planetary Defense Lead)*

This report summarizes discussions and findings of the SBAG ARM SAT. The report will be presented at the SBAG meeting on July 30, 2014, and made available to the SBAG community for comment. The report will be finalized in August, 2014, following the opportunity period for comments. The SBAG ARM SAT echoes the statement in the CAPTEM ARM report: of necessity, this is a preliminary report. If such a mission goes forward, we recommend that the prioritization of the science, planetary defense, and resource utilization requirements be refined through a more comprehensive process.

TOPIC 1: Science

What new science, beyond what's already planned for missions in development, could be done robotically at a large (>50 m) asteroid or small (<~10 m) asteroid? Or with crew at a captured and returned boulder from a large asteroid or at an entire small asteroid? As part of this assessment, we request your scientific assessment in sample selection and collection.

Follow-on related request:
What is the value to the Science community of characterization of a large >50 m NEA that hasn't been visited before? Also what is the value of re-characterization of a previously visited NEA? What is the difference in value between the two options?

- **The type of asteroid sampled is of high scientific importance.** The Decadal Survey outlines the top science-driven priorities and emphasizes the importance of the type of asteroid sampled. Primitive asteroids associated with prebiotic materials (water, C, organics) are prioritized for science. Such materials may address important science questions related to the inventory and delivery of such materials to the inner Solar System. Such materials also may not be fully represented in meteorites, due to losses related to passage through Earth's atmosphere, necessitating the need for sample return missions to acquire such materials. A substantial mass of asteroid samples are already available for scientific study by examination of meteorites, and thus the scientific priority is to sample asteroids that have the highest potential to provide new materials not available in meteorite collections. For science, target composition is a much higher priority than target mass returned.

- **Characterizing and returning a sample from an asteroid not already, or planned to be, sampled is of higher science priority than characterizing and returning a sample from one that has been.** The asteroid population is numerous and diverse, and meteorite samples further support the widespread diversity present between asteroids. Characterizing and sampling that diversity is of high scientific value. Only samples collected from Itokawa are currently in our collections, and samples from Bennu and 1999 JU3 are planned. Samples from asteroids other than these three would provide new scientific insights and hence are of higher science value. The value to the science community is much higher for characterizing a previously unexplored NEA than re-characterizing one that has been previously visited.

- **Involvement of a science team is critically important to maximize the science, including during the concept development portion of the mission.** The science team should be involved in all aspects of the mission and its development, including target selection, scientific instrument development, the robotic asteroid encounter, and characterization and sampling by the crewed mission. The early application of the best available science insight can reduce complexity, cost, and mission risk. A science team, or science advisory group, should be integrated into current and ongoing ARM development efforts.

- **Ground-based characterization of the target asteroid is scientifically important.** Along with providing crucially important operational and tactical information that will be used to implement the mission, an extended ground-based observing campaign provides unique scientific context in which to interpret the robotic spacecraft characterization observations and the returned sample.

- **Remote characterization prior to, during, and following sampling is required for scientific context.** Remote characterization can cover many aspects, included but not limited to surface morphology, compositional characterization, and physical properties. In particular, diversity characterization may influence subsequent science driven sampling decisions. Valuable remote characterization can be done robotically. Input from the science community should be used to define the requirements, needs, and instruments for such robotic characterization. Involvement of an active science team is needed for sample selection decisions based on the robotic characterization of the asteroid. Sample collection should aim to minimize the disturbance to the sample, be recorded and documented to understand aspects that were not preserved, and strive to minimize contamination. Characterizing the surfaces of a larger host body after sampling has science value for evaluating surface properties of the asteroid.

- **The CAPTEM findings on sample selection and collection by the crew during EVA are very good assessments.** We support those findings and haven't duplicated that effort in this report.

- **An asteroid sample return mission offers a wide range of possible science investigations, both with remote characterization and through study of the returned sample.** Specific investigations depend on the nature of the target asteroid. Many open science questions exist as relate to asteroids and the overall NEA population, and remote characterization scientific investigations to any asteroid would cover investigating physical properties, composition, heterogeneity, surface morphology, interior structure, and relating the sample to meteorites. Both options also have the potential to provide unique science. A few examples for each are provided below, but this list is not exhaustive. The science community should be engaged to define the science mission of any such opportunity.

    - <u>For capturing a small (~<10 m) asteroid:</u> Much is unknown about this numerous population as it is a very difficult population to observe from Earth and has never been visited by spacecraft. What is the nature of such objects? Coherent monoliths or rubble piles? How strong are such objects? How homogenous/heterogeneous, for both composition and physical properties? How does the surface compare to the interior? How long has the object been this size? How does the object reaction to spacecraft operations and collection?

    - <u>For capturing a boulder from a >50 m NEA:</u> What is the nature of the boulder? What is the boulder population and how does it compare to the boulder sampled and to the larger surface geology in general? How strong is the boulder? How homogenous/heterogeneous is the boulder? How does the surface compare to the interior and what does this mean for space weathering? How long has the boulder been this size, at the surface? What are the characteristics of the surface below the boulder and that disturbed by its collection? How does the regolith move in response to the boulder being collected and other spacecraft operations? How does the sampled boulder relate in the larger context of the whole asteroid?

TOPIC 2: Planetary Defense

What realistic impact threat mitigation techniques or strategies and what trajectory deflection demonstrations, if any, make sense to be performed by the asteroid redirect robotic mission?

- **Involvement of the planetary defense community will be vital for optimal leveraging of the ARM mission for planetary defense studies.** Involving the wider community in order to incorporate their expertise will help ensure that any planned demonstrations are correctly scoped for the available resources and allow the most efficient leveraging of independent programs already underway.

- **All mitigation technologies, except for the gravity tractor, will likely modify or transform the asteroid or boulder surface to some extent beyond that resulting from just the capture activities**. The choice of a planetary defense demonstration will inevitably have implications for any subsequent science investigation, though we treat them as independent for the remainder of these findings. This could be an issue for future interaction or interpretation of the body, however we will not limit our analysis with regard to this except in one instance: We do not discuss nuclear blast approaches as they could make the returned asteroid or boulder unsuitable for human interaction and could also compromise the parent craft (ignoring any additional legal issues that seem to preclude such a demonstration).

- **Neither the Option A target nor the block retrieved from the Option B target will be of a size *per se* relevant to planetary defense.** While objects as small as only a few meters in diameter can produce meteorites, and bodies the size of the Chelyabinsk impactor (~15-20 m) can cause damage on the ground, the cost and effort required to mitigate such impactors combined with the likely very short warning time and limited damage they cause make them unlikely candidates for any future mitigation campaigns. This is reflected in the unofficial Torino Scale, which considers all impactors less than 20 m to register as a 0 on the scale.

- **The Option B target from which the block would be retrieved is likely to be of a size of greater interest to the planetary defense community.** The candidates we are aware of have diameters in the hundreds of meters range, large enough that mitigation would be seriously considered if such an object were threatening to impact Earth.

- **Demonstrations of new technologies and deployment tests may be fruitfully conducted with either Option A or Option B, though specifics depend on the particular technology/test.** The smaller size of the Option A target will lead to deflection measurements being completed more quickly than for Option B, however Option B studies may be more directly applicable to truly dangerous objects and may preserve the scientific integrity of samples more easily than Option A studies.

Appendix: Short description and discussion of selected mitigation techniques

We have taken a systems engineering approach to our observations, noting that it is not necessary to carry out an end-to-end engineering demonstration of a mitigation technology in order to advance the technology level of any particular deflection approach. Rather, in keeping with the spirit of advancing the Technology Readiness Level (TRL) of various methods, we note when some demonstrations short of a measured deflection could be important. With this philosophy, significant testing and development of most relevant mitigation technologies can be carried out for either option. In the following, for each mitigation technology we note what aspects of them could be tested for either option, if any. In all cases, if it is desired to measure a deflection, it is required that the spacecraft be tracked relative to the asteroid prior to the attempt and then after the attempt for a suitably long enough period of time to provide a statistically significant detection. These time periods can vary widely as a function of the asteroid physical properties and the deflection method. Their detailed discussion is beyond the scope of this report.

Kinetic Impactor: This option uses a second spacecraft to impact the asteroid to transfer momentum to the body. The method relies on a beta factor greater than 1 to enhance the effectiveness of the approach.

We view it as risky to apply this approach to Option A as it could severely affect the target asteroid due to its small size. For Option B we view this as a feasible approach, assuming that the boulder has first been taken from the surface, as the approach could compromise or alter key areas of the asteroid where boulder sampling is viable. For a large enough impactor, it may be feasible to estimate the degree of deflection. Carrying out a test without deflection detection could serve as a demonstration of the targeting technology and for providing an assessment of how a rubble pile asteroid responds physically to an impact. In particular, estimates of beta can be developed based on observations of the ejecta, independent of a direct measurement of deflection.

Gravity Tractor: This option places a spacecraft or massive object in close proximity to the asteroid in order to generate a net attraction between the bodies. If the spacecraft is then maneuvered in such a way that it does not place propellant on the asteroid, the center of mass of the system can be deflected.

This demonstration is viable for either Option A or B. For Option B, the spacecraft should use the retrieved boulder as the massive object for the test. Deflection detection may be feasible in both cases as the physics of the interaction is well understood. A non-detection experiment could also be of use and demonstrate the hovering and proximity control technology.

Ion Tractor: This option places a spacecraft with a “dual” ion propulsion system that can simultaneously thrust in opposing directions in close proximity to the asteroid. Once dual thrusting begins, the spacecraft places the asteroid in the field of one of the ion plumes, which transfers momentum to the asteroid.

This option is viable for either Option A or B. Deflection detection may be feasible in both cases, although the scaling is highly favorable to Option A. As the interaction of an asteroid surface with an ion beam is not fully understood, non-detection deflection experiments could still be of interest to better understand how the incident ion beams will react with the asteroid surface, if such measurements can be made.

Induced Surface Outgassing: This option heats a small region of the asteroid to high enough temperatures to induce vaporization, providing an outgassing jet on the asteroid surface, which can deflect the asteroid. Most methods either use a laser or refocused solar light to generate the surface heat.

This demonstration is viable for either Option A or B. It is unclear whether the detection of a deflection is viable, although Option A would be more favorable than Option B for this. Non-detection deflection experiments would be valuable to understand the thermodynamics of vaporization in the asteroid environment and to quantify the degree to which the asteroid environment becomes filled with products from these reactions. For either Option, it may create a hazardous environment for the spacecraft due to an enhanced number of particulates in the close proximity environment.

Surface Albedo Modification: This option deploys an albedo-modifying material across an asteroid to control or shut-off the Yarkovsky effect for a given body.

This demonstration is viable for either Option A or B. It is unclear whether either of these could yield a detection due to the possibly weak effect of this method. Non-detection deflection experiments would be of use to understand the mechanics of material deployment to the asteroid surface and its subsequent evolution due to charging effects. For either Option, it may create a hazardous environment for the spacecraft due to an enhanced number of particulates in the close proximity environment.

TOPIC 3: Resource Utilization

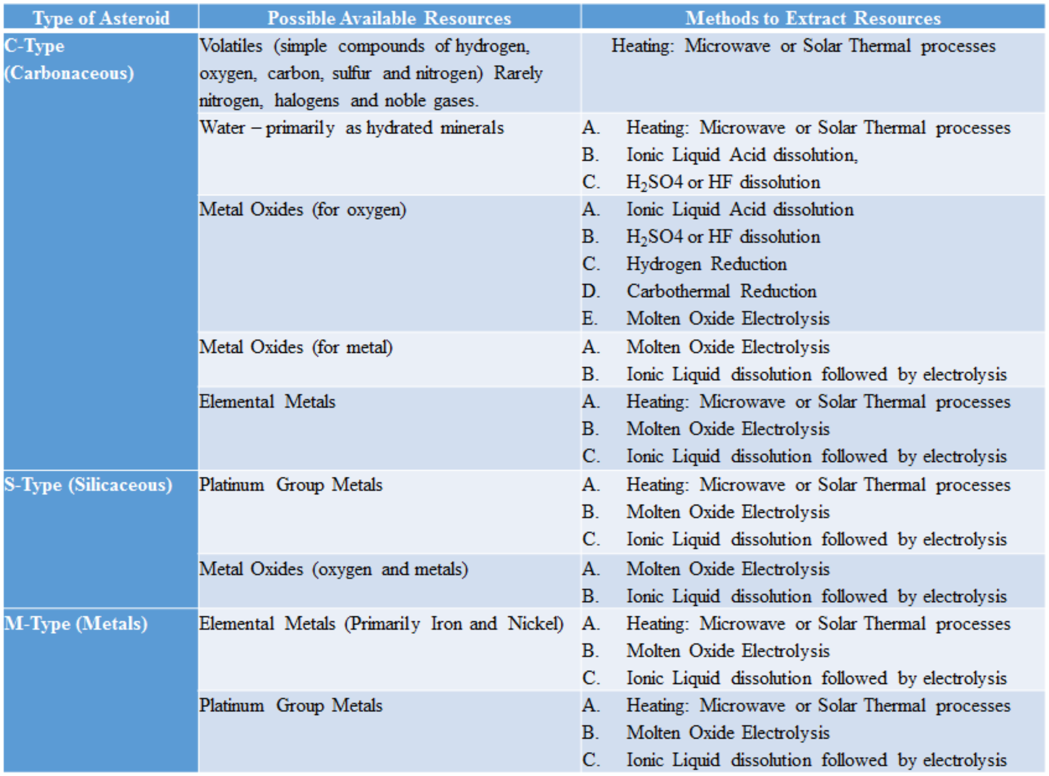
What key resource utilization demonstrations could be done robotically at a large (>50 m) asteroid or small (<~10) asteroid? Or with crew at a captured and returned boulder from a large asteroid or at an entire small asteroid?

Motivation: NASA roadmaps and technology prioritization plans consistently include the utilization and technology development for the generation of resources found in-situ. ARM is intending to send a vehicle to a near Earth asteroid. The ARM vehicle plans to include significant power capability and potential excess mass capability. At the mission's conclusion, the mission intends to provide a small asteroid or a boulder from a larger asteroid in cis-lunar space for future crew operations. While not an exhaustive list, general findings are noted below as related to the task statement at the top of this page that was provided to the SBAG ARM SAT.

Available Resources: The solar system provides a wealth of resources for future exploitation. Carbonaceous, C-Type, asteroids have the greatest variety of resources available for extraction. C-type asteroids include water, primarily as hydrated minerals, metal oxides for both metal and oxygen extraction, and metals. Primitive S-Type asteroids also offer metal oxides in addition to metals. Finally Metal, associated with M-Type, asteroids offer potential for platinum group metals and also elemental metals such as iron and nickel. The desire for volatiles would prioritize a C-Type asteroid as the highest valued target, though the volatile content of C-type bodies may vary considerably, as supported by the range of abundances measured in carbonaceous chondrite meteorites.

Resource Extraction Methods: Both the resources available and the methods of resource extraction are dependent on the constituency of the source. Many of the simplest methods of resource extraction are fundamentally heating the surface, subsurface, or bulk collected sample to sublimate the target constituent for deposition by the collector. NASA has proposed methods of both solar concentrators and microwave systems for heating. Given the ARM spacecraft's available power, microwave systems are practical and offer many advantages. NASA has also performed experiments using ionic liquids combined with electrolysis using meteoritic material for water extraction, metal extraction, and water electrolysis for hydrogen and oxygen generation. Ionic liquid demonstrations are well suited for small scale demonstrations. However, industrial scale extraction methods are typically higher in complexity including beneficiation, acid leach and fluorination, molten oxide electrolysis, and carbothermal regolith reduction. Industrial scale extraction methods may be inhibitive for autonomous operations in the near or mid-term and may create hazardous conditions during initial crew activities in an unknown environment. Table 1 is a preliminary subset of potential extraction methods for demonstration based on the desired resources and asteroid type. Several resource extraction experiments and demonstrations have been successfully performed in the lab for water and volatiles in simulated lunar and martian environments. Experiments have been proposed, but never accepted and completed, using the International Space Station (ISS) for microgravity demonstration of resource extraction. It is assumed that the highest priority resources for extraction are water and oxygen. Regardless of the highest priority resource, based on the desired extraction method to demonstrate, a C-type target provides the greatest diversity for extraction method demonstrations. Extraction demonstrations, even of small scale methods, in a relevant environment, are invaluable to the ISRU community and would fill a current gap in ISRU technology development. It is also noted that currently there is little agency coordination to focus asteroid ISRU technology development.

Table 1: Potential extraction methods for demonstration based on desired resources and asteroid type.



Type of Asteroid	Possible Available Resources	Methods to Extract Resources
C-Type (Carbonaceous)	Volatiles (simple compounds of hydrogen, oxygen, carbon, sulfur and nitrogen) Rarely nitrogen, halogens and noble gases.	Heating: Microwave or Solar Thermal processes
	Water – primarily as hydrated minerals	A. Heating: Microwave or Solar Thermal processes B. Ionic Liquid Acid dissolution, C. H_2SO4 or HF dissolution
	Metal Oxides (for oxygen)	A. Ionic Liquid Acid dissolution B. H_2SO4 or HF dissolution C. Hydrogen Reduction D. Carbothermal Reduction E. Molten Oxide Electrolysis
	Metal Oxides (for metal)	A. Molten Oxide Electrolysis B. Ionic Liquid dissolution followed by electrolysis
	Elemental Metals	A. Heating: Microwave or Solar Thermal processes B. Molten Oxide Electrolysis C. Ionic Liquid dissolution followed by electrolysis
S-Type (Silicaceous)	Platinum Group Metals	A. Heating: Microwave or Solar Thermal processes B. Molten Oxide Electrolysis C. Ionic Liquid dissolution followed by electrolysis
	Metal Oxides (oxygen and metals)	A. Molten Oxide Electrolysis B. Ionic Liquid dissolution followed by electrolysis
M-Type (Metals)	Elemental Metals (Primarily Iron and Nickel)	A. Heating: Microwave or Solar Thermal processes B. Molten Oxide Electrolysis C. Ionic Liquid dissolution followed by electrolysis
	Platinum Group Metals	A. Heating: Microwave or Solar Thermal processes B. Molten Oxide Electrolysis C. Ionic Liquid dissolution followed by electrolysis

Small versus Large Target Advantages: If all a priori knowledge is equal, there should not be any differentiator between a boulder from a large asteroid, a whole small asteroid, or a larger parent body. However, compositional characterization of the target can be critical depending on the extraction method to be tested. Also, knowledge of the surface properties and regolith may impact the complexity of the material collection and processing.

Robotic versus Crewed Demonstration Advantages: A large number of laboratory environment experiments with intensive human in the loop operations have validated the efficacy of small ISRU demonstrations for extraction of resources from meteoritic material. There has been minimal autonomy developed into ISRU demonstrations applicable to asteroid resource utilization. Due to the limited existing autonomous systems and current level of maturity, it may be difficult to deliver a well-tested autonomous ISRU demonstration given the baseline ARM schedule. A moderate focused investment has a lower risk posture to deliver a demonstration system to meet the crewed launch. The small-scale demonstrations are relatively simple and may benefit from crew participation for sample selection, coring or raking, and transferring into the ISRU extraction system. The industrial scale extraction methods may pose a hazardous environment for the crew.

Summary Findings: An initial assessment of the asteroid resource utilization demonstration potential for either the ARM spacecraft or crewed mission to the asteroid yield several summary findings.

- Simple small-scale demonstrations in a relevant environment are both feasible and invaluable to the community.
- Knowledge of the asteroid composition may be critical to optimizing a resource extraction demonstration.
- Knowledge of the surface properties may be critical to a resource extraction demonstration.
- If the target composition (knowledge) is equivalent, there is no major differentiator between a small target, large target, or a boulder from a large target.
- For science and resource utilization priorities, target composition is more important than target mass. A volatile-rich C-type target provides the greatest diversity for extraction method demonstrations.
- Techniques for small scale resource extraction demonstrations are likely not optimized and are potentially dissimilar from full scale industrial operational techniques.
- ARM provides a unique opportunity, with advantageous power, and may provide an opportunity to jumpstart or focus asteroid ISRU investments.
- Focused investments are required to delivery an autonomous asteroid ISRU demonstration; there are no existing turn-key autonomous experiments readily available. It is unclear if an autonomous demonstration system can be matured for flight with appropriate testing and meet the baseline ARM launch date without immediate and modest investment.
    - Crew-assisted extraction demonstrations could greatly simplify initial demonstrations:
        - Eliminates the need for autonomous material selection and handling
        - The schedule for crew-assisted demonstration allows additional terrestrial testing
        - Crew safety impact on demonstration techniques have not been assessed
- Studies for simple demonstrations in the very near-term may be valuable to ARM secondary objectives.