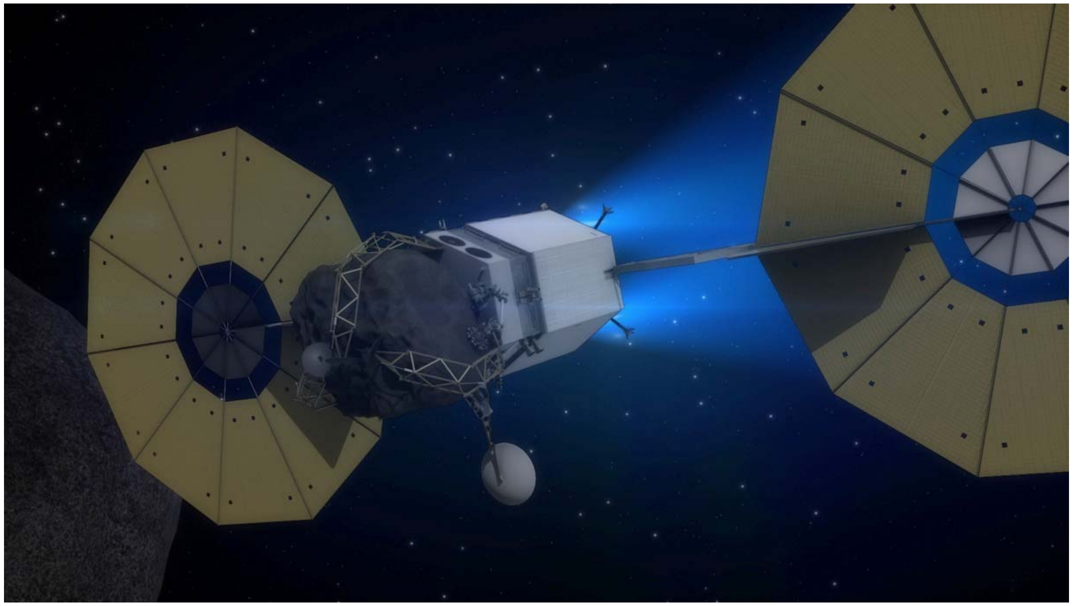


Asteroid Redirect Mission Formulation Assessment and Support Team (FAST) Summary

14th Meeting of the
NASA Small Bodies Assessment Group

Dan Mazanek
NASA Langley Research Center

January 28, 2016

Asteroid Redirect Mission

Outline

- Introduction & Team
- Project Questions
- Potential Investigations and Inputs on Potential Payloads and Partnerships
- Additional Findings
- Public Inputs to FAST Final Report
- Recommendations by FAST Leadership
- Plans for Investigation Team
- Backup

Introduction

- FAST chartered by NASA to:
  - Provide timely inputs for mission requirement formulation in support of the Asteroid Redirect Robotic Mission (ARRM) Requirements Closure Technical Interchange Meeting (RCT) held December 15-16, 2015.
  - Assist in developing an initial list of potential mission investigations and provide input on potential hosted payloads and partnerships.
- Inputs focus on scientific return and knowledge gain from ARM in the areas of:
  - Science
  - Planetary defense
  - Asteroidal resources and in-situ resource utilization (ISRU)
  - Capability and technology demonstrations
- U.S. membership composed of 18 NASA and non-NASA participants, plus Mission Investigator, Deputy Investigator, and Analysis and Integration Lead. Participants selected from exactly 100 applicants.
- Two-month effort: initial meeting at Langley Research Center on September 15-17, 2015 and final meeting at Goddard Space Flight Center on November 16-17, 2015.
- Final report available at the end of January/early February: http://www.nasa.gov/feature/arm-fast

Team

Last Name	First Name	Roll	Organization
Mazanek	Dan	ARM Mission Investigator	NASA Langley Research Center
Abell	Paul	ARM Deputy Investigator	NASA Johnson Space Center
Reeves	David	Analysis and Integration Lead	NASA Langley Research Center
Asphaug	Erik	Member	Arizona State University
Abreu	Neyda	Member	Penn State University - DuBois
Bell	Jim	Member	Arizona State University
Bottke	Bill	Member	Southwest Research Institute
Britt	Dan	Member	University of Central Florida
Campins	Humberto	Member	University of Central Florida
Chodas	Paul	Member	Jet Propulsion Laboratory
Ernst	Carolyn	Member	Johns Hopkins University-Applied Physics Laboratory
Fries	Marc	Member	NASA Johnson Space Center
Gertsch	Leslie	Member	Missouri University of Science and Technology
Glavin	Dan	Member	NASA Goddard Space Flight Center
Hartzell	Christine	Member	University of Maryland
Hendrix	Amanda	Member	Planetary Science Institute
Nuth	Joe	Member	NASA Goddard Space Flight Center
Scheeres	Dan	Member	University of Colorado
Sercel	Joel	Member	TransAstra
Takir	Driss	Member	United States Geological Survey
Zacny	Kris	Member	Honeybee Robotics

FAST & ARRM Project Team Members at Initial Meeting

Project Questions

- High-priority questions were derived from the ARRM engineering team's risk analysis.
- The answers from the FAST have aided in the design and development of the ARRM mission, spacecraft, and capture system.
  - Responses were formulated to support the ARRM RCT.
  - Assisted in the development of Boulder and Asteroid Reference Document (BARD).
- 2008 EV_5 has been identified as the reference target for the ARRM.
  - Provides a valid target that can be used to help with formulation and development efforts.
  - Near-Earth Asteroid (NEA) around which the FAST focused its efforts and attention.

Project Questions

- Project questions grouped into seven topics:
  1. Origin of 2008 EV_5
  2. Boulder Spatial and Size Distributions
  3. Surface Geotechnical Properties
  4. Boulder Physical Properties
  5. Post-Collection Boulder Handling
  6. Pre-ARCM Boulder Assessments for Crew Safety
  7. Containment Considerations
- Major findings are summarized in this presentation.
- Additional details are included in presentation backup and the final report (along with associated appendices and references).

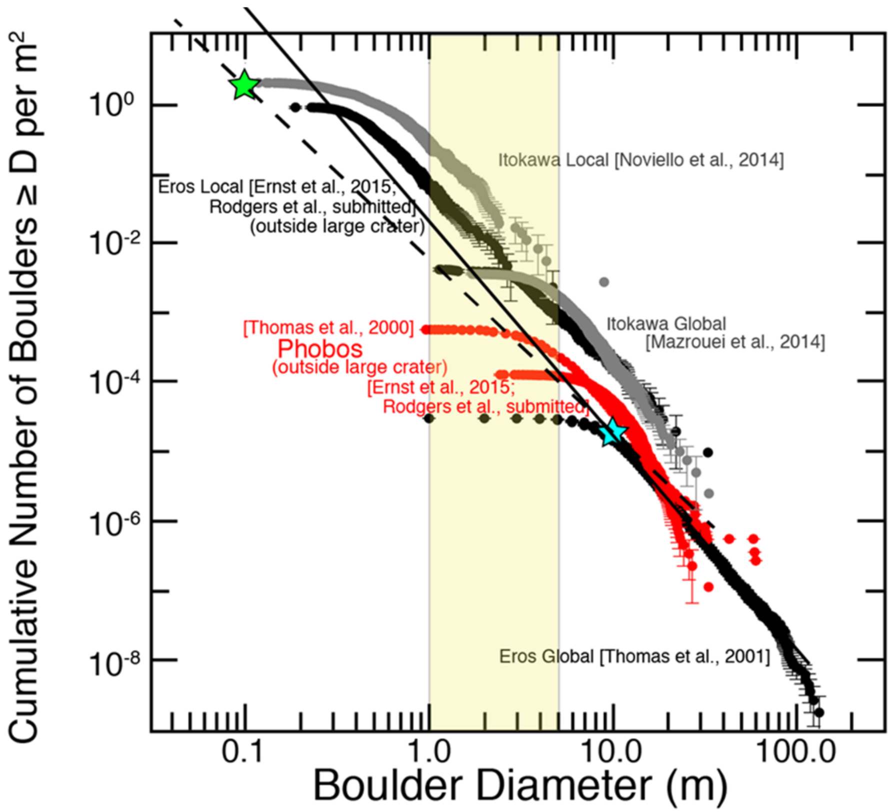
1. Origin of 2008 EV_5

Question: What is the orbital history of 2008 EV_5 and has that history affected the properties of the asteroid and candidate boulders?

- Based on initial dynamical modeling, 2008 EV_5 likely originated in the asteroid belt. Before reaching its current orbit, it was likely not close enough to the Sun for a long enough duration to deplete the subsurface and boulder interiors of hydrated minerals and organics (below ~5 cm).
- Based on its measured albedo, visible and near-IR reflectance spectra, the best match to 2008 EV_5's composition is likely a CR carbonaceous chondrite, however, CI, CM, and CK carbonaceous chondrites are also possible meteorite analogs.

Probability	2%	14%	24%	44%	60%	80%	100%
Surface Temperature	1,030 K	730 K	600 K	510 K	460 K	420 K	340 K
Corresponding Perihelion	0.1 AU	0.2 AU	0.3 AU	0.4 AU	0.5 AU	0.6 AU	0.9 AU

2. Boulder Spatial and Size Distributions



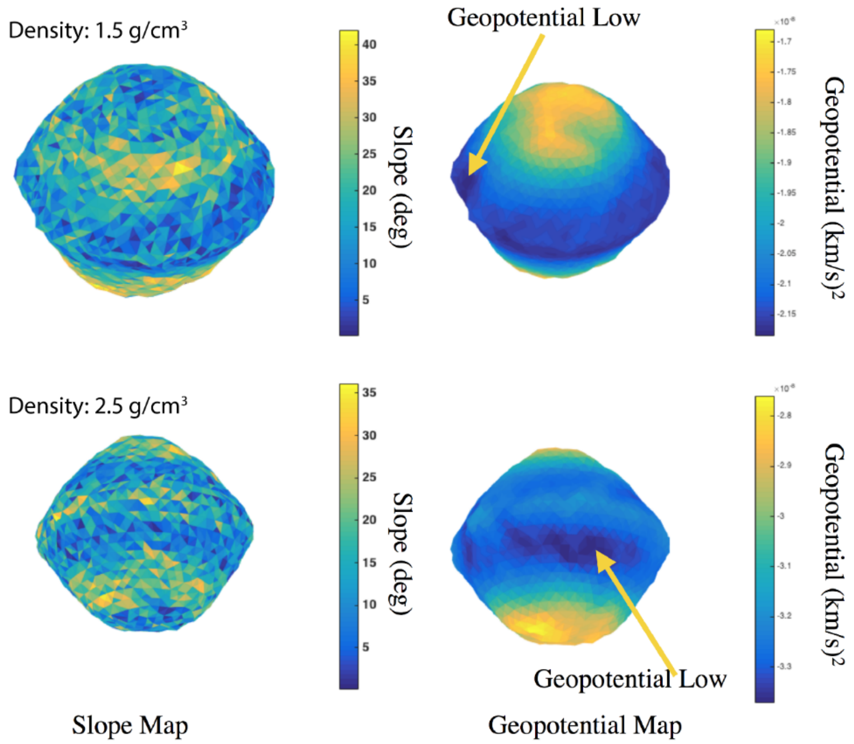
Question: What is the expected size-frequency distribution for boulders on 2008 EV_5?

- Based on radar imaging and size distribution power laws that have been seen in data from laboratory experiments and spacecraft observations of other asteroids, 2008 EV_5 is expected to have:
  - 3,000-16,000 boulders with 1-5 m diameters
  - 360-1,300 boulders with 2-3 m diameters

☆ 10-m boulder;
☆ 10-cm cobble for 2008 EV_5 based on radar images

2. Boulder Spatial and Size Distributions (Cont.)

- **Question: What is the expected spatial distribution of ~1-5 meter boulders on 2008 EV$_5$?**
  - Based on the assumed number of boulders from the previous slide, an areal density can be calculated assuming a uniform distribution.
  - There is not enough information to make any definitive statements on the actual distribution, however due to the geopotential (which varies with asteroid bulk density), higher concentrations of boulders are expected in the equatorial and near-equatorial regions.



2. Boulder Spatial and Size Distributions (Cont.)

Question: What is the expected distribution of boulder shapes on 2008 EV_5?

- Boulders found on Itokawa are typically elongated with b/a ratios of ~0.7 (width/length) and mean c/a ratios of ~0.5 (height/length), although boulder height cannot be determined in most Hayabusa images.
- Several past laboratory impact experiments have been conducted and show that the fragments produced are irregular in shape and not regular 3-axis ellipsoids (b/a ratios of ~0.6-0.9 and c/a ratios of ~0.4-0.7).
- An open question is whether the aspect ratio would be different for weaker rocks subject to thermal degradation, like those expected on 2008 EV_5. This question will be addressed by data from OSIRIS-REx and Hayabusa2.

Reference	Target	Projectile	Impact Velocity	b/a	c/a
Fujiwara et al. 1978	Basalt	Polycarbonate cylinders	1-4 km/s	0.73	0.50
Capaccioni et al. 1986	Basalt Concrete	Aluminum spheres	9 km/s	0.7 ± 0.15	0.5 ± 0.15
Giblin et al. 1998	Porous ice	Solid ice	6 km/s	0.56-0.71 ± 0.1–0.2	0.40-0.48 ± 0.1–0.2
Durda et al. 2015	Basalt	Aluminum spheres	4-6 km/s	0.72 ± 0.13	0.39 ± 0.13
Michikami et al., 2014	Basalt	Nylon spheres	1.6-7.0 km/s	0.7	0.5

2. Boulder Spatial and Size Distributions (Cont.)

Question: What is the expected distribution in safe landing areas around ~1-5 m boulders on 2008 EV_5?

- Nothing more beyond uniform distribution estimates can be definitively stated at this time.
- However, relatively flat regolith regions, with boulder-populated areas are predicted to be present on 2008 EV_5.

Question: What is the expected distribution in depth of burial for ~1-5 m boulders on 2008 EV_5?

- Minimal information with regard to the depth of burial has been obtained from other asteroids (Eros and Itokawa).
- With visual information only, the best way to estimate depth of bury would be to assume the aspect ratios given on previous slide combined with 3D images from the Asteroid Redirect Vehicle (ARV).
- Thermal imaging and ground penetrating radar (GPR) could potentially provide more information if included in the ARRM sensor suite (GPR viability is subject to processing time, resolution, and signal-to-noise issues, as well as cost).

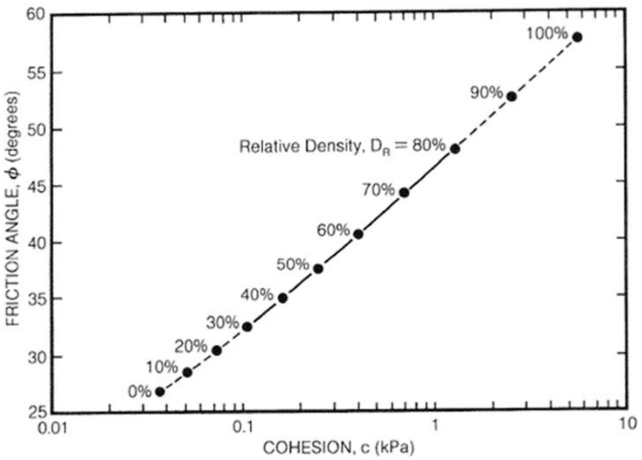
3. Surface Geotechnical Properties

Questions: What are the expected surface regolith geotechnical properties of the target asteroid?

- Due to low surface acceleration and solar radiation pressure, the asteroid surface is likely to be a pebble-rich lag depleted of fines.
- Cohesion is a function of particle size among other things, so the depletion of fines will act to reduce the cohesion on the surface.

What is the expected distribution in cohesion between ~1-5 meter boulders and the surface of 2008 EV_5?

- Asteroid to boulder cohesion is expected to range from 25-250 Pa.
- Looking at lunar basaltic simulant cohesion and assuming low relative density as an asteroid analog supports this cohesion range.



Measured shear strengths of a basaltic simulant of lunar regolith (showing friction and cohesion) as a function of relative density [Heiken et al., 1991].

3. Surface Geotechnical Properties (Cont.)

Question (Cont.): What is the expected distribution in cohesion between ~1-5 meter boulders and the surface of 2008 EV_5?

- Cohesion is a function of particle size as well as particle shape, compaction history, and other material properties.
- Fines have higher cohesion per unit volume than coarse material.
  - Modeling predicts that fine grains will preferentially attach to larger grains, and thus larger grains embedded in a matrix of fine grains could be held in place by the strength of the matrix itself.
  - Cohesion between large boulders and regolith will be driven by cohesion between fine particles and is estimated at 25-250 Pa. A high-resolution camera (mm/pixel or better) would be needed to provide good estimates of regolith size distribution.
- During the mission, measured particle size distribution could be used together with the models to assess regolith cohesion.
  - Models need to be calibrated using at least one direct surface interaction experiment (low-velocity impactor and imaging of crater).

4. Boulder Physical Properties

Question: What is the expected distribution in densities for ~1-5 meter boulders on 2008 EV_5?

- 2008 EV_5 appears to be composed of material similar to CR or CM chondrite meteorites, although CI and CK types cannot be ruled out.
- For these carbonaceous chondrite groups, the bulk densities range from 1.58-3.94 g/cm^3 and porosities are between 35% for CI chondrites and 9.5% for CR chondrites.

Meteorite Type	Average Bulk Density (g/cm^3)	Bulk Density Range (g/cm^3)	Average Grain Density (g/cm^3)	Grain Density range (g/cm^3)	Porosity (%)	Porosity Range (%)
CI	1.58	single measurement	2.43	single measurement	35	single measurement
CM	2.20	1.88-2.47	2.92	2.74-3.26	24.7	15.0-36.7
CV	3.03	2.59-3.46	3.54	3.25-3.68	14.6	0.6-27.7
CO	3.03	2.18-3.48	3.52	2.99-3.78	13.6	0-41.3
CK	2.90	2.54-3.39	3.58	3.37-3.66	17.8	0-23.4
CR	3.11	2.29-3.94	3.42	3.06-3.88	9.5	0-25.0
CB	5.25	4.90-5.55	5.65	5.63-5.66	3.9	2.0-5.8

4. Boulder Physical Properties (Cont.)

Question: How can a conservative mass estimate be derived from this information in order to ensure the selected boulder does not exceed the ARV return capability?

- If the composition can be identified, data on asteroid bulk density for the major carbonaceous chondrite groups can be used to derive the upper bound on meteorite bulk density and mass.
- Some combination of remote sensing measurements prior to boulder selection and in-situ measurement prior to collection would identify the mineralogy of the boulder:
  - Multi-wavelength Spectroscopy (e.g., UV, visible, NIR, thermal, etc.)
  - Alpha particle X-ray spectrometry (APXS) and/or laser-induced breakdown spectroscopy (LiBS) for elemental abundances
  - Neutron and gamma-ray spectroscopy for volatiles and elemental abundances
  - Mössbauer spectroscopy for Fe mineralogy
  - X-Ray diffraction (XRD) for general mineralogy

4. Boulder Physical Properties (Cont.)

Question: What is the expected distribution in minimum shear, compressive, and tensile strengths for ~1-5 meter boulders on 2008 EV_5?

- Hard data on asteroid material strength comes from two sources:
  - Laboratory measurements of small meteorites
  - Data from bolide entry events
- Meteorite strength data is measured from small samples and its applicability to large boulders requires an extrapolation which is uncertain.
- Bolide data shows a range of breakup altitudes that are dependent upon uncertain material properties and component sizes. The nature of those components and the body's reaction to entry are subject to interpretation.
- Given these caveats, along with the uncertainty in 2008 EV_5's classification, it is the judgment of the ARM FAST team members that boulders on 2008 EV_5 could exhibit strength characteristics that fall within the following ranges:
  - shear: 0.1-5 MPa
  - compressive: 0.50-50 MPa
  - tensile strength: 0.05-3 MPa
- More experimental data on relevant meteorite types is needed to refine estimates.
- Stronger boulders may be more angular while weaker boulders become more rounded faster from the erosion driven by thermal shock.

5. Post-Collection Boulder Handling

Question: How should the boulder be handled after collection to minimize impacts to science and to the structural integrity of the object?

- To avoid fragmentation of the boulder after collection, minimizing physical handling of the boulder until it is in a stable, cis-lunar orbit is suggested.
- However, additional physical contact of the boulder after collection could provide valuable engineering data to aid in safe transportation and the design of tools for future robotic or human sampling of the boulder.
- Risks can be mitigated by examination of the boulder via imaging, and some means to help identify internal cracks such as seismic experiments. These could be conducted prior to any drilling or sample coring operations.

5. Post-Collection Boulder Handling (Cont.)

Question: What is the suggested allowable contamination of the boulder surface prior to sample acquisition by the crew?

- The OSIRIS-REx contamination control requirements for the returned boulder could be used as a starting point.
- Reducing the levels of organic contamination on hardware surfaces that come into direct contact with the boulder surfaces.
- The contamination plan should also specify inorganic contamination limits for other elements of scientific interest.
- A best effort approach to reduce volatile contamination of the boulder surface (e.g., keep thrusters pointed away from the boulder surface) would be reasonable.
  - Active volatile monitoring near the boulder surface and spacecraft and passive witness control materials would help document the contamination environment around the boulder surface.
  - Contamination modeling is also needed of the spacecraft thruster exhaust products, and spacecraft outgassing.

6. Pre-ARCM Boulder Assessments for Crew Safety

Questions: Besides the existing capabilities of the ARV (i.e., cameras and feedback loads), are there other ways to assess the condition of the boulder prior to crew access to determine if it's safe to approach and sample? What post-capture (or post-LDRO insertion) measurements should be made prior to crew interaction to ensure crew safety? What measurements prior to crew interaction would enhance scientific or other knowledge gain?

- High-heritage and/or flight-proven measurements and techniques could be employed during cruise or after insertion into the Lunar Distant Retrograde Orbit (LDRO) and prior to crew interaction to ensure crew safety.
- Following table has been prioritized as: (A) most critical to astronaut safety; (B) relevant to astronaut safety and/or science/knowledge, but not as critical; and (C) primarily relevant to science/knowledge.
- All measurements that provide information relevant to crew safety could also provide important new information for science or other knowledge gain (e.g., ISRU potential and planetary defense implications).

6. Pre-ARCM Boulder Assessments for Crew Safety (Cont.)

Priority	*Measurement*	*Possible Methods*	*Safety*	*Science/ Knowledge*
A	Assess fragility, hardness, sharpness, and volatile release potential of samples	• Movies or time-lapse imaging of the samples while poking, pressing, drilling, brushing, scraping, hammering, and/or grinding • Use simulators of end effector tools that will actually be used later by astronauts	✓	✓
A	Assess presence of fractures or textures that might suggest spallation or breakage	• Acquire stereo images of the boulder and regolith samples to construct 3-D models of their surfaces prior to any tool interactions	✓	✓
B	Assess any physical movement or dramatic temperature changes of the samples during the transit to the Moon	• Use CRS feedback loads (as planned) • Thermal measurements of the samples • Acoustic sensors to assess stability/motion	✓	✓
B	Characterize and determine abundance of any dust, volatiles, and/or organics in the samples	• Ion Neutral Mass Spectroscopy covering masses relevant to potential volatiles, PAHs, or other potential carcinogens • High-resolution imaging survey (possibly including UV imaging) to assess dust environment • Potentially active-source (*e.g.,* laser) analysis of chemistry of released gases and/or dust/fragments	✓	✓
B	Characterize the chemistry and mineralogy of the samples prior to astronauts, to make eventual EVAs most efficient	• UV, Visible, Near-IR, Mid-IR imaging spectroscopy • APXS and/or LIBS for elemental abundance. • Neutron and Gamma-ray spectroscopy for volatiles and elemental abundances • Mössbauer spectroscopy for Fe mineralogy • XRD for general mineralogy	✓	✓
B	Assess swatches of space suit material and other relevant witness samples during the robotic mission to influence ultimate choice of ARCM materials, coatings, etc.	• Microscope-scale UV, Visible, Near-IR, Mid-IR imaging and spectroscopy	✓	✓
C	Assess electrostatic potential of the boulder	• Langmuir probe, or volt meter	✓	✓
C	Use mass determination and volume of the boulder to estimate its density	• Mass determination from radio tracking • Volume from imaging-derived shape model		✓
C	Estimate the ages of the samples	• Mass spectrometer for exposure age • Mini radiogenic isotope analyzer for absolute age		✓

7. Containment Considerations

Question: Given the uncertainties in the properties of the boulders, potential for contamination, possible thermal effects, and potential for particulate release that could affect spacecraft or crew safety, should some form of containment of the boulder be considered and, if so, what type of containment and materials should be considered?

- It is likely that some particulates will evolve from an unprotected boulder while it is attached to the spacecraft.
- These particulates are likely to be small, have a very low relative velocity to the spacecraft, and are not expected to remain in the vicinity of the boulder due to spacecraft motion and solar radiation pressure.
- These particulates do not present a hazard to crew operations.
- Monitoring the boulder throughout initial collection by ARRM and sampling operations during ARCM to assess debris generation, contamination, and alteration is prudent.
- Physical containment of the boulder is not required unless further analyses deem it necessary.
- Thermal effects may be the primary factor in contamination and alteration of the boulder. These effects can be reduced with a system designed to reduce thermal shock and peak temperature (i.e., Sun shade).

Potential Investigations and Inputs on Potential Payloads and Partnerships

- Provided an initial list of potential mission investigations that resulted from brainstorming activities by the FAST and inputs on potential payloads and partnerships that was developed by the FAST.
- Not intended to be inclusive of all possibilities.
- 63 areas identified have been sorted and grouped based on their likely benefit to ARM and relevance to NASA's science, ISRU, planetary defense, and exploration goals by the FAST leadership (Mazanek, Abell, and Reeves) incorporating input from the rest of the FAST.
- Listed in the final report in the order they were proposed by the FAST with no priority or significance implied by the order within each grouping. Currently in the process of prioritization of ARRM related areas with the ARRM project team.
- Further descriptions of the investigations are presented in the "Potential Investigations" section of the report.

Potential Investigations and Inputs on Potential Payloads and Partnerships (Cont.)

- **High Benefit to ARM and High Relevance to NASA Goals:**
  - Asteroid Surface Interaction
  - Dust/Particulate Mitigation Techniques
  - Sample Thermal Control
  - Thermal Imaging of Asteroid Surface
  - Collect Regolith Samples
  - Surface Contact Science Package
  - Collect Samples From Boulder
  - Characterize Boulder and Geotechnical Properties
- **High Benefit to ARM and Medium Relevance to NASA Goals:**
  - Low-Velocity Penetrator
  - Mineralogy and Composition
  - Multi-Spectral Imaging of Asteroid
  - Global Mapping of Asteroid
  - High-Power Radar
  - Comprehensive Boulder Imaging
  - LDRO Free-flying Observer
  - Asteroid Free-Flyer for Observation
- **High Benefit to ARM and Low Relevance to NASA Goals:**
  - None identified.

Additional Findings

- Unique Knowledge Gain from ARM: ARM provides a unique opportunity that can provide a wide range of valuable knowledge gain beyond other asteroid missions or what is available in the current meteorite collection.
  - Pristine sub-surface material, preserved with stratigraphic context (boulder core sample) that have not been significantly altered by the space weathering and ionizing radiation environment (e.g., how organic content, hydration, volatile content, etc. varies with depth).
  - Multi-ton boulder, along with surrounding surface regolith samples for context that would provide valuable information about the surface of asteroids and allow for measurements and investigations that require large mass/samples.
  - Returning multiple kilograms of samples to Earth will allow for sensitive laboratory measurements and experiments (i.e., destructive to the sample) – not possible with the limited primitive meteorite collection.
  - Creating an "orbital laboratory” that can be used to demonstrate asteroidal ISRU and other technologies and instruments in an operational environment.
  - Opportunity to correlate observed reflectance spectrum to the sampled asteroid surface (“ground truth”), asteroid interior (through boulder investigations), as well as known meteorite classes.

Additional Findings (Cont.)

- NASA Goal Traceability: Although the FAST did not specifically address traceability to the current planetary decadal survey and other NASA exploration roadmaps, there are many NASA goals that could be addressed using the results and opportunities provided by this mission.

- Pre-launch 2008 EV_5 Characterization: All existing data should be analyzed to provide physical characterization of 2008 EV_5 to understand mission risks.
  - This includes the ESA MarcoPolo-R team investigations (e.g., observations and modeling) and telescopic data sets.
  - Opportunities for acquiring new data sets should also be investigated (e.g., Spitzer).

- Meteorite and Simulant Analog Work: More wide-ranging laboratory studies of appropriate candidate meteorites and simulants are warranted (e.g., spectral reflectance, strength, density, etc.). Investigating the effects of grain size, packing density, and powders-on-slabs would provide stronger insights into the possible physical and chemical composition of 2008 EV_5.

Additional Findings (Cont.)

- Characterization Precursor: A precursor to the ARRM target body in order to scout for boulders and obtain physical characteristic data would effectively increase the characterization phase duration and should be investigated further.
  - This precursor could be a dedicated mission or be co-manifested with the ARV, arriving at the target earlier.
  - Additional benefits would be gained if the precursor had some means of interacting with the surface to provide geotechnical data.
- Characterization Phase: Characterization of the target asteroid, candidate boulders, and associated collection areas are critically important.
  - Increasing, to the greatest extent possible, the time allocated for characterization will maximize both the knowledge return from the ARRM and probability of mission success.
  - Minimizing the time required for data acquisition, transmission, processing and analysis, as well as decision making, can reduce the overall characterization timeline.

Additional Findings (Cont.)

- Geotechnical Property Estimation: A mechanical interaction with regolith representative of the boulder collection area is the only way to provide an accurate estimate of the regolith's geotechnical properties (e.g., cohesion, friction angle, porosity, etc.).
  - These properties are critical for boulder collection.
  - Before and after images of the interaction area at sub-cm/pixel resolution would provide context to inform cohesion mapping around target boulders.
- Boulder and Regolith Characterization: On a best-effort basis, sufficient camera resolution is required to characterize:
  - The morphological relationship of the boulder to the surrounding terrain. Sub-cm/pixel resolution of a representative area of boulder/regolith interface with more of the image devoted to the regolith than the boulder.
  - The physical integrity of the boulder (e.g. cracks, fissures, etc.). Sub-cm/pixel resolution over as much of the boulder surface as possible is desired.

Additional Findings (Cont.)

- Thermal Imaging: The thermal inertia of boulders, and the entire asteroid surface, is indicative of their near-surface characteristics (e.g., porous vs. solid), and can be measured relatively easily with a thermal detector.
  - Ideally, this detector would have two or more wavelengths (e.g., 5 and 10 microns) and a spatial resolution greater than several pixels per boulder (a minimum of about 0.5 meters per pixel).
  - Over an asteroid's rotation period these observations can distinguish between the thermal inertia of low-density, porous aggregates and higher-density, potentially-stronger, monolithic material, which would aid in boulder and site selection and in determining the homogeneity of boulder and surface properties.
- Previously Visited Target: While selecting a C-type target that will not have been visited before (i.e., not Bennu or Ryugu) is compelling, there is value in returning to a previously visited asteroid and there would be interest in returning a boulder to cis-lunar space for subsequent study and sampling.

Public Inputs to FAST Final Report

- The final report provides a summary of all public inputs received by the FAST prior to the close of the public comment period on December 4, 2015, that are relevant to the FAST Charter and in the scope of the mission formulation.

- Inputs will be posted in their entirety on the FAST website with the final report: http://www.nasa.gov/feature/arm-fast. This posting also includes other inputs that were applicable to the ARM in general, but were not directly relevant to the FAST activity and report.

- The FAST final report and complete set of public inputs will be posted at the end of January/early February.

- Documentable inputs were received from a total of 15 individuals representing a variety of affiliations, and are listed in the final report in the order that they were received.

Recommendations by FAST Leadership

- Consider including a thermal imager as an ARRM baseline payload.
- Consider remote sensing spectral measurements prior to boulder selection and in-situ measurement prior to collection which would identify the mineralogy of the boulder leading to better estimates of bulk density and strength.
- Investigate the use of acoustic/ultrasonic sensors to provide boulder characterization during and/or after collection during the ARRM.
- Assess processing time and data acquisition for boulder and surface characterization.
- Develop traceability to NASA science and exploration goals.

Recommendations by FAST Leadership (Cont.)

- Consider follow-up observations of 2008 EV_5 with Spitzer and other observing assets (ground-based and space-based) in 2019.
- Engage with science and ISRU communities to study in detail more the basic physical properties of the relevant meteoritic material for 2008 EV_5.
- Examine potential for robotic precursor for 2008 EV_5.
- Coordinate with EVA operations and tool development/containment groups for sample acquisition, handling, and storage (boulder and regolith samples).
- Determine how potential payloads and investigations will be prioritized and sought from within NASA and external partners (both domestic and foreign).

Plans for Investigation Team

- As of December 2015, the FAST has been formally retired.
- The funded ARM Investigation Team (IT) is planned to be formed in the summer of 2016 with a call for membership expected following Key Decision Point (KDP)-B.
- The multidisciplinary IT will support ARM through mission formulation, mission design and vehicle development, and mission implementation.
  - Assist with the definition and support of mission investigations.
  - Support ARM program-level and project-level functions.
  - Provide technical expertise.
  - Support NASA Headquarters interactions with the technical communities.
- Formulation of how the IT will be structured is currently in process.
- The entire ARM team looks forward to continued engagement with the small bodies community and others with potential interest in the mission!

Thank you for your time and attention!

Backup

Outline of the BARD

1. Introduction
2. Background on 2008 EV5
3. Physical Size
    - 3.1. Equivalent Diameter
    - 3.2. Shape
    - 3.3. Dynamically Equivalent Equal Volume Ellipsoid (DEEVE) Dimensions
    - 3.4. Volume
4. Mass Properties
    - 4.1. Bulk Density
    - 4.2. Mass
    - 4.3. Gravitational Parameter
5. Rotational Properties
    - 5.1. Sidereal Rotation Period
    - 5.2. Direction of Rotation
    - 5.3. Pole Position 6
    - 5.4. Non-Principal Axis (NPA) Rotation
6. Orbital Properties
    - 6.1. Aphelion
    - 6.2. Perihelion
    - 6.3. Inclination
    - 6.4. Orbital Period
    - 6.5. Synodic Period with Earth
    - 6.6. Orbit Condition Code
7. Surface Properties
    - 7.1. Surface Regolith Cohesion
    - 7.2. Geometric Albedo
    - 7.3. Thermal Inertia
    - 7.4. Grain Density
    - 7.5. Grain Size
    - 7.6. Presence of Boulders
    - 7.7. Surface Stiffness
    - 7.8. Surface Damping
    - 7.9. Surface Slope
    - 7.10. Terrestrial Surface Analog Suite
8. Spectroscopic Properties
    - 8.1. Taxonomy
    - 8.2. Meteoritic Analogs
9. Boulder Size and Shape
    - 9.1. Maximum Extent
    - 9.2. Aspect Ratio
    - 9.3. Size Distribution
10. Boulder Mass Properties
    - 10.1. Mass
    - 10.2. Bulk Density
    - 10.3. Center of Gravity
    - 10.4. Moments of Inertia
11. Boulder Mechanical Properties
    - 11.1. Strength
        - 11.1.1. Compressive Strength
        - 11.1.2. Tensile Strength
        - 11.1.3. Shear Strength (Near Surface)
    - 11.2. Surface Roughness
    - 11.3. Hardness
    - 11.4. Porosity
    - 11.5. Diurnal Thermal Skin Depth
    - 11.6. Terrestrial Analog Boulder Suite
12. Boulder Composition
    - 12.1. Taxonomy
    - 12.2. Optical Albedo
    - 12.3. Thermal Inertia
13. Surface Interaction
    - 13.1. Orientation on Surface (including gravitational slope)
    - 13.2. Cohesion Between Boulder and Surface
    - 13.3. Depth of Bury
14. References

3. Surface Geotechnical Properties

Question: What are the expected surface regolith geotechnical properties of the target asteroid?

- Likely to be a pebble-rich (1-cm or greater) lag depleted of fines with higher porosity and lower compaction than asteroid's bulk compaction and porosity.
  - Relevant to all ARRM candidate target-sized asteroids.
  - Effect of the low surface acceleration and solar radiation pressure, stripping off fines and leaving larger, harder to move particles (should be fairly uniform across landing site-sized regions.
  - Exceptions are "low" areas observed for example on Eros and Itokawa that were filled with relatively fine material.
- Coefficient of friction is a function of the magnitude of cohesive forces between regolith and the Contact and Restraint Subsystem (CRS) contact pads.
  - The main sources of cohesive forces are van der Waals and electrostatic forces, but van der Waals forces should dominate.
  - Rough analytical estimate of the expected range of bearing strength of the surface regolith is 185-4,368 Pa. Numerical models should be used to provide better estimates and sensitivities.

3. Surface Geotechnical Properties

Question: What impact do these geotechnical properties have on the CRS contact pads?

- Mission risk is likely reduced if the three contact pads are oversized (with appropriate margin) to prevent excessive sinkage during boulder extraction.
- With the surface assumed to be covered in pebble-sized lag, the cohesion between the pad and the surface should be relatively low.
- If cohesion is a concern, pads could be designed with a “decoupling” mechanism.
- Regolith samplers should target specific particle size ranges.
  - Less complex designs.
  - Could have one on each pad for different size ranges.

Question: What is a set of earth analog surfaces (e.g., concrete, sand) that could be used to bound the expected range of surface variability for use in validating the design of the landing system?

- Asteroid simulants be used rather than terrestrial analogs.
- Simulants can be produced with varying and targeted properties.
- Two different simulants are currently in production.

4. Boulder Physical Properties

Question: What is the expected distribution in the coefficient of thermal expansion of ~1-5 meter boulders from 2008 EV_5?

- The coefficient of thermal expansion of CM and CR chondrites are not well studied, but some informed estimates based on analogs to terrestrial materials can be made.
- The expected distribution of the coefficient of thermal expansion is expected to be small.
  - Direct measurements of the coefficient of thermal expansion for CM chondrites are in the works and results should be available soon.
  - In the meantime, the coefficient of thermal expansion in the range of 5-15 x 10^{-6}/K, similar to that of terrestrial sandstones, dolomites, and concretes, should be assumed.

Parameter	Min	Typical	Max
Specific Heat (J/kg/K)	1,000	2,000	3,000
Density (kg/m^3)	1,900	2,250	3,000
Thermal Conductivity (W/K/m)	1.0	2.0	3.0
Poisson's Ratio	0.18	0.20	0.25
Young's Modulus (Pa)	1.0E+10	2.0E+10	3.0E+10
Tensile Strength (Pa)	3.0E+05	1.0E+06	3.0E+06
Compressive Strength (Pa)	1.0E+06	3.0E+07	5.0E+07
Shear Strength (Pa)	5.0E+05	1.0E+07	2.0E+07
Coefficient of thermal expansion (10^{-6}/K)	5	10	15

4. Boulder Physical Properties

Questions: How homogenous are the boulder strength properties within a boulder? What is the potential, and likely, variability throughout the boulder? What is the potential for defects (fracture planes, etc.)? Is there any reason to believe the strength of boulders on an asteroid would vary with latitude or any other spatial parameter or orientation due to thermal cycling or other effects?

- Meteorite experience suggests that the density of fractures in asteroidal boulders will be high. However, fractures can be zones of strength as well as weakness. The shock history of meteorites does vary across the meteorite collection, but variation within a single meteorite is small. Data from the major meteorite showers are homogeneous to first order.
- The near surface material on an asteroid will probably be more space-weathered than the interior so it could be weaker and more fractured.
- The diurnal thermal skin depth is about 3 cm and that will be the major source of erosion from thermal shock.
- The extent of thermal shock will depend on the insolation distribution. Latitude variation is possible but will probably be much less important than more critical factors such as boulder strength, shock history, and albedo.

5. Post Collection Boulder Handling

Question: For the tools currently planned for sampling the boulder by the crew, what is the likelihood the boulder will shed material, fracture, or break up, due to the forces applied by these tools?

- There is a high likelihood that the boulder will locally fragment and shed material due to the forces applied by tools (e.g. anchoring drills) if indeed the ARM target body is similar to CR, CM, and CI chondrites.
- Tools that exert low cutting forces include an efficient drill cuttings removal system to help contain particulate release during the coring operation can minimize the risk of particle shedding during drilling or other similar activities.
- Monitoring the boulder during the anchoring process, such as adding cameras to the ends of the robotic arms is highly beneficial.

5. Post Collection Boulder Handling

Question: After collection, the boulder will experience a different thermal environment than it did on the surface of 2008 EV_5. What thermal environment constraints are reasonable for protecting the boulder?

- Thermal models of the selected boulder on the asteroid surface and the spacecraft plus boulder combination should be developed.
- Limiting the thermal shock (e.g., cooling/heating rate) of the boulder during transit to cis-lunar orbit to be no greater than the thermal cycling it experienced on the surface of the asteroid prior to capture will minimize the likelihood of any fracturing or other structural changes.
- An important potential application of this modeling activity will be to inform the advisability of adding a thin film or sheet metal shield to the CRS to potentially mitigate the effects of differential solar exposure and contamination of the boulder from spacecraft effluents.

Potential Investigations and Inputs on Potential Payloads and Partnerships (Cont.)

- **Medium Benefit to ARM and High Relevance to NASA Goals:**
  - Optical Communications Demo
  - Small Body Seismic Network on Asteroid
  - Ultrasonic Investigation of Boulder
  - Anchoring Techniques
  - Long-term Orbit Determination
  - Contamination Environment Monitoring
  - Boulder Organics and Volatiles Characterization
- **Medium Benefit to ARM and Medium Relevance to NASA Goals:**
  - Surface & Subsurface Composition.
- **Medium Benefit to ARM and Low Relevance to NASA Goals:**
  - None identified.

Potential Investigations and Inputs on Potential Payloads and Partnerships (Cont.)

- **Low Benefit to ARM and High Relevance to NASA Goals:**
  - Demo of Mining Techniques
  - Micro-g Mobility Demo (Robotic & Crewed)
  - ISRU Radiation Protection
  - Planetary Protection (“Break the Chain of Contact”)
  - Tether Demo with Boulder Counterweight
  - High-Velocity Asteroid Impactor
  - Radiation Environment Characterization
  - Collect Boulder Core Sample
  - Large Sample Return
  - Cold Trap Volatile Collection Demo
  - ISRU Product Characterization
- **Low Benefit to ARM and Low Relevance to NASA Goals**
  - None identified.

Potential Investigations and Inputs on Potential Payloads and Partnerships (Cont.)

- **<u>Low Benefit to ARM and Medium Relevance to NASA Goals:</u>**
  - Small Body GPS
  - Remote Stand-off Interaction Demo
  - Future Planned Instrument Demo
  - Space Weathering Measurements
  - Plasma Environment Characterization
  - Magnetic Environment Characterization
  - Deploy Science Package
  - Occultation Exosphere Observations
  - Dust Mobility Characterization
  - Characterize Boulder Porosity
  - Rubble Aggregation Experiment
  - Observe Kinetic Impact on Asteroid
  - Deploy Explosive Penetrator on Asteroid
  - Additional Planetary Defense Demo(s)
  - Plume Generation and Observation
  - Ablation and/or Spalling Test
  - In-Space Printing with Asteroid Materials
  - Asteroid Material Manipulation Demo
  - Instrumented Drill on Asteroid and/or Boulder
  - Boulder Composition Characterization
  - Deliver Samples to International Space Station (ISS)
  - Encapsulate the Boulder for Volatile Collection
  - Characterize Boulder Permeability
  - Soil Simulation with Asteroidal Material
  - Microwave Volatile Extraction Test
  - Use of Robotic Arms for Strength Tests
  - Full ISRU Demo

Key Comments from Public Inputs

- The following is a list of investigations and potential payloads provided:
  - Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) Torque and Rotation State
  - Cause of Surface Restructuring
  - Granular Physics and Cohesion
  - Contextual Sampling of the Target Asteroid
  - Electrostatic Levitation
  - Comparison with Ground Based Observations
  - Planetary Defense Data
  - Geodetic Control During Enhanced Gravity Tractor (EGT)
  - Laser Retroreflectors
  - Presence of Water
  - Deep Space Atomic Clock (DSAC)
  - Small Spacecraft
  - Bi-Static Radar Reflections

Marshall Eubanks (Asteroid Initiatives, Inc.)

Key Comments from Public Inputs (Cont.)

- If 2008 EV_5 is potentially hydrated, then it is a science imperative to monitor the local exosphere about that asteroid and volatiles that will most certainly evolve from it upon encounter with the spacecraft and its necessary tools.
  Edward L. Patrick (Southwest Research Institute)

- Value of precursor - important to more fully discuss the concept of sending one or more smaller surveyors to identify the best target for a later boulder-extraction mission.
  Laszlo Kestay (United States Geological Survey Astrogeology Science Center)

- Quantitative requirements for the quality of the topographic information are not clearly established. The choice of techniques, types of instruments, and specific instrument requirements depend on the level of precision required by the mission. Processing could be accelerated with new photogrammetric techniques and tools. However, this is a significant new R&D effort that would take some years to complete.
  Laszlo Kestay (United States Geological Survey Astrogeology Science Center)

Key Comments from Public Inputs (Cont.)

- Use of ultrasonic sensors for in-situ measurements for physical properties characterization and analysis.
  Raffi Sahul (TRS Technologies)

- A reference model of the target asteroid needs to be defined at a sufficient level of detail to be usable to define design requirements for ARM, with clear parameter uncertainties. Then it would be possible to decide what range of uncertainties of what parameters can be accommodated at what cost. It would also be possible (and needed) to then do a full-up risk assessment.
  Mark Sykes (Planetary Science Institute)

- Assessments are made about “science” gains with no traceability to specific NASA Science Objectives or to Planetary Science Priorities described by the Decadal Survey.
  Richard P. Binzel (Massachusetts Institute of Technology)

Key Comments from Public Inputs (Cont.)

- Methods and tools mapping small bodies are not well developed, tested, and robust. Problems in processing including:
  - Significant manual effort required for processing.
  - Substantial periods of time required for processing (i.e., no near real-time or real-time processing).
  - Lack of uncertainty information for the mapping products produced.
  - No tools for rigorous joint processing of stereo and lidar data.
  - No tools for “true 3D” modeling of planetary surfaces (including boulders on such surfaces).
  - Misunderstandings of coordinate system standards.
  - Lack of any standards for planetary instrument calibration and instrument boresight measurement.
  - Lack of visualization tools for the appropriate map projection and display of such products and their uncertainties.
- Tool development to address these issues will be required in order to successfully carry out the ARRM. This will be particularly true if mapping products are to be generated near real-time for mission operations use.
- Another practical issue with regard to small body mapping tools is that some of the tools that do exist are only in use with international partners and not at any U.S. institutions.

Brent Archinal (United States Geological Survey Astrogeology Science Center)

Key Comments from Public Inputs (Cont.)

- For developing 3-D surface maps, recommendation to carry out studies to determine:
  - How such data would be collected (e.g. from different directions to obtain stereo), at what resolution, and with what accuracy, and given various possible lighting conditions.
  - How such data would be successfully processed into relevant shape models and mapping products.
  - Whether such methods can provide sufficient uncertainty information.
  - Whether models at the desired level of accuracy and resolution would be likely achieved.
  - Under what timeline the results are needed and whether additional development is needed in order to meet that.

Brent Archinal (United States Geological Survey Astrogeology Science Center)

Key Comments from Public Inputs (Cont.)

- The draft report attempts to constrain the strength of boulders on 2008 EV_5 using primarily bolide data and physical measurements on meteorites. Missing from the report is any discussion of the cosmic-ray exposure ages and breccia properties of meteorites, which both suggest that boulders on 2008 EV_5 are probably very weak.
  - Stony meteorite cosmic-ray exposure ages are typically 1-100 Myr
  - CI and CM chondrites mean cosmic-ray exposure ages are 1.8±2.1 and 2.8±3.1 Myr, respectively
  - CR chondrites have longer exposure ages of 1-25 Myr, with an average of ~8 Myr
- CM chondrites are nearly all shock stage S1 (<5 GPa) as more highly shocked materials did not survive as coherent rocks.
- The parent asteroids of CR chondrites probably have somewhat stronger boulders than the CI and CM asteroids as shock levels in CR chondrites are mostly S2 (5-10 GPa) and they have longer exposure ages.

Ed Scott (University of Hawaii)

Key Out-of-Scope Comments from the Public Inputs

The following public comments were relevant to ARM, but out-of-scope for the FAST:

- The relevance of ARM to the human exploration of Mars is not at all well-supported. There has yet to be a complete flow down of Mars requirements from which an argument can then be made that a group of those requirements can be most cost-effectively addressed to the level needed for a Mars mission by executing ARM.

Mark Sykes (Planetary Science Institute)

- Suggest the follow policy changes beginning with highest-priority:
    1. Target Phobos/Deimos in place of NEOs to better connect with the ultimate goal of Mars orbit/Mars.
    2. Emphasize how a Phobos/Deimos-ARM will follow the same route as crewed Martian expeditions.
    3. Stress how a sample of the Martian moons can identify usable resources and test extracting them ahead of human flights.
    4. Test technology useful to crewed vehicles and especially vital to cargo vehicles.

William T. Taylor (no affiliation cited)