National Aeronautics and Space Administration

# Exploration of Near Earth Objects Objectives Workshop

Summary Report
20 September 2010

# Table of Contents

**1.0 Exploration of Near-Earth Objects Objectives Workshop (Explore NOW) Executive Summary ..... 3**
1.1 Purpose ..... 4
1.2 Participants ..... 4
1.3 Day One ..... 5
1.4 Day Two ..... 6
1.5 Conclusion ..... 6

**2.0 Introduction ..... 8**
2.1 Purpose ..... 8
2.2 Participants ..... 8
2.3 Workshop Scope and Strategy ..... 9
2.4 Results ..... 9

**3.0 Presentations and Panel Sessions – Day One ..... 9**

**4.0 Breakout Sessions - Day One: Objectives of a Human Mission to a NEO ..... 13**
4.1 In-depth Review of Objectives ..... 14

**5.0 Explore NOW Breakout Sessions – Day Two ..... 18**
5.1 Precursor Investigations (Two Breakout Groups) ..... 18
5.2 Capabilities and Technologies ..... 22
5.3 Concept of Operations ..... 26
5.4 Planetary Defense ..... 29
5.5 Synergies with the Moon and Mars ..... 32
5.6 Policy and Public Engagement ..... 35

**6.0 Conclusion ..... 37**

**Appendix A: Breakout Sessions – Process and Framework ..... 39**

**Appendix B: Invitation Letter ..... 43**

**Appendix C: Agenda ..... 44**

**Appendix D: Breakout Sessions – Questions & Answers ..... 46**

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Specific acknowledgement is due to the vision of NASA Exploration Systems Mission Directorate (ESMD) Associate Administrator Mr. Douglas Cooke and Deputy Associate Administrator Dr. Laurie Leshin; and the leadership of ESMD's Directorate Integration Office Director Dr. John Olson.

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# 1.0 Exploration of Near-Earth Objects Objectives Workshop (Explore NOW)

## Executive Summary

On August 10-11, 2010, many of the world's top leaders in human spaceflight, planetary defense, science, and space policy converged on Washington, D.C. to brainstorm about human missions to near-Earth objects (NEOs), defined to include asteroids and comets. NASA hosted the interactive workshop at The Renaissance Mayflower Hotel and streamed the proceedings live via webcast.

*Exploration of NEOs Objectives Workshop*

There has been significant work over the past several decades focused on the objectives and capabilities needed for human missions to the moon and to Mars. In comparison, the knowledge base, analysis and implications of human missions to a Near Earth Object (NEO) are extremely limited. This workshop opened the aperture to include NEOs as an exciting opportunity for human exploration into deep space, and a stepping-stone to human exploration of Mars.

## 1.1 Purpose

The primary workshop goals were to:

- Increase the collective knowledge and understanding of NEOs;
- Communicate NASA's preliminary plans for a human mission to a NEO; and
- Invite and capture participants' ideas on mission objectives.

## 1.2 Participants

Approximately 175 registered participants attended, including NASA leaders and experts from industry, academia, other government agencies and the international community. Several of NASA's international partners participated in the workshop as well, including representatives from the Canadian, European, German, Japanese and Korean space agencies (CSA, ESA, DLR, JAXA and KARI, respectively). An additional 1,700+ individuals worldwide tuned into the live webcast, and those remote participants were encouraged to provide feedback through a web-based form during and after the workshop. The top ten countries in order of volume of participation were: USA, Russian Federation, China, United Kingdom, Czech Republic, Germany, Netherlands, Ukraine, Canada and Japan.

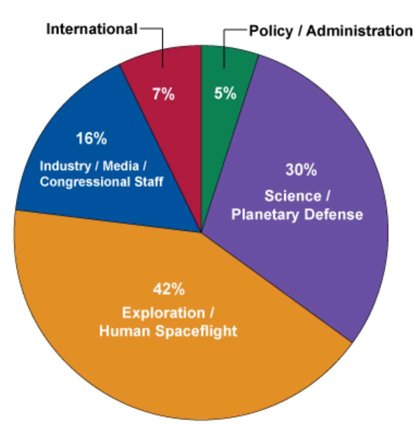


*Figure 1. Workshop Participation*

Distinguished NASA leaders, including Administrator Charles Bolden and Associate Administrator for Exploration Systems Douglas Cooke, spoke with participants to frame the vision and the challenges ahead. Presenters and panelists included representatives from JAXA, ESA, the Aerospace Corporation, the Johns Hopkins University Applied Physics Laboratory, the Planetary Society, the United States Air Force, the University of Arizona, the University of Notre Dame, and the White House Office of Science and Technology Policy (OSTP).

## 1.3 Day One

This groundbreaking workshop focused specifically on the objectives of human missions "at or near" a NEO.

A significant portion of Day One was focused on increasing participants' (and the public's) collective knowledge and understanding of NEOs. This was accomplished through a series of briefings and panel sessions conducted by colleagues from the science and planetary defense communities and experts in administration policy, who shared their perspectives on the objectives of a human NEO mission. Workshop participants then adjourned to concurrent breakout sessions to share, discuss and assemble their own input on the human mission objectives, as well as the specific activities needed to achieve those objectives and the desired characteristics of a target NEO.

More than 300 ideas were captured on the objectives of a human NEO mission. After assessing the input and identifying duplications, NASA linked the ideas to the following three primary objectives, as follows:

1. Demonstrate deep space capabilities – operations, human health, systems
2. Characterize NEOs – composition, porosity, size, spin rate, binary, etc.
3. Mitigate the threat of NEOs to planet Earth

Several important goals would be met by achieving these objectives, including:

- Answering questions on the history and evolution of the solar system
- Enabling human exploration of interplanetary space en route to Mars and beyond; and
- Improving the quality of life on Earth through improvements in human health (radiation protection, combat osteoporosis, telemedicine), technological advancements, and protection from devastating impacts from space.

The primary activities identified as being necessary to support achievement of these objectives may be summarized as follows:

1. Collection, examination and handling of samples
2. Testing hardware and software systems
3. Deploying scientific instruments
4. Testing NEO deflection techniques

Target identification and selection were common discussion themes among the workshop participants. As a follow up action, NASA is studying all of the identified NEOs – as catalogued in the JPL Small Body Database since September 1, 2010 – and comparing their physical characteristics and orbital dynamics to the objectives for a human mission to assess the quantity of known candidate NEOs.

## 1.4 Day Two

The rich discussions and tremendous input from participants on the objectives and activities were critical for accomplishing the goals for Day Two. The Day One input was reviewed and assessed, then presented to workshop participants on Day Two. This data served as the basis on which the questions identified below were addressed. The breakout session topics and a synopsis of their key findings are below.

### 1. What do we need to know before we can send a human to a NEO? (Two groups)

Participants agreed that increasing the knowledge about a target(s) <u>before</u> humans arrive increases the probability of meeting the objectives <u>during</u> the human mission. A key observation was that regardless of the specific human objectives at a NEO, the same kind of knowledge and measurements is desired from precursor missions. Given the relatively large number of known NEOs and the extreme diversity in their composition, the type of information needed fell into two categories: target selection and general characterization.

### 2. What technologies and/or capabilities are needed for a human mission to a NEO?

The primary capability gaps center around four areas: 1) systems for maintaining human health, 2) proximity operations, 3) target characterization and 4) mission autonomy. Participants identified technology development options to address the capability gaps for all of these areas, and acknowledged several crosscutting capabilities, including reliability, autonomy and smart systems.

### 3. What are the concepts of operations for a human mission to a NEO?

Participants identified specific concepts of operations for each of the four, top-level phases of a mission to a NEO: 1) LEO preparation, 2) outbound transit to a NEO, 3) NEO operations – human spacecraft, EVA, science and robotics, and 4) Earth return transit. The participants focused first on operational concepts identified for the NEO mission because operational requirements would drive requirements for the other phases.

### 4. What NEO knowledge do we need for planetary defense? What capabilities are needed?

Participants identified the characterization of NEOs as a key, enabling objective to help mitigate the threat of a NEO impacting Earth. Developing and testing approaches to modify the composition and/or orbital path of the object are key capabilities that are needed. Many reasons were cited on how human missions to NEOs would be advantageous in achieving these planetary defense objectives and capabilities. In particular, humans can improvise, synthesize, and adapt based on unexpected environmental conditions. Humans could also place and anchor sensors and systems in the most favorable locations.

### 5. What are the synergies with a human mission to the moon and Mars?

Participants identified numerous and significant synergies among human missions to NEOs, the moon and Mars (and its moons), especially in terms of sampling (acquisition, storage, handling, and in-situ analysis), EVA dust mitigation, tele-operation of robots, reliance on mobility systems, and the capabilities required to support basic human health. Synergies between a human mission to a NEO and to Mars were also identified and captured by mission phase. The areas of synergy may provide the greatest opportunities for investment and collaborative partnerships.

### 6. What policy considerations must be addressed? How could we engage the public?

Participants discussed the need for a sustainable human spaceflight program – one that would endure changes in the executive and legislative branches of government. Participants agreed that a human space exploration decadal study based on the National Academies model may be a potentially viable means to increase stability. Participants discussed several public engagement ideas, including an “open” mission control center that would allow participants to gain an insider’s perspective on mission control activities. Participants also suggested using the term “near-Earth asteroids” instead of NEOs or near-Earth objects to increase public understanding and engagement.

## 1.5 Conclusion

The workshop garnered a high level of interest and participation, both in person and virtually through the webcast. Participants identified a breadth of capabilities needed for human exploration of NEOs that are also required for human missions to Mars, as well as a breadth of NEO characterization objectives that are shared by the science, planetary defense and human spaceflight communities.

NASA is using the valuable input collected through this workshop to help formulate its programs, develop its human exploration framework, and advance collaborations within the agency and with the international community, industry and other federal agencies. NASA is also incorporating the input from this workshop into the formulation of its concept maps on human exploration of the solar system. These internet-based, interactive concept maps are targeted for release to the public by the end of the 2010 calendar year.

Presentations and videos from Explore NOW are available at:
http://www.nasa.gov/exploration/new_space_enterprise/home/neoworkshop.html

# 2.0 Introduction

There has been significant work over the past several decades focused on the objectives and capabilities needed for human missions to the moon and to Mars. In comparison, the knowledge base, analysis and implications of human missions to a Near Earth Object (NEO) are extremely limited. This workshop opened the aperture to include NEOs – defined to include near-Earth asteroids and comets – as an exciting opportunity for human exploration into deep space, and a stepping-stone to human exploration of Mars.

On August 10-11, 2010, many of the world's top leaders in human spaceflight, planetary defense, science and space policy converged on Washington, D.C. to brainstorm about human missions to near-Earth objects (NEOs), defined to include asteroids and comets.  NASA hosted the interactive workshop at The Renaissance Mayflower Hotel and streamed the proceedings live via webcast.

## 2.1 Purpose

The primary workshop goals were to:

- Increase the collective knowledge and understanding of NEOs;
- Communicate NASA's preliminary plans for a human mission to a NEO; and
- Invite and capture participant's ideas on mission objectives.

## 2.2 Participants

Approximately 175 registered participants attended, including NASA leaders and experts from industry, academia, other government agencies and the international community. Several of NASA's international space agency partners participated in the workshop, as well, including representatives from the Canadian, European, German, Japanese and Korean space agencies (CSA, ESA, DLR, JAXA and KARI, respectively). The breadth of expertise and diversity of experience among the invited participants was critical to accomplish the objectives of the workshop. The composition of workshop participant area of expertise is reflected in Figure 2.

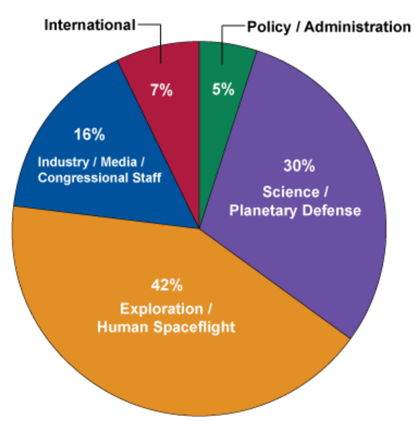


*Figure 2. Workshop Participation*

An additional 1,700 individuals worldwide tuned into the live webcast, and those remote participants were encouraged to provide feedback through a web-based form during and after the workshop. The top ten countries in order of number of participants were: USA, Russian Federation, China, United Kingdom, Czech Republic, Germany, Netherlands, Ukraine, Canada and Japan.

## 2.3 Workshop Scope and Strategy

This groundbreaking workshop focused specifically on the objectives of human missions “at or near” a NEO. A large portion of Day One was focused on increasing the collective knowledge and understanding of NEOs and NASA’s interest in exploring NEOs. This was accomplished through a series of briefings and panel sessions designed to 1) share current science knowledge, understandings and theories of NEOs and 2) provide an overview of NASA’s Exploration Systems Mission Directorate study team activities. An additional panel comprised of experts from the administration policy, science and planetary defense communities shared their perspective on the objectives of a human NEO mission. The workshop breakout session framework and process is provided in Appendix A; the agenda is provided in Appendix C.

The remainder of the workshop was dedicated to capturing and discussing input from workshop participants. While the first two goals of the workshop would be achieved by having the largest possible audience, achieving the third goal required a smaller number of people with specific expertise.

To enable comprehensive discussion among the experts and maximize the opportunity for individual input, participants were assigned to one of seven breakout groups with 18-25 people per room. Each room was further divided into two tables with a facilitator and scribe for each group of 9-13 people. A NASA topic lead was assigned to each breakout room and was responsible for briefing the input in the general session. On Day One, all of the breakout groups focused on the same topic. On Day Two, six different topics were addressed by the seven groups (one topic was addressed by two groups). The input from Day One was critical in driving discussion topics on Day Two.

## 2.4 Results

NASA found the input immediately useful and will continue to analyze, share and build upon the data through additional forums. The input collected through this workshop has proven valuable in helping to formulate programs, develop NASA’s human exploration framework, and advance collaborations within the agency and with the international community, industry and other federal agencies. NASA is also incorporating the input from this workshop into the formulation of its concept maps on human exploration of the solar system. These internet-based, interactive concept maps are targeted for release to the public by the end of the 2010 calendar year on http://www.nasa.gov/exploration.

## 3.0 Presentations and Panel Sessions – Day One

The Day One presentations and panel sessions were focused on increasing the collective knowledge and understanding of NEOs and NASA's exploration plans.

*Panel sessions on Day One focused on increasing knowledge and understanding of NEOs.*

Presenters and panelists from academia, industry and the Department of Defense identified compelling reasons to send humans to a NEO – such as the accessibility of NEOs; ability to answer science questions about the evolution of the solar system; potential availability of valuable resources; opportunity to gain deep space operations experience; and to assist in protecting planet Earth from NEOs.

The key planetary defense objectives for human exploration of NEOs include gathering data and developing test techniques for improving threat prediction, mitigation and verification. Accomplishing these objectives would require 1) measuring mass properties of near-Earth objects to better characterize NEOs and 2) returning samples to estimate porosity, which is a key activity in developing mitigation techniques. Some of the activities that humans would be especially well suited to conduct include testing and characterizing techniques for attaching transponders or other devices to a NEO; testing the technology required for long-term station-keeping and orbiting a NEO; collecting detailed information on shape, size, mass, bulk density, thermal properties and rotation; and emplacing the capability to verify the effectiveness of mitigation techniques.

The chair of the Lunar Exploration Analysis Group presented the utility of lunar exploration to facilitate exploration of NEOs. Using the moon as a stepping-stone to a NEO could increase the ability to operate on geologic surfaces, airless bodies, and in extreme radiation environments. Moon missions could also increase our experience in conducting operations with different lighting conditions; developing mitigation options for suit or tool failures due to dust interaction; enabling and optimizing human-robotic interactions; and increasing our experience in conducting operations in harsh environments.

NASA presented innovative concepts for NEO exploration that it had developed from multiple "Blue Sky" brainstorming sessions over the past several months. Examples included using a centrifuge to get partial- or full-Earth gravity and using inflatables for large living volumes using existing launch shrouds. Additionally, one could connect two space exploration vehicles with a Space Shuttle Remote Manipulator System-like arm. One vehicle could approach the surface without using Reaction Control System (thrusters) jets that would disturb regolith, while the other vehicle stabilizes system center-of-mass.

NASA also briefed its international framework for human space exploration that culminated in a recently completed global point of departure for lunar missions. The International Space Exploration Coordination Group is the strategic coordination group comprised of 14 countries including the U.S. The group has initiated an effort to develop a global exploration roadmap that will likely include multiple destinations of interest for human space exploration.

In an effort to leverage the knowledge and experiences from previous missions to NEOs, panelists representing NASA, JAXA, and ESA science missions presented their lessons learned. A synopsis of their lessons is described below:

**A. Near-Earth Asteroid Rendezvous (NEAR) (NASA Mission):**
The NEAR mission was NASA's first mission to an asteroid. NEAR performed a flyby of asteroid Mathilde (C-type main belt asteroid) and then rendezvous with its primary target Eros (S-type near-Earth asteroid). This was the first orbital operations around and landing on a small body and enabled other asteroid touchdown/lander mission concepts to go forward such as Hayabusa. NEAR planning followed the "faster, better, cheaper" concept. NEAR lessons learned include:

- Short timelines motivated an achievable 36-month "start to launch" schedule.
- Small, experienced technical teams with complete mission authority are efficient and capable of accomplishing the mission objective.
- Spacecraft and instruments can be successfully designed to cost and schedule.
- It is beneficial to assign a lead engineer to each subsystem.
- It is important to incorporate reliability and redundancy into the design.
- It was beneficial to have the Reliability and Quality Assurance engineer report directly to project manager.
- Having a single agency manager interface with the contractor was a key to success.
- Utilizing the internet for internal and external project communications and outreach was efficient and effective.
- The unplanned Eros flyby allowed for mission operations refinement during the subsequent mission rendezvous at Eros.

**B. Deep Impact (NASA Mission):**
Deep Impact was designed to study the composition of the interior of the Tempel 1 comet by releasing an impactor into the comet. Deep Impact lessons learned include:

- A precursor mission to the specific initial target body was a must for mission confidence and safety.
    - Tempel 1 looked differently, reacted to impact differently, and the material was much finer than was planned for.
- There must be a well-established and exercised process for handling the unexpected and adapting the plan dynamically during the mission.

**C. Hayabusa (JAXA Mission):**
Hayabusa was an unmanned spacecraft developed to return a sample of material from a small near-Earth asteroid (Itokawa) to Earth for further analysis. Hayabusa lessons learned include:

| Technology | Status | Counter Measures |
|---|---|---|
| Altitude Control | 1st loss of three Reaction Wheels (RWs) | Established 3-axis attitude control with two RWs |
| | 2nd loss of three Reaction Wheels | Established 3-axis attitude control by short pulse operation of 2-prop thrusters |
| | Loss of 2-prop thrusters | Established 3-axis attitude control by a RW and Ion Engines |
| Trajectory Correction Maneuvers | Loss of 2-prop thrusters | Substitution of Ion Engines |

*Table 1: Hayabusa Lessons Learned*

**D. Cassini–Huygens, Rosetta, Don Quijote (ESA Missions):**
On its way to Saturn, Cassini–Huygens crossed the Asteroid Belt and took pictures of asteroid 2685 Masursky, which revealed that the side of Masursky is roughly 15 to 20 km across.

Rosetta is a robotic spacecraft mission intended to study the comet 67P/Churyumov-Gerasimenko. On its way to Churyumov-Gerasimenko, Rosetta flew by asteroids Steins and Lutetia and transmitted images.

The primary purpose of the Don Quijote mission is to impact a target near-Earth asteroid and be able to determine the deflection resulting from the impact. This mission has not yet flown.

Lessons learned from Cassini–Huygens, Rosetta and Don Quijote that were proposed as ideas for human missions include:

- A minimum stay on the asteroid should be guaranteed to allow for a useful scientific return
- The trajectory should allow for a safe way to rapidly return to Earth in case of problems, up to half way to the target asteroid.

# 4.0 Breakout Sessions - Day One: Objectives of a Human Mission to a NEO

Participants offered more than 300 ideas during the breakout sessions on Day One. Each breakout group used the same framework and process for capturing ideas on the objectives of a human mission to a NEO and the activities needed to accomplish the objective. Each group brainstormed on these topics and recorded their ideas among three themes – Science, Planetary Defense, and Demonstration of Deep Space Capabilities.

All input was captured and breakout session leaders presented a summary of the input to all Explore NOW participants. The workshop leadership conducted a further assessment of each of the groups' presentations, received subject matter expert reviews of the consolidated ideas (raw data) provided on each theme, and conducted an assessment across each of the experts' assessments of each theme. These assessments culminated in the primary objectives a human NEO mission and the activities needed to achieve them; the objectives were presented to workshop participants at the beginning of Day 2 and are identified below.

1. Characterize NEOs
    a. NEO population in terms of location and number
    b. Physical and chemical properties
    c. Asteroid mineralogy, material science, and utilization
    d. Sample collection
    e. Human interaction and exploration
2. Demonstrate deep space capabilities
    a. Systems – radiation/hazards shielding, closed-loop environmental control and life support system (ECLSS), power, in situ resource utilization (ISRU), communications
    b. Operations – autonomous operations, in-flight training
    c. Human Research – physiological, radiation, psychological
3. Mitigate threat of NEOs to planet Earth

Several important goals would be met by achieving these objectives, including:

- Answering questions on the history and evolution of the solar system
- Enabling human exploration of interplanetary space en route to Mars and beyond; and
- Improving the quality of life on Earth through improvements in human health (radiation protection, combat osteoporosis, telemedicine), technological advancements, and protection from devastating impacts from space.

The need and interest for characterizing NEOs was shared among human spaceflight, science, and planetary defense communities. The synergies are depicted in Figure 3.

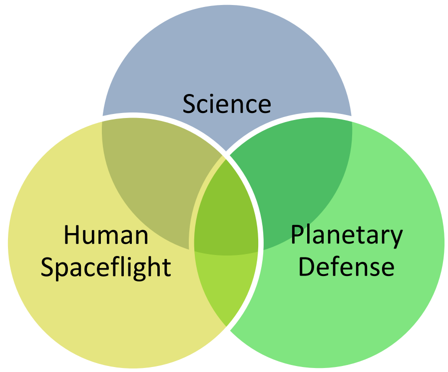


**Figure 3. Synergies among mission objectives**

The primary activities identified as being necessary to support achievement of these objectives may be summarized as follows:

1. Collection, examination and handling of samples
2. Testing hardware and software systems
3. Deploying scientific instruments
4. Testing NEO deflection techniques

The desired target NEOs for human exploration were those characterized as water-rich, slow rotating, heterogeneous, rubble-pile, and a potential Earth impact hazard. Identifying and selecting the target NEO was a challenge cited by all of the breakout groups. Participants agreed that more information about potential targets is needed in order to be able to make an informed selection on the target NEO for human exploration. Additional in-depth discussion and assessment is needed to correlate the target characteristics with the specific mission objectives.

## 4.1 In-depth Review of Objectives

For each of the primary objectives identified above, additional discrete objectives and activities are identified below.

### 1. Characterize NEOs

NEOs are a dynamically transient population and represent ancient materials from the earliest stages of solar system formation. A human mission would provide the ability to select scientifically interesting locations to study and address specific science questions. As such, there were ample discussions about characterizing the NEO surface, its internal structure, and its physical and chemical properties. This information is necessary to design the appropriate tools and/or instruments to be used or emplaced at a NEO for scientific research. Inherent to NEO surface characterization is the study of its mineralogy, material science and its prospects for potential utilization.

Another objective of significant interest to the science community was acquiring, screening, and returning multiple samples of NEOs to Earth.

Discrete science characterization objectives included studying the physical and chemical properties of the NEO population; studying the NEO's mineralogy, material science; and sample collection. Workshop participants also identified specific activities to accomplish each of these discrete objectives, as follows:

**Physical and Chemical Properties of the NEO Population**

- Measure characteristics of asteroid surfaces under different lighting conditions
- Investigate astro-biological implications for the evolution of life on Earth
- Emplace observation instruments and/or telescopes
- Study NEO internal structures/porosities
- Investigate surface, near-surface characteristics, and dust

**Asteroid Mineralogy, Material Science and Utilization**

- Learn about deep space materials and elements
- Learn how to manipulate asteroid materials on a human scale in order to mine it for use in space exploration
- Understand NEO mineralogy/composition with respect to meteorite analogs

**Sample Collection**

- Conduct on-site collection of high value samples
- Study regolith properties (e.g., fine particulates, rubbles, pebbles) and particulate structure
- Identify and characterize surface alteration/evolution

Characterizing the NEO population is also critical to informing and identifying potential NEO threats. A human mission with the objective of characterizing a NEO not only provides physical and geophysical information of great interest to the science community but also better postures NASA and its partners to mitigate threats to planet Earth. Specifically, a human mission could explore the NEO internal structure, analyzing composition (e.g., monolithic vs. rubble pile); characterize surface thermal and electrical properties; measure bulk physical properties (e.g., mass, shape, density, porosity, spin, strength); characterize surface mechanical properties (e.g., momentum multiplier for kinetic impact, attachment methods for slow push techniques); and determine factors affecting the gravity field of a NEO, which are all key activities for planetary defense.

**Human Interaction and In-Situ Resources**

NEOs have a microgravity environment, which makes it difficult to remain firmly on the surface of the object. Their internal structure also varies from monolithic to a loosely bound rubble pile. Because of these and other characteristics, mobility on the surface of a NEO will be challenging. The appropriate technique for human systems to attach (i.e., anchoring, netting, etc.) will depend on the characteristics of the target NEO. Additionally, characterizing NEOs is an essential element of qualifying and enabling ISRU and exploitation of NEO resources. Depending on its composition, a NEO could be used as an in-space source for propellant or for raw materials for manufacturing or mass shielding.

## 2. Demonstrate Deep-Space Capabilities

More than 150 human mission objectives pertained to the demonstration of capabilities for deep-space exploration. The objectives can be grouped into three primary areas: 1) system capabilities, 2) operations capabilities, and 3) human health capabilities. Demonstrating reliable and capable systems for human exploration in deep space is essential. The capabilities to land or attach, stabilize, and conduct work at a NEO will need to be demonstrated. Human missions to a NEO also require capable and reliable systems, approaches and technologies to maintain good crew health.

The groups identified multiple discrete objectives and activities under each primary objective:

**Systems**

- Develop the reliable systems necessary for deep-space travel
- Develop and test architectures, operations, and systems for deep-space missions
- Demonstrate long-term, autonomous crew operations
- Demonstrate deep space human spaceflight capabilities
- Develop optimized human and robotic systems for exploration of the solar system

**Operations**

- Investigate the resource potential of NEO materials that may enable future robotic and human exploration
- Demonstrate astronaut-led decision-making to conduct close proximity operations
- Demonstrate anchoring techniques to firmly attach to a NEO and learn how to maneuver on the surface
- Demonstrate proximity operations and landing
- Demonstrate real-time landing site selection
- Develop, study and demonstrate concurrent human/robotic operations
- Demonstrate resource ore extraction and processing
- Potentially establish an ISRU propellant factory
- Conduct operations on an airless surface in near free-fall

**Human Health/Research**

- Develop and test regenerative life support for long-duration missions without resupply
- Understand human factors on long-duration missions
- Assess human capabilities to tolerate radiation exposure, isolation and confinement, and bone and muscle loss

## 3. Mitigate the Threat to Planet Earth

Participants provided more than 100 human mission objectives that were characterized as mitigating threats to planet Earth (planetary defense). The primary goals for planetary defense are to assess potential threats early, identify mitigation options and demonstrate capabilities for a future deflection. Sample return and precise orbit determinations were also key objectives for a human mission to a NEO for hazard mitigation.

Human crews have a substantial role to play in planetary defense preparations, apart from the actual deflection operations (which will likely be done robotically). Specific activities for such objectives include:

- Test deflection methods (e.g., gravity tractor, kinetic impact, other slow push/pull techniques);
- Test mobility techniques that could be employed by future deflection missions;

- Emplace scientific packages to sound NEO interior or observing deflection demonstrations;
- Develop and mature techniques and technologies for anchoring and emplacing surface instrumentation and systems;
- Test effective and safe proximity operations and anchoring techniques;
- Demonstrate the ability to conduct complex operations at a NEO;
- Conduct surface geological and civil engineering studies of NEO surface and internal structure and setting charges for active seismometry;
- Assess in-situ resources for potential use with deflection technologies;
- Emplace navigation transponders for accurate orbit determination in the future;
- Collect a specific array of NEO samples to support deflection engineering; and
- Observe the effects of lasers and solar concentrators on surface materials.

Some of these activities were also identified in the objectives discussions for “Characterization of NEOs” and “Demonstration of Deep Space Capabilities,” yet another indication of obvious synergies among the primary objectives. Further, a human mission with the objective of mitigating a threat to planet Earth provides information of great interest to the science and human spaceflight communities, while advancing the state-of-the-art planetary defense techniques.

The objectives of a human mission to a NEO and the activities needed to achieve those objectives that were captured on Day One served as the point of departure for the breakout sessions the following day.

# 5.0 Explore NOW Breakout Sessions – Day Two

On Day Two, participants engaged in concurrent breakout sessions focusing on specific topics that would drive more detailed objectives and activities for human missions to NEOs. The six topics were: 1) Precursor Investigations, 2) Technologies, 3) Concept of Operations, 4) Objectives and Capabilities for Planetary Defense, 5) Moon/Mars Synergies, 6) Policy and Public Engagement.

*Breakout session topic leads and facilitators discuss their findings on Day Two.*

## 5.1 Precursor Investigations (Two Breakout Groups)

The two Precursor Investigations breakout groups focused on identifying critical information that NASA and its partners need to know before sending a human to a NEO. This information is critical for planning the robotic precursor missions to NEOs. Participants focused specifically on precursor activities required to enable human missions, not activities that have utility primarily from a scientific viewpoint, nor astronaut activities at the NEO.

Discussions touched upon a threshold question of the minimum amount of information required prior to sending humans to a NEO. Participants agreed that knowledge gained from robotic precursor missions increases the probability of meeting all of the objectives of a human mission. There were concerns that the current filter set being used to identify the potential targets out of the cataloged NEO population are not the appropriate set of filters. As a follow up action, NASA is studying all of the identified NEOs as of September 1, 2010, catalogued in the JPL Small Body Database, and comparing their physical characteristics and orbital dynamics to the objectives for a human mission to assess the quantity of known candidate NEOs.

Targets were identified as important in both quantity and in access frequency. Depending on the viable target environment and perhaps the operations concepts for a human mission to a NEO, more efforts may be required to survey the target population. Participants agreed that a combination of ground- and spaced-based measurements would be the ideal methodology to identify and enhance the potential target population, and that supplemental use of ground telescopes would be an important factor in further characterizing targets once they were identified.

A summary of the major knowledge gaps and subsequent measurements required to fill those gaps is located in Table 2 and Table 3.

| Knowledge Gap | Potential Measurement Techniques | Desired Information | Criticality |
|---|---|---|---|
| Unknown distribution and Availability of targets | • IR telescope survey<br>• Ground Based<br>• Telescopes | • Size<br>• Spin/rotation rate<br>• Spectral type<br>• Shape<br>• Debris environment<br>• Rotation axis<br>• Brightness<br>• Pole orientation<br>• Accurate orbit info | Critical |
| Relationship between spectral type and chemistry/structure | • Surface based measurements | Needed if precursors do not go to exact NEO humans will explore | Critical |
| Gravity field | Note: There was debate on whether this information was truly needed. Thought by some to be negligible. | | |

*Table 2. Target selection*

<table>
<tr><th>Knowledge Gap</th><th>Potential Measurement Techniques</th><th>Desired Information</th><th>Criticality</th></tr>
<tr><td>Regolith properties</td><td rowspan="2">• Radar imaging<br>• High resolution imagery<br>• Mineralogy (XPS, GRS)<br>• Langmuir probe<br>• Light meter probe<br>• Thermal imager<br>• Geo-tech measurements<br>• Mossbauer spec<br>• Contact probes<br>• Impact tests<br>• Drilling tests<br>• Sample collection</td><td>• Penetration resistance<br>• Particle size distribution<br>• Composition<br>• Electric properties<br>• Magnetic properties<br>• Toxicity<br>• Chemistry</td><td rowspan="2">Criticality of specific information<br>Is dependent on main objectives of human tasks at the asteroid. Most focused on understanding human interaction with body, hazards, dust behavior.</td></tr>
<tr><td>Surface/sub-surface structural properties</td><td>• Morphology<br>• Shear strength<br>• Stability<br>• Porosity<br>• Cohesion<br>• Temperature<br>• Density</td></tr>
</table>

*Table 3. NEO characteristics*

**In-Depth Discussion of Results**

Participants agreed that precursor Investigations will need to fill knowledge gaps on NEO target selection and characterization. Engineers and mission planners for future human missions to NEOs would rely heavily on the critical data returned from precursor investigations to inform selection of instruments, tools, and the concepts of operations for human interaction with the surface.

A key observation was that regardless of the specific objectives for the human mission at or on a NEO, the same detailed knowledge of the NEO target characteristics is desired from precursor missions.

**Target Selection:**
Target identification and selection were very important to participants. Many were interested in the concept of an IR telescopic survey mission to continue to identify potential targets. Participants suggested conducting robotic missions after several targets were selected, to obtain detailed surveys of the topography and NEO environment. Other activities discussed were radar imaging, LIDAR surveys and photography in order to map the terrain, understand the size and shape of the NEO and determine spin and the gravity field.

Participants agreed that Earth-based measurements are also needed in order to complement the measurements being taken by an orbiting precursor spacecraft. While there are several telescopes on Earth that can take useful measurements – such as recording spin – to help characterize NEOs of interest, the telescopes would need to be programmed with that as a priority. The various objectives for human missions may also determine the types of targets that would be of interest. For example, potentially hazardous NEOs would be of interest for achieving planetary defense objectives, whereas NEOs that are water-rich will be of interest for fulfilling scientific and resource utilization objectives.

The primary objectives for the human missions would also determine the types of targets that would be of interest. For planetary defense, for example, all types of NEOs would be of interest, while other classes of NEOs would be a higher priority for resource utilization or science purposes.

**NEO Characterization:**
There was significant discussion on characterizing the surface and structural properties of the NEO. Surface and structural data would help inform the options for how humans would interact with the NEO, as well as how to build the tools and other instruments that could be left on the surface to support future science returns.

The surface of the NEO was of primary interest, particularly, the type of regolith present, the particle size and distribution, depth, variation in surface properties and toxicity. Understanding the characteristics of the dust and loose rocks after they are disturbed is also critically important. For example, once the dust and rocks are disturbed, how long does it take to return to their initial states? Do they return to their initial quiescent states or do they become a debris field for the duration of the visit? Does the disturbed material attach itself to the spacecraft?

Participants identified several types of characterization measurements, including radar imaging, mineralogy and neutron spectroscopy, Langmuir probe measurements, APXS, Mossbauer spectroscopy, and imaging - gamma ray broad spectrum, thermal, IR, and photometry.

The fundamental structure of the asteroid was of interest from the viewpoint of its cohesiveness. It is important to know if the object is a loose agglomeration of particles or whether it is exists as one coherent entity. In order to have an idea of what kind of drills and other depth gauging equipment to design, a precursor mission that experiments across many different methods of interaction with the subsurface should be considered. Impact via blunt instrument, harpoon like projectiles or augers of different material and construction are useful trials for a precursor to conduct in order to inform the design for a more sophisticated set of tools for utilization during the human mission. In addition, the results of such precursor experiments would help inform the operational concepts for EVA type activities, including anchoring science equipment.

Participants agreed that the objectives of a human mission would determine the necessity of a precursor mission for sample return and ISRU demonstrations. If the objectives include eventually using the NEO resources for economic purposes, conducting an ISRU precursor investigation prior to a human mission would be a means to verify the target selection. For purposes of planetary defense, an ISRU investigation could assist in characterizing the NEO in ways that would enable more optimally designed human mission tasks. It was noted that there were no lunar samples collected before humans landed on the moon.

## 5.2 Capabilities and Technologies

This breakout session focused on identifying the capabilities and/or technologies that would be needed for a human mission to a NEO. The desired outcomes for this session were to identify:

1. The capability gaps that would preclude full achievement of objectives for a human mission to the NEO during the on-site portion of the mission;
2. The capability gaps, in order of necessity, to be closed prior to mission start; and
3. The technology development options that could close the top 5-10 capability gaps.

While multiple capability challenges exist for other phases of the mission, the scope of this workshop focused on the ‘at/on the NEO’ mission phase. Capabilities solely related to planetary defense were not considered by this breakout group, but addressed by a different breakout group.

During the weeks prior to the workshop, members of this breakout group were asked to address the question: “Which potential activities or functions during the on-site portion of a human NEO mission present the greatest technical challenges?” The responses included the following inputs:

- Deep coring to determine internal structure
- Life support and mobility systems that do not contaminate the measurements
- Suit lock and compatible EVA suit
- Anchoring/tethering (for mobility & sampling)
- Megawatt solar electric propulsion (SEP) systems for reusable long-lived in-space systems
- Safe, efficient proximity operations with non-uniform gravity field, rotating body, dust and satellites, lighting conditions
- Operating safely without ground operations in the decision/control loop

Using this input and the nature of the objectives and activities identified during the first day of the workshop, the breakout session lead pre-identified possible categories for capability gap themes, which the participants subsequently accepted:

- Proximity Operations – proximity operations for surface and subsurface access to cover the challenges associated with station keeping (i.e., hovering in the vicinity of the object), approaching and safely interacting with the NEO surface
- Characterization – target characterization covering the desired measurements of the surface and subsurface properties and the internal structure, plus sample acquisition and handling
- Autonomy– mission system autonomy and robustness required for deep-space missions far from earth, with little or no possibility for support, service or logistics delivery from ground operations
- Human Systems – covering all life support systems and challenges for human health and performance with little or no possibility for support, service or logistics delivery from ground, and no possibility of rapid return to Earth for medical services

A total of 108 individual technology or capability gaps were identified, including some duplicates. The discussion and results indicated that all categories contained important capability gaps. Some crosscutting themes that emerged were reliability, autonomy, and smart systems.

After removing duplicates, participants individually ranked the gaps according to the importance of closing them prior to mission start. They also brainstormed on technology development options for the capability gaps that received the highest sum of individual scores. The process revealed eight capability gaps and associated technology development options, which are organized by gap theme and presented in tables 6-9, below. Due to insufficient time, the technology development options were not assessed or ranked, but merely recorded.

## Proximity Operations:

Participants identified key proximity challenges relevant to the unknown environment, including the physical environment (spanning possible rubble piles to monolithic rocks); non-uniform gravity field; dust electrostatic properties; and lighting. Astronaut safety was deemed particularly challenging under these unpredictable conditions. The group identified specific proximity capability gaps focused on astronaut access to the surface and the control of the spacecraft to keep it at a safe standoff distance. Technology development options identified for each of the proximity capability gaps include:

**EVA/robotics operations & anchoring**

- Teleoperating robotics on site
- Jetpacks to maneuver astronauts to the surface
- Free-flying lighting & cameras to provide situational awareness
- Anchoring/tethering to the surface for surface access
- Suit/robot information systems for smart maneuvering
- Dust mitigation to deal with dust raised by surface activities
- Surface access vehicle with suitlock for rapid egress/ingress
- EVA tools to effectively interact with the surface

**Situational awareness, station keeping & rendezvous**

- Fuel-efficient proximity operations propulsion for station keeping
- Position determination of the spacecraft relative to the object
- Real-time trajectory control relative to the object
- Plume impingement and resulting effects on the target
- Information systems & modeling for terrain relative navigation
- Lidar, radar or other sensors for dynamic measurements of the distance to the surface

## Characterization:

Participants identified key characterization challenges relevant to subsurface and interior structure determination, and on-site analysis of samples for high-grading and selecting samples to be returned to Earth. Participants recognized that the exploration, science and planetary defense objectives of a mission to a NEO greatly depend on the ability to take the necessary on-site measurements. Technology development options identified for each of the characterization capability gaps include:

**Sampling and prospecting**

- Subsurface sample acquisition especially when it is important to retain the subsurface stratigraphy
- Preserving volatiles both during sample acquisition and for transport back to Earth

- Intelligent sample selection to ensure that samples are collected/extracted from the most interesting locations and with representative composition
- Sample encapsulation for the return trip to Earth
- Plume/ejecta creation and collection as a means of sampling
- Drilling/coring tools to access subsurface samples, especially for retaining information on stratigraphy
- Sensors for subsurface characterization to determine the interior structure of the target body
- Anchoring of instruments that require emplacement on the surface or subsurface, and/or strong physical contact with the underlying solid body

**On-board science**

- On-board laboratory for on-site high-grading of samples
- Miniature instruments providing definitive sample assessment at low mass and power
- High-bandwidth communications to return all the needed measurement information to allow ground assistance in the selection of samples
- Expert systems to assist on-site sample assessment and selection
- Clean containment to avoid contamination of samples to be measured on site or returned to Earth

### Autonomy:

The capability gaps identified in this theme apply not only to performance functions during the first human mission to a NEO mission, but also to human missions to even more remote, deep-space destinations. Participants agreed that autonomy and reliability are key mission system attributes. Given the remoteness and mission duration, human missions to NEOs and other deep space destinations also require adoption of advanced logistics and sparing approaches. To operate without ground support, both autonomy and reliability are critical. Without logistics support from ground operations, a new approach to logistics and sparing, as well as a robust response to the inevitable faults will be necessary. Technology options identified for each of the autonomy capability gaps include:

**System autonomy, automated planning and mission operations**

- Reconfigurable/adaptable systems to provide mission flexibility and robustness
- Artificial intelligence for system adaptability
- On-board mission planning to respond to new and unpredictable conditions
- Diagnostics for repair to provide on-board situational awareness of system state
- Just-in-time training to develop astronaut skills adapted to the new environment

**System reliability and repair capabilities**

- Fault detection, isolation, & recovery (FDIR) to respond to and correct the inevitable system faults not supported by ground-in-the-loop time scales
- Common components to reduce the number of spare parts that must be brought along
- Design for sustainability to provide new approaches for robustness
- Self repair to support on-board repair in the absence of ground support
- Test programs for reliability to ensure that on-board systems are as reliable as planned and needed
- Spare part manufacturing on demand to provide replacement parts in the absence of a logistics train from distant Earth

- Functional and dissimilar redundancy to reduce the mass and volume of spare parts that must be transported on board

### Human Systems:

Participants recognized that the capability gaps identified in this theme are some of the most challenging. While relatively “rad-hard” hardware has been developed over the years, humans remain radiation-soft, creating significant challenges to protect this precious and vulnerable cargo. In addition, life support systems for near-Earth space systems are relatively massive, power hungry and represent a substantial portion of the mission logistics train – all of which must be changed as humans move into deep space activities. While NASA is currently addressing a number of these challenges, further challenges remain. Technology development options identified for each of the human systems capability gaps include:

**Radiation protection and warning**

- Detection and warning systems to allow adequate preparation and protection of crew
- Predictive models to allow adequate time for these preparations
- Pharmaceutical countermeasures to counteract the unavoidable radiation exposure
- Personnel dosimetry to assess individual exposure
- Habitat design to provide radiation protection for the astronauts
- Shield vehicle with NEO, especially as an approach to block solar event radiation exposure
- Radiation hard systems to ensure that life support systems continue to operate properly after radiation exposure

**High reliability life support**

- Miniaturization / low consumable footprint to reduce the overall mass and power of the life support systems
- System closure (air & water) to reduce the amount of makeup air and water required for long-duration deep space missions

## 5.3 Concept of Operations

This breakout session focused on the concepts of operations for a human mission to a NEO. Operations concepts are inherently structured around mission phases, so the group chose to use a small set of human NEO mission phases to focus its work: LEO preparation, outbound transit to NEO, NEO operations, and Earth return transit. The brainstorming sessions focused first on the mission phase of operations at the asteroid. The operational concepts identified during this phase were used to derive the concept of operations during the other phases. The following sections depict the high-level concept of operations during the different phases.

*The Concepts of Operations participants discuss EVA operations on a NEO.*

### Low Earth Orbit (LEO) Preparation

Concept of operations participants assumed that the human NEO mission began from LEO utilizing elements that were integrated in space. They did not make assumptions regarding launch vehicle type or capacity, orbital assembly node location, or assembly operations. It was agreed that the NEO mission would involve a single integrated vehicle departing from LEO with all propulsion, crew accommodations, exploration systems, and Earth return systems to complete a 6-12 month, round-trip NEO mission. No assumptions were made regarding propulsion or life support technologies, vehicle size or volume. An example configuration that was identified included:

1. Core module - including environmental controls and life support systems (ECLSS), power, logistics storage, medical facilities, science laboratory, etc.
2. Two Space Exploration Vehicles (SEVs) (defined as a two-person, free-flying vehicle with good visibility for close operations with the NEO, rendezvous and docking / anchoring systems, extra-vehicular activity (EVA) systems (suits and suitport for easy and quick access to the NEO), living quarters, and robotic arms for sample manipulation and collection
3. Propulsion stages for in-space transportation to and from the NEO
4. One or two small Earth return vehicles
5. A small advanced reconnaissance probe
6. A crew of 3-4 astronauts

### Outbound Transit to NEO

The group discussed the relative length of the outbound and inbound transit legs and suggested biasing the shorter duration leg to the Earth return segment of the mission, thus having an extended outbound leg. The crew would spend the nominal six-month outbound trip performing microgravity experiments, monitoring the space environment to measure interplanetary radiation levels and solar radiation events, monitoring spacecraft system performance, conducting in-flight training for NEO operations, and monitoring their physiological and psychological health.

The concept for deployment of a small advanced reconnaissance probe was also discussed and identified as a possible enabler for the mission. While the primary characterization of the target NEO would be accomplished by the robotic precursor mission, participants recognized that narrow launch windows or other launch or mission issues may necessitate travel to a backup target. In such a case the crew could deploy an advanced reconnaissance probe on an accelerated transportation system. The probe would arrive at the newly targeted NEO relay identification and characterization information back to the crew. This information would then be used for mission planning and training simulations and operations.

### Operations at NEOs

Arrival of the crew at the target NEO signals the most operational intensive segment of the human NEO mission. Following a multi-month transit, the crew will spend only 14 days in the vicinity of the target before beginning the return transit to Earth. The two-week time period is dictated by the increasing amounts of propulsive energy required to return to Earth as the NEO stay-time is increased. The operations at the NEO are segmented into four categories for discussion, although many of the operations apply to multiple categories: Human Spacecraft, EVA, Science, and Robotics.

### Human Spacecraft Operations

A significant segment of the crew's time will be spent operating the spacecraft. The spacecraft elements include propulsive stages that decelerate the "stack" in order to co-orbit the NEO; a propulsive stage to accelerate the crew back toward Earth; one or two Earth entry capsules for direct return into Earth's atmosphere; and a "core module" that will provide crew habitation and other essential spacecraft systems for the mission. The stack would also include two Space Exploration Vehicles (SEVs) that could allow astronauts to traverse the distance between the propulsion stage/mission module ("mother ship") and the NEO surface, and also provide manipulator and EVA capability. Small robotic vehicles would complete the complement of space vehicles. The crew would monitor the health and condition of all these spacecraft components as an essential part of their routine operations.

The crew would insert their integrated spacecraft into an orbit that matches the NEO, and station-keep at some distance from the NEO. At that location, the first task would be to perform far- and near-field surveys for validating robotic precursor and advanced reconnaissance probe information. This information would then be used for situational awareness, hazard characterization and resource assessments.

Once this information has been captured, the crew would navigate the SEV to the surface of the NEO. It would provide closer views of the NEO and then perform rendezvous and anchoring once the best location(s) was identified. If the anchoring system was unable to secure the vehicle, the backup operation would be for the vehicle to station keep and deploy the astronauts via EVA, as required. Once the activities at the NEO were complete, the SEV would then leave the vicinity of the NEO to rendezvous and dock with the mother ship.

### EVA Operations

An essential element of a human NEO mission is to allow talented scientists to have the closest proximity to the target, so EVA is a fundamental operation. Though there will be robotic assistance, the primary science operations will be accomplished by astronauts working in contact with the surface of the NEO. A minimum team of two astronauts will perform each EVA, and will be monitored by the Intra-Vehicle Activity (IVA) crew.

The EVA astronauts will use translation systems that allow them to be tethered to the asteroid or to a vehicle at all times. Concepts discussed include having the astronauts stand on one of the space exploration vehicle's robotic arms and have the arm position the astronaut in the optimum position to perform the required tasks, such as sample collection or instrument deployment. Another concept discussed was to have a grid of cables anchored to the NEO to which the astronauts could attach themselves and translate to the various locations around the NEO to perform their required tasks. A similar approach to the cable grid would be using just one line (similar to a clothes line) to aid the astronaut in the translation across the NEO surface.

### Science Operations

The predominant fraction of EVA time will be dedicated to surface science operations. This includes the emplacement of science packages, core sampling, deep drilling, and collection of bulk and selective samples. The EVA crew will also deploy technology experiments to assess the ISRU viability of the NEO, techniques to modify the NEOs orbital parameters, and emplace transponders or reflectors (i.e., tags) to the NEO to enhance future tracking. Other activities would include the deployment of seismic sensors to be used during and after the crew operations.

### NEO Robotic Operations

Robotic assets can be operated by IVA crewmembers or tele-robotically from Earth following the departure of the NEO crew. Robotic assistants to the EVA astronauts, including remote autonomous extravehicular robotic cameras (AERCAM) can allow the IVA crew to participate in EVA operations and monitor EVA activities. After science packages are emplaced, experiments for deep drilling and ISRU can be operated remotely. This will free the astronauts to perform other, more time critical tasks rather than hold a drill for several hours to extract the required core sample.

### Inbound Transit to Earth

The nominal three-month return to Earth begins with the Trans-Earth Injection burn and NEO departure. During the trans-Earth cruise, the crew will operate and monitor robotic devices left behind at the NEO (perhaps including one of the SEVs), and continue to monitor their vehicle systems. They may activate planetary defense experiments that were left behind to alter a NEO’s orbit by impulse, impact or gravity tractor (using a spent propulsion stage for the latter two). The crew will also perform life science research to monitor their physical and psychological states, radiation dose, and zero-g effects.

## 5.4 Planetary Defense

Based on the objectives of a human mission to a NEO, this breakout session focused on identifying the knowledge and capabilities needed for purposes of planetary defense. Though motivated differently, the planetary defense and science communities recognize significant synergy between the information needed in terms of identification and characterization of NEOs required to meet their objectives.

The objectives of planetary defense are to detect and verify hazardous NEO threats while the NEOs are as far away from Earth as possible, to move each impact hazard NEO to a non-threatening orbit, and to verify that the deflection attempts were successful – i.e., that the modified NEO orbits are no longer threatening. Participants cited many ways that human missions to NEOs would be advantageous in achieving planetary defense objectives. In particular, humans can improvise, synthesize, and adapt based on what they find when they arrive, conducting new experiments and gathering unanticipated data. Humans could also emplace and anchor sensors and disruptors in the most favorable locations.

To support planetary defense, a human mission to a NEO would have the following basic goals:

- Characterize properties of the NEO. Determine mass, density, and other physical properties of the target asteroid.
- Determine the effectiveness of different deflection techniques. Conduct experiments and take measurements that reduce uncertainties for planetary defense missions.
- Test various capabilities that relate to proposed techniques for moving a NEO. These include techniques for attaching thrusters, transponders, mass drivers, or other instruments or devices to the surface, as well as the ability of a spacecraft to operate autonomously in the vicinity of the object for an extended period.
- Verify remote characterization (i.e., learn ground truth) - compare actual properties with those predicted pre-mission to get "ground truth" and help to calibrate observational data on other objects.
- Simulate a multi-national planetary defense campaign. There is general recognition that an actual planetary defense effort would be multi-national. The human mission could be structured to simulate such a multi-national effort.
- Prototype activities related to planning, operation, and coordination of large deep space missions. This will increase confidence that such activities can be effectively accomplished for a large-scale planetary defense effort.
- Increase public buy-in for planetary defense mission: increase the public's awareness and understanding of NEOs, the nature of NEO impact threats to Earth, and how a defensive campaign might evolve.
- Involve international community: gain confidence and experience in the planning and implementation of large-scale international deep space operations.

Activities that support these goals include:

- Collecting and returning samples. Characterization will support both impulsive and some slow push deflection techniques.
- Conducting tests that relate directly to various deflection techniques, including terminal phase guidance and control; drilling to verify processes and tools; and obtain samples (useful for predicting the effectiveness of kinetic impact and surface and subsurface explosive techniques)

- Operate avatars to explore parts of the NEO to verify that sensors, tracking beacons, and other devices can be emplaced remotely.
- Implanting seismic sensors and stimulators to collect information on the internal structure of the object and possibly measure effects of post human mission mitigation experiments, such as detonating a sub-scale explosive device on and/or below the surface or impacting an object at high velocity.
- Measure and examine the NEO environment. A concern is that dust and material disturbed during the mission might collect on lenses and other surfaces and affect their short and long-term operation. Experiments will help measure these effects.
- Observe response to laser and other energy focusing techniques. Proposed deflection techniques include using lasers and focusing sunlight on the surface to heat and "boil off" surface material. Although the objective is to get material to leave the surface, some results might lower the effectiveness of these techniques. For instance, tests would determine whether the beam or spot must be moved periodically.

Participants also identified considerations relating to the selection of possible NEOs. The following ideas were identified.

- Conduct a thorough survey to get as complete a catalog as possible of target NEOs.
- Select target asteroids that are representative of those that present the most likely potential impact hazards (i.e. The more numerous smaller objects — objects less than ~500 meters in diameter).
- Develop a queue of accessible targets that are available over a course of several years to enable planning several primary and back-up missions in case of problems and schedule delays.
- Initially, choose targets with fairly simple characteristics (e.g., simple shapes, slow spin rates, no moon, etc.) to increase likelihood of mission success.
- Subsequently, choose a more challenging object (e.g. complex shapes, vaster spin rate, with moon(s)) for a follow-on mission. The type of object that will be the target for an actual deflection campaign is unknown, so the breadth of knowledge gained will help understand how properties vary.

The group recognized that solar electric propulsion (SEP) or other high-specific impulse propulsion techniques would enable greater pool of accessible objects for target selection.

**Why a human mission?**
From the planetary defense perspective, a human-led mission is advantageous because:

- Humans could make test equipment and experiments work and reduce risk of failure.
- As has been learned from the ISS and Hubble, humans can improvise, synthesize and adapt from data based on what they find when they get there and conduct new experiments and gather unanticipated data.
- A human mission would build confidence in our ability to mount a campaign of operations involving intercepting a NEO.
- Properly executed experiments could increase confidence in impact effects, such as the momentum multiplier for kinetic impacts.
- Humans could place and anchor sensors and disruptors in most favorable locations and develop characteristics for selection of best points for attachment and landing.
- Following the activities of a human crew would inspire sustained human interest during NEO missions - humans on Earth would follow the mission and would become more knowledgeable of asteroid characteristics and planetary defense issues.

- A human mission with international partners would facilitate and increase confidence in international collaboration and decision-making.

**Other Thoughts**

The search for and characterization of possible target NEOs are required for planetary defense, science, precursor and human missions. With these synergies, humans can provide information to help reduce uncertainties for planetary defense. In addition, the knowledge and experience gained would benefit all mankind for both purposes of planetary defense and solar system exploration.

Information on these missions would help the public become aware and knowledgeable about the steps being taken to develop a planetary defense tool kit and demonstrate the capability to move/deflect asteroids. Planetary defense might provide a principal rationale for a sustainable program—it is instantly recognizable as an important and continuing overall objective and the technologies developed to move a NEO could potentially be profitable.

## 5.5 Synergies with the Moon and Mars

The purpose of this breakout session was to identify possible synergies and overlaps between systems, capabilities, and objectives of human missions to a NEO, the moon and Mars. Understanding these synergies may help inform investment strategies and operations philosophies to benefit human exploration of multiple destinations.

Prior to the workshop, participants were provided access to the NASA's "Mars Design Reference Architecture" (DRA) 5.0 material and internationally developed summary report of the International Space Exploration Coordination Group "Reference Architecture for Human Lunar Exploration."

**Findings**

Participants started by listing some key synergies among human lunar missions and human NEO missions:

- EVA dust mitigation in both locations may be similar. The group felt that NEOs may actually prove to be a worse environment for dust due to the possibility of creating a 'cloud' of suspended dust particles when interacting with the NEO surface.
- Sample acquisition, storage and handling, sample in-situ analysis (triage) needs are likely to be very similar at both destinations.
- Tele-operation of robots with real time control by on-site astronauts is an important capability for both destinations.
- It is critical that crew time be devoted to achieving mission objectives rather than system maintenance tasks.
- Capabilities for accomplishing similar science tasks are likely to share many characteristics (e.g. search for volatiles, geology, plasma interactions, dust and surface charging, sample acquisition and handling capabilities and techniques).
- The operations model should be similar - rely heavily on mobile systems where astronauts can stay inside while moving about, get out at appropriate locations (EVA) and work, then get back in and go to another location, all in a very short span of time.
- Most of the technologies/capabilities required to support basic life, human health and comfort (ECLSS, thermal control, radiation shielding, etc.) are likely to be similar at both locations.

Participants also defined some important considerations in preparing for human Mars missions and human NEO missions:

- Dedicate more attention on the synergies in high-cost systems to enable the greatest return on investment.
- NEO missions are a critical opportunity for preparing for and demonstrating systems for use on future Mars missions, so this should drive a "design for Mars, use for NEO" approach.
- Strong, extensive international engagement in both Mars and NEO missions are needed, both from a science coordination standpoint and from a mission planning and execution standpoint.

At this point, some specific synergy opportunities for Mars and NEO missions were identified by mission phase, noting the importance of keeping the crew healthy and productive because of the long mission durations.

| Mission Phase | Potential Synergy Opportunity |
|---|---|
| Launch | Important to use similar systems for both NEO and Mars mission, such as Heavy Lift and/or propellant depots |
| Transit | 1) Transit Habitat (including power, life support, etc) are likely to be very similar. This area in particular represents an ISS demonstration opportunity.<br>2) Cargo/logistics storage capability<br>3) Advanced in-space propulsion and upper stage (EDS)<br>4) Launch window sensitive capabilities<br>5) Crew support/health risk management capabilities<br>6) Radiation monitoring and protection capabilities<br>7) Nuclear power could be used for NEO missions and may be necessary for Mars missions<br>8) Need for crew training capability |
| Surface Activity – Martian Moons and NEOs | 1) Surface access to Phobos/Deimos would be very similar to NEO missions<br>2) The science equipment for both missions would be similar<br>3) ISRU capabilities (if any) are likely to be similar<br>4) Operations concept similarities |
| Surface Activity – Mars and NEOs | 1) Instrument deployment, sampling<br>2) Autonomous operations |
| Surface Activity – Mars and Martian Moons | 1) Nuclear power<br>2) Tele-robotics<br>3) Autonomous operations (crew/Earth interactions)<br>1) 4) Communication/navigation/software |
| Earth Return | Crew re-entry techniques and capabilities |

*Table 4. Synergies by Mission Phase*

The team also examined synergies between lunar missions and NEO missions. Synergies were identified in the following areas: Keeping Humans Alive, Keeping Humans Productive, Autonomous Operations, Sampling and Human Training.

- **Keeping Humans Alive:** Radiation Shielding and Mitigation, Dust Mitigation, Vacuum, Life Support System (food, water, and oxygen), and Medical
- **Keeping Humans Productive:** Dust Mitigation, Robotic Tools, Ability to Sample, Mobility through the Environment, and Psychological Aspects
- **Autonomous Operations:** Earth/crew interactions
- **Sampling:** Sub Surface, Curation (of possible ices), Training, and Acquisition
- **Human Training:** Best possible samples for an unusual environment

Some key differences exist between NEO missions and Mars or moon missions.

- Keeping Humans Alive
  - Radiation shielding and mitigation is going to be different on the surface of Mars.
  - Dust mitigation at Mars will have some differences due to gravity, atmospheric effects, global dust storms and Martian dust may be potentially biologically hazardous.
  - Life Support Systems (food, water, and oxygen) at Mars may be able to use atmospheric ISRU and may require pre-positioning of resources.
  - Medical care at lunar outposts or for Mars missions may require longer duration and may need to cover a wider range of contingencies.
  - Abort profiles are different for all three missions and may require different mission hardware

- Keeping Humans Productive
  - Again, the differences in dust mitigation on Mars in particular (the interactions are different) may require more active dust protection techniques in systems
  - Robotic tools on Mars and the moon may wear and tear in different ways and the nature of the robotic systems in gravity environments make many elements different.
  - The ability of humans or robots to gather samples may be different in a gravity environment
  - Mobility through the environment will be different. It's more important on Mars or the moon than on NEO because the scale is different.

- Autonomous Operations
  - Since the moon is closer than most NEOs or Mars, it offers the opportunity for teleoperated systems when humans are not there or as a complement to human activities. These same systems either can't be used in the same way at a NEO or on Mars, or they must be automated

- Planetary Protection (on Mars in particular)
  - Highgrading (selection) of samples within their Martian context will be different
  - Both forward planetary protection and backward planetary protection measures will be much more stringent on Mars than at a NEO.

## 5.6 Policy and Public Engagement

This breakout session discussed two topics focusing on 1) policy considerations for a human mission to a NEO, and 2) ideas for engaging the public in this mission.

The President recently released the “National Space Policy of the United States.” Some of the principles from the policy include that the U.S. will explore space for peaceful purposes; will encourage the commercial space sector; is not in a space race; and will explore space in collaboration with international partners. With the objectives of a human mission to a NEO and these high level principles as the context, the participants discussed a variety of ideas.

Participants were particularly interested in identifying what could be done to ensure sustainability of long-term U.S. human spaceflight programs. The group recognized that science missions are driven by, and compelled to answer, clearly identified and communicated questions. There was common agreement that it would be of tremendous value to have similarly compelling objectives for human spaceflight that would transcend any mission along the flexible path into exploration of the solar system. Participants also discussed and supported Congressional draft language suggesting NASA should support a decadal study on human space exploration. Congress has repeatedly indicated they rely on decadal studies for science because it is an independent assessment with a well-considered list of priorities.

It was agreed that sustainability is dependent on gaining stakeholder support. This could be achieved by establishing a human spaceflight stakeholder community with interests associated with the specific driving objectives and questions defined in the decadal study. Participants believed that using this dual approach, the stakeholder community would be involved in the decision process regarding ‘how’ the question would be answered.

Participants also thought that current international agreements could limit the achievement of economic or commercial gains from planetary resources. Although international agreements state that no one nation can claim sovereignty, it remains a watch item on intent and potential limitations once a commercially viable resource is discovered.

Continuing with the policy discussions and focusing on planetary defense, participants recognized that the U.S. has not identified leadership responsibility for planetary defense or developed international plans for working together to protect Earth from NEOs.

Transitioning to the topic of engaging the public, there was agreement that the term “Near Earth Objects” or “NEOs” is not appealing or understandable to the general public. Given that the public is somewhat familiar with “asteroids,” communicating using “Near Earth Asteroids,” “NEAs” or simply “asteroids” would be advantageous.

NASA shared its definition of “participatory exploration” with participants. Five degrees of public engagement were defined – 1) information dissemination, 2) content interaction, 3) conversation, 4) contribution, and 5) collaboration. The most engaging means is collaboration and there is interest in developing more and better approaches in this area. One idea was to design an “open” mission control center (or other mission control like activities) so the public can experience what is going on during mission. Outreach groups could conduct contests and announce winners, i.e., participants who are admitted to the mission control center.

Outreach and communications discussions focused on both method and content. While the government can educate and inform, it may not lobby or market itself. Therefore, several participants suggested that NASA could leverage stakeholders who could communicate in ways NASA cannot. Additionally, there was a suggestion to shift NASA's messaging from promoting "study and you can become as astronaut," to "come with us and explore the universe." Participants also suggested that NASA should expand its focus to recognize there are many other opportunities at NASA than being an astronaut.

## 6.0 Conclusion

The workshop garnered a high level of interest and participation. Based on comments from workshop participants and the magnitude of participation from around the world, NASA achieved the following objectives to:

- Increase the collective awareness and knowledge of NEOs;
- Facilitate networking across the human spaceflight, science, and planetary defense communities;
- Communicate NASA's interest in human exploration of a NEO in the 2025 timeframe; and
- Collect external input on the objectives of a human NEO mission.

Capturing external input on the objectives for human mission to a NEO was of utmost importance to NASA. These objectives helped establish a basis from which to address several other key aspects of mission planning, specifically - the information needed prior to a human mission to a NEO; capabilities needed during a human mission; advances in planetary defense achievable from a human mission; and possible concepts of operations.

As a result of thoughtful discussions among experts and leaders, a plethora of questions, ideas, concepts and opportunities were identified. This input serves as fertile ground for additional study and analysis.

**Next Steps:**
Several areas of forward work include the following:

1. Address whether humans can go to a NEO that has not been visited by a robotic precursor.
2. Identify and prioritize knowledge needed before sending humans to a NEO. What is our tolerance for unknowns and what flexibility can we build into the mission?
3. Conduct a study of the database of known NEOs using various filters to evaluate the potential known target set for a human mission.
4. Develop a clear understanding of the wide range of assets available to help characterize NEOs across the international community and other government agencies.
5. Identify mission cadence and phasing. If the prime human spaceflight launch window is missed, is there a backup target? What types of intervals would be expected not only between the prime and backup opportunities but also between missions?
6. Conduct human space exploration architecture studies utilizing input from the workshop.
7. Identify NEO deflection techniques through which some or all elements could be tested by a human NEO mission.
8. Identify synergies in the science, planetary defense, and human spaceflight discrete NEO characterization objectives, requirements, and interests.
9. Review capabilities and technologies needed for a NEO mission against 1) existing capabilities, 2) those needed for moon and Mars, 3) those needed for science and/or planetary defense, and 4) those in development by others, both domestic and globally, for possible collaboration.
10. Conduct a workshop focused on participatory exploration utilizing input provided from this workshop.

NASA is using the valuable input from the workshop and its follow up actions to help formulate its programs, develop its human exploration framework, prioritize its technology investments, and advance collaborations within the agency and with the international community, industry, and other federal agencies. NASA is also incorporating the input from this workshop into the formulation of its concept maps on human exploration of the solar system. This internet-based interactive product is targeted for release to the public by the end of this calendar year.

# Appendix A: Breakout Sessions – Process and Framework

## A.1 Breakout Session Process Description

One of NASA's primary goals of the Explore NOW was to capture external input on a human mission to a NEO, to help inform the agency's program formulation, develop its human exploration framework, and advance collaborations within the agency and with the international community, industry, and other federal agencies.

As part of the registration process, the invited experts and leaders ranked the 6 breakout topics according to their ability to contribute and their interests. The topics were as follows:

1. What do we need to know before we can send a human to a NEO? (Precursor Investigations)
2. What technologies and/or capabilities are needed for a human mission to a NEO? (Technologies)
3. What are the concepts of operations for a human mission to a NEO? (Concept of Operations)
4. For purposes of planetary defense, what do we need to know about NEOs and what capabilities are needed? (Planetary Defense)
5. What are the synergies with a human mission to the moon and Mars? (Moon/Mars Synergies)
6. What policy considerations must be addressed? What are possible ways to engage the public? (Policy & Public Engagement)

With the goal of both respecting participant's choices and providing a balance of perspectives to each breakout session, each participant was assigned to a topic. All participants were assigned to either their highest ranked topic or second choice. There were a total of seven breakout groups with two groups addressing topic #1. Each breakout group included approximately 18-30 participants, a topic lead, two facilitators, and two content capturers. To enable greater participation among attendees, the breakout sessions were divided into two tables of ~9-15 participants addressing the same topic. The topic lead was responsible for setting the context and framework for the session, helping to integrate the ideas captured, and briefing it to workshop participants in the general session.

One to two weeks before the workshop, "homework" assignments were provided to participants to help them prepare for the workshop. The preparation material included reference documents and idea-stimulating questions for the specific breakout session in which they would be participating. Having the breakout sessions adequately planned and participants prepared was important to maximize the input that could be successfully captured in a short amount of time.

All participants were asked to provide input on the same topic on the first day. These inputs were the driving force and context for all breakout session discussions on the second day. The questions used in each breakout session to address the thematic topic question are provided below. This information was provided to participants in advance of the workshop for their preparations.

## A.2 Breakout Session Framework

### Day One – Tuesday, August 10: Input on Human Mission Objectives

**What are the objectives for a human mission to a NEO?**

- What are the specific objectives – perhaps in the areas of scientific research, planetary defense, deep space capabilities, others?
- What activities near/on a NEO are needed to meet the specific objectives identified?
- What are the characteristics of the target NEO to achieve these objectives? (Is it different or the same for the various objectives?)

### Day Two – Wednesday, August 11: Seven Concurrent Breakout Sessions on Six Topics

**Topic 1: Precursor Investigations: (Two Breakout Sessions)**

1. Based on the objectives and activities for a human mission to a NEO identified on Day One, identify the knowledge gaps that need to be filled prior to sending humans to a NEO(s).
2. What knowledge gaps apply to all NEOs? What knowledge gaps apply to a specific objective(s) or to specific locations?
3. What precursor measurements and investigations are needed to fill these knowledge gaps?
4. For each knowledge gap, what human objective/activity does it support?
5. Categorize knowledge gaps based on the following:
    a. Engineering boundary condition needed to develop the human spaceflight systems?
    b. A hazard identification to ensure astronaut and vehicle safety?
    c. A resource characterization to support exploration sustainability?
    d. Target selection - Discriminator for human spaceflight destinations
    e. Other
6. For each knowledge gap, how critical is it to the human spaceflight objective noted (i.e., critical, important, nice to have)?
7. **Bonus Question** (to be answered in session if time allows. 3x5 card submissions received either way): Assuming a human NEO mission in 2025 to engage in the objective of your choice, what TWO precursor missions would you launch to prepare?

***Pre-workshop idea stimulating questions:***

<u>Knowledge Gaps</u>

1. What are the environmental conditions we need to understand about a NEO before sending people there?
2. What potential hazards may we encounter that we would need to characterize before designing human spaceflight systems or before sending people?
3. What characteristics make a “good” NEO target compared to a “bad” NEO target for human exploration? For any human spaceflight objective, how would we choose the best target?
4. What resources would be of interest or use?
5. What NEO characteristics need to be known before a crewed vehicle should come into close proximity to potential targets? Before touching potential targets? Before manipulating potential targets?

Precursor measurements and investigations needed to fill these knowledge gaps

1. Is there more than one method of obtaining the needed knowledge?
2. Are some of these measurements attainable from ground observation, or is a precursor mission needed? Are there ways investigations could be coordinated across missions or ground assets?
3. Is there any time dependency to these measurements?
4. How long would such a measurement take? Could be done in a fly-by? A rendezvous? A touch down?
5. Would these measurements need to be separately repeated?
6. Does the measurement need to occur at the final destination NEO, or can a NEO type be characterized by similarity?

**Topic 2: Technologies and/or Capabilities**

***Pre-workshop Question:*** *Which potential activities or functions present the greatest technical challenges during the on-site portion of a human NEO mission?*

1. What currently unavailable capabilities are needed to safely and affordably achieve mission objectives during the on-site portion of a human NEO mission?
2. Please rank the capability gaps in terms of the necessity to close them prior to mission start.
3. What technology development options could close the key gaps?

**Topic 3: Concepts of Operations**

1. Given the objectives of a human mission to a NEO and the activities required to achieve them (Day One), how should the tasks be performed?
    - How should humans interact with the NEO? (directly, robotically, types of rendezvous and docking)
    - Mission operations (task authority/control, crew/science backroom relationship)
2. Given these operations, what resources/assets are needed to perform tasks?
    - Crew (e.g., size, and technical skills)
    - Sample collection tools (e.g., drills, anchors, tethers, survey instruments)
    - Robotic systems
    - Crew mobility system concepts

**Topic 4: Planetary Defense (PD)**

1. How might the mission add value for purposes of Planetary Defense?
2. What tasks might humans perform that would minimize uncertainties for a future PD effort?
3. What capabilities and tools are needed to perform these tasks?
4. What insights would human presence at a NEO bring to the PD mission arena?

**Topic 5: Synergies**

1. What synergies might exist in human activities or tasks between NEOs, the moon, and Mars?
2. What synergies might exist in systems used while at a NEO, the moon, and Mars?
3. What synergies might exist in observations or instruments used at a NEO, the moon, or Mars?
4. Do these synergies (or lack) suggest anything about the sequence that we visit each of the destinations?

**Topic 6: Policy & Participatory Exploration**

1. What steps can be taken to ensure policy stability for long periods of time?
2. What policy barriers/gaps exist for human NEO missions?
3. From a public engagement perspective, given the concept of operations, how do we best engage the public?

# Appendix B: Invitation Letter

National Aeronautics and Space Administration

Headquarters
Washington, DC 20546-0001

July 12, 2010

Reply to Attn of: Exploration Systems Mission Directorate

Dear Colleague:

On April 15, 2010, the President proposed sending crewed missions beyond the Earth-moon system and into deep space, including a human mission to an asteroid for the first time in history.

The National Aeronautics and Space Administration (NASA) will host an interactive workshop to identify objectives for exploration missions to Near-Earth Objects (NEOs). The Exploration of NEOs Objectives Workshop will be held August 10-11 at the Mayflower Renaissance Hotel in Washington, D.C., and will include a reception at the Meteorite Hall of the Smithsonian Institution's National Museum of Natural History.

The primary goals for the workshop are to increase the collective understanding of NEOs, communicate NASA's plans for a human mission to a NEO in the 2024-2026 timeframe, and receive community input on mission objectives. In support of these goals, we are inviting experts and key leaders from industry, academia, other government agencies, and the international community to participate and we hereby invite your participation in the workshop. With the collective breadth of expertise and experience represented by your input and participation, we anticipate robust workshop discussions that will lead to a well-informed set of initial objectives.

Although participation in the workshop is limited (invitation only and non-transferable), NASA TV will provide a live video stream of the event via the web for maximum public insight and engagement.

Please visit the following website to register and for other detailed information on the Exploration of NEOs Objectives Workshop:

https://www.nasaexplorenow.com/

I look forward to and appreciate your support and participation as we consider NEO exploration.

Sincerely,

Douglas R Cooke

Douglas R. Cooke
Associate Administrator
for Exploration Systems Mission Directorate

# Appendix C: Agenda

## Day One – August 10, 2010

| Time | Agenda Item | Speaker |
|---|---|---|
| 8:00-8:15 | Opening Remarks: Setting the Stage | D. Cooke |
| 8:15-8:35 | Why go to a NEO? | T. Jones |
| 8:35-8:50 | Opportunities for NEO Exploration | L. Johnson |
| 8:50-9:05 | Considerations for Planetary Defense | B. Ailor |
| 9:05-9:25 | Update on Exploration Study Teams | M. Hecker |
| 9:25-9:45 | Exploration Precursor Robotic Mission (xPRM) Study Team Update | J. Jenkins |
| **9:45-10:15** | **Break** | |
| 10:15-10:30 | **Innovative Concepts for NEO Exploration** | B. Wilcox |
| 10:30-10:45 | Using the Moon to Facilitate Exploration of NEOs | C. Neal |
| 10:45-11:00 | International Framework for Human Space Exploration | K. Laurini |
| 11:00-11:15 | Hayabusa Mission Update | H. Kuninaka |
| **11:15-12:15** | **Lunch** | |
| 12:15-13:15 | Panel Session: Lessons Learned for NEO Missions | P. Abell (Facilitator) |
| | NEAR | A. Cheng |
| | Deep Impact | L. Johnson |
| | Hayabusa | H. Kuninaka |
| | Don Quijote/Marco Polo/Rosetta | M. Coradini |
| 13:15-13:30 | Discussion | |
| 13:30-14:00 | Panel Session: Objectives of Human Mission to NEO | L. Leshin (Facilitator) |
| | Administration Policy/Technology Perspective | D. Wells |
| | Planetary Defense Perspective | P. Garretson |
| | Science Perspective | F. Vilas |
| 14:00-14:15 | Discussion | |
| **14:15-14:30** | **Adjourn into Breakout Sessions** | |
| 14:30-16:00 | Breakout Sessions – Input on Objectives of Human Mission to NEO | *No Web Stream* |
| **16:00-16:15** | **Return to Plenary Session** | |
| 16:15-17:30 | Session Outbriefs (10 min each) | |
| 18:30-20:30 | Reception at the Smithsonian Institution's National Museum of Natural History | |

## Day Two – August 11, 2010

| Time | Agenda Item | Speaker |
|---|---|---|
| 8:00-8:15 | Recap of Day 1 and Looking Ahead | M. Broadwell |
| 8:15-8:30 | Public Participation in the Exploration of NEOs | B. Betts |
| **8:30-8:45** | **Adjourn to Breakout Sessions** | |
| 8:45-10:45<br>*No Web Stream* | Concurrent Breakout Sessions - In the context of the objectives for a human mission to a NEO, address the following:<br>1. What do we need to know before we can send a human to a NEO (i.e. characterization, knowledge gaps, and precursor investigations)?<br>2. What technologies and/or capabilities are needed for a human mission to a NEO?<br>3. What are the concepts of operations for a human mission to a NEO?<br>4. For purposes of planetary defense, what do we need to know about NEOs and what capabilities are needed?<br>5. What are the synergies with a human mission to the moon and Mars?<br>6. What policy considerations must be addressed? What are possible ways to engage the public? | |
| **10:45-11:00** | **Break** | |
| 11:00-12:00 | Outbrief (15 min) and Audience Input (15 min) | Topics 1-2 |
| **12:00-13:00** | **Lunch** | |
| 13:00-14:30 | Outbrief (15 min) and Audience Input (15 min) | Topics 3-5 |
| **14:30-15:00** | **Break** | |
| 15:00-16:00 | Outbrief (15 min) and Audience Input (15 min) | Topics 6-7 |
| 16:00-16:30 | Closing Remarks | L. Leshin |
| **16:30** | **Workshop Adjourned** | |

# Appendix D: Breakout Sessions – Questions & Answers

The section captures some of the discussion on Day Two of the workshop when each of the six different breakout session topic leads briefed the general session on the input received during their brainstorming session. All workshop participants were invited to offer comments and ask questions. The discussions are provided by topic in sequence of the briefings.

## D.1 Precursor Investigations:

**Do you really care that much about the internal structure of the object from a planetary defense perspective?**
*From a standpoint of structural integrity and being able to manipulate the NEO, interact with it, tether to it, dock with it, its stability in the sense of perturbation. It comes down to a hazards issue. The exact type of measurement with respect to the internal structure may be different if your objective is to understand how it was formed versus how to blow it up or deflect it, versus trying to keep it together so you don't injure yourself. Structural integrity is very important.*

**Is looking for possible signs of life something that you would think about in terms of the instruments that you place out there? And is that something that you would need to know before you send humans or before you plan to do planetary defense techniques?**
*This goes back to how you characterize the environment you're going to be in and the probability that there could be signs of life there. If it looks like it, you could potentially add instruments to the human mission. We can go back to how much you want to characterize NEOs before you arrive. NASA can give you a viewpoint on planetary protection regarding the necessity or the lack of necessity for characterizing objects prior to sending humans. Even with Mars we do not have a requirement to take samples back from Mars and analyze them before sending humans.*

**What is the minimum amount of characterization we would need to do before sending the first human mission? Could we send a human to a place that we had not actually touched or landed on?**
*We did have that conversation and there was a lot of discussion with parallels to Apollo and how we approached the moon. It really comes down to the risk of the investment and whether or not you need to do some minimum level of precursor investigation so that you get the minimum level of investment return on the human mission. The bare minimum is very possibly nothing, if you are willing to get there, see that it is dangerous, and go back home. That is probably not sufficient for mission minimum success criteria. There is a lot of forward work we would have to engage in to define exactly what the threshold is. We have a list and we took our first cut as to whether or not we thought the measurement was critical or important or nice to have. A three point scale is insufficient to get your differentiation and prioritization, but this is the first step. We can start developing some potential instrument manifests and see if this makes sense. We are planning on having the objectives definition teams to assist in the preparations for what do on these precursor missions, what the payload has to be, and what the minimum measurements have to be.*

**Imagine there is a scenario where we've picked out a target that we've had a precursor for, but all of a sudden we miss our launch window and have to go to a backup target that we've never send a precursor to but have characterized some objects like it. What is the level of confidence needed for going to something we have never been to?**
*We discussed extensibility, or how comparative data is between the NEOs we visit and other NEOs to be able to make any kind of extrapolation like that. We have to try to understand how to have options. One issue that would need to be addressed is, what kind of ground truthing you*

*need to do robotically that would give you a higher confidence level than the remote sensing measurements of other potential targets. Also, if we miss the target, what is a reasonable amount of time needed for another launch opportunity? Depending on that, do we have enough understanding of the NEO population to determine if we have a real target so that if we miss this window, we have another one ready?*

**During your discussion, did you look into the timing aspect of the instruments and measurements that you want to do in preparing for a human mission, to inform system design?**
*We tried to assess whether the measurement would be required in the next five years, 10 years or 15 years out, explicitly to assess whether or not it would need to affect the engineering of the systems to carry the astronauts. There is a range as to when these measurements would have to take place.*

**How specific were you in defining the criteria for developing your prioritization?**
*Very high level… Criticality was high, medium, and low. So, it is going to take more work to define exactly what it is we are going to be doing and what the criticality is for getting those precursors into place in time to affect the architecture. We started off with a world of possibilities and asked if this is something that is an absolute "must have" before we send humans. That is a high level of criticality.*

**What I am asking is, how do you reach that judgment, and can you write down criteria that would allow you to recognize something as being more valuable than something else? Until you have criteria, you can't defend a set of judgments in an abstract way.**
*In a two-hour session, starting from ground zero, the best we were able to identify was "must have", "really want", and "nice to have." Clearly, the more qualitative measurement would have to be made for decision-making but this helps guide us and point us towards the right direction and where the community is seeing things that are relatively important. It is a top-level guide right now. It is not a decision-making tool at this point.*

**If we had the survey satellite telescope in Venus orbit, what is the maximum information we can gain from that to allow us to go to backups or to choose it as our only precursor? How much information can we gain from that telescope that will allow us to pick alternates? Did you look at criteria like that?**
*The discussion was focused on "what will you learn?" The net value of the survey mission is going to depend on the filters you are using to say which objects to consider. Having that discussion prior to the one that you are talking about would allow you to define what are the capabilities of the survey mission and whether or not you need it or you know enough already.*

**As you outlined the IR survey mapping, as we look at the Venus trailing telescope, what other options, in terms of in space, did you address? Any DOD intelligence community, international, commercial capabilities in space surveillance network related or ground-based assets that could be further leveraged in terms of characterization? Affordability is a huge driver.**
*The way we are trying to approach this, is trying to define the requirements of "what do we think we need to know." In the next round, as you start to formulate the plan and go through the criteria ranking, you would start looking at international partners. We actually captured it to make sure that we use space-based assets. I think focusing on what ground assets we could bring to bear also came up, but it was focused on what is it that we need to measure and secondarily, how do you make that measurement?*

**Finding NEOs and having good ones to pick from is important and characterizing them seems more important, but I wonder a little bit about the value of spending a whole lot of money looking for something that is not there or may not be there. I know there are a lot of objects out there, but if we are just going to use surveys to try to find something we have no idea whether it is there or not, is that something that we want to do?**
*It really does come down to the pushing on those filters. If we have several options to choose from, we are not going to be pre-cursing so we have more than enough. But, if the filters say that we have exactly one option every 11 years, then that is probably an unattainable. Seems to be an unsustainable architecture and do we need a survey mission to fill those gaps? We have ground assets; we have other space-based assets and other people making observations and international participants. We don't necessarily need to do it. If, in fact, we have a targeting problem, if the filters indicate that we don't have many options, then we have a need to find targets. There is an overlap in terms of need, so then comes to who is the responsible party? Can we collaborate to meet a common objective? It is a broad discussion that needs to take place and we are engaging in that conversation.*

**Is there a possibility of doing anything meaningful with ISRU? Is it a misconception that we can't get to these very often? If we can get to them very often but we can only go for a short time, is ISRU realistic?**
*It goes back to the big question of what the purpose of the human mission to NEOs is and from the first blush, if you are trying to enable the mission, you are not using ISRU to get there or return; maybe extra radiation shielding if you find part of the way through that you had to do that. However, there may be things that you want to do on a human mission or precursor with respect to mitigation strategy. If you have to move an asteroid, using the resources of the asteroid to move it, whether it is a mass driver or volatile or something like that, maybe worth considering or, if you were to move the asset closer to Earth from an economic point of view. The other item that comes up when we talk about synergy is synergy between NEOs and Phobos, such that you might want to set up a propellant depot in Mars orbit using Phobos as a resource. We might do something on a NEO mission along those lines. And then, in general, the last, is, a lot of science in prospecting aspects are very similar. Even if you don't do a ISRU demo, understanding the minerals, understanding the volatiles, understanding the material aspects such that I can plan a mining aspect if I want to; and if you want to go beyond Mars into the main asteroid belt, obviously there would be things that we would learn on a NEO mission that would be used there. Bottom line, if you are thinking of using ISRU to enable a human NEO mission, no, that does not make sense because that typically requires you to preposition; but if you want to use that knowledge per mitigation or economic or Mars exploration, there may be subscale activity you want to do on a human NEOs mission or robotics that may make sense. It is open for discussion and debate.*

### D.2 Technologies:

**Did anything come up with regard to the feed-forward aspect …making the technology applicable to multiple destinations rather than just being for NEOs? In case we go to Mars, is there some flexibility of these systems? What will need to be unique? And what could be carried on to other destinations?**
*We didn't talk specifically about synergy because there is another panel addressing that, but we talked about the sense that all of these activities are taking place in deep space. Reliability, repair, robustness and autonomy, are things that carry forward in any mission, and will be more important in missions that are longer than this one. In particular, we had more discussion on mission duration and how that relates to the technologies required rather than anything that was specifically a destination dependent issue. There was considerable discussion on both the mission duration and how that affects what you do.*

**One of the things you touch on is logistics. Were there any specifics on the architectural issue as well? Making sure that there wasn't one particular card design for every single function, but rather taking a look at the architecture of the system design to minimize the number of different designs that were incorporated into the system so that there would be reuse or possible interchange of functionality from one system or another.**
*We had a fairly lengthy and exhaustive discussion on that. In terms of having dissimilar redundancy of any one particular system, but also in the suite of systems that are required for space flight in general. We talked about multiple independent systems that have some level of common component that are interchangeable. Instead of doing large orbital replacement unit pull-out and push-in methodology, you could swap boards and think about your logistics chain as a philosophy of sparing, a philosophy of architecture and a philosophy of logistics, and that those things have to be related.*

**In looking at the close loop versus robustness and reliability, was one deemed to be a higher fidelity factor? You mentioned both. Was one more of a driver?**
*Reliability. Given mission duration and the amount of consumables that we could carry with us, (which is relatively small), if we go to a longer duration mission, reliability will be more important. It is essential that we have reliable systems.*

**You talk about drilling or injection type kinetic attachment. Did you look at anything non-kinetic like nets, blankets, barges, adhesives, freezing, cramp-ons, etc.?**
*We didn't have a lengthy discussion, but we are all aware of a variety options. They need to be looked at and understood. I think we were clear that in many cases, there are approaches that are thought to be relatively well in hand for anchoring. Which one you want to use depends on the nature of the body. The understanding was to look at things that could work for a variety of ranges, but to be ready for any of them is most important.*

### D.3 Concept of Operations:

**You seemed to be satisfied with having the robotic precursor launched in the same opportunity and get there a few weeks before, which seems different from other views. Did you talk about that?**
*We talked about it a little bit, but the idea was that the robotic precursor would provide us with more information on the number of different types of NEOs and give us the information that we could use for the advanced probe. Obviously, we would like to have the precursor of the exact asteroid we are going to. But the notion is that if you slip through your launch and you go to a secondary target, this provides having some insight for the flight plan on the way out.*

**In our synergy group, we talked a little bit about the EVAs. One of the things that came up in our discussion was because of the dust and kicking up plume, one approach is that we do most things with robotic assets near real time with the astronauts there, and the astronauts be used for contingency or problem-solving. On your charts -- the bulk of the activities were EVA related. I wanted you to respond to the present can't -- pros and cons.**
*We had that same conversation in our group. Our thought was that the reason we were sending humans to a NEO was to put scientific hands and minds as close to the subject matter as we can. So we tend to agree that scientists in EVA are really what you are there for. Robotics are certainly important. But the EVA experience was really what you were there for.*
*We would use our judgment. If there were parts of the asteroid that we could anchor to, the SEV would anchor, the crew would be attached to the SEV, we could deploy for drilling without stirring up dust. If there were areas that were dusty and interesting, we could use a different*

*combination of assets. We could really use the humans for what they're best at, but judgment certainly goes along with that. If it turns out the whole thing is stirring up dust, you probably don't want to do that.*

**Are there solutions that don't necessarily rely on the ability to couple strongly with the surface of a small object?**
*It would be preferable if we could, but the fallback plan that we think would work on almost any asteroid is to station keep the exploration vehicle and have an arm that would position the astronaut. Much like we do space walks on space station. That would be an integral part of the capability.*

**Was there any concept about how much you would be bringing back in terms of sample in terms of inbound mass of the whole system?**
*We talked about a wide range of ideas. We thought if we had two small return vehicles, each one would be capable of bringing the crew back, but all of the living, and exercise, and EVA, robotics, would be in the space exploration vehicle. If we have these redundant Earth return vehicles, we can load one of them full of samples. Instead of giving you 100 pounds, they could bring back potentially more. I think that the science community will advise us on the right amount of samples to bring back.*

**Do you have any thoughts on the utility or the specifics of how you might high-grade samples on the way back?**
*A lot of work was done with the moon related to having a lab in the habitat. There was never really a consensus among the community, but simple is better. Think of doing field geology on Earth. You high-grade your samples when you go over a terrain. It depends on what your science objectives are and what you are trying to do with the samples. When you answer those questions, you'll know what type of sample to bring back.*

**Going back to Apollo, how much mass quantity did we bring back, assess and distribute out of what we brought back 40 years later?**
*We have quite a few samples brought back from Apollo. They have all been characterized to one level or another. The real issue is being able to find the right set in the right portions of the sample, within any return. We still have on the order of 300 samples allocated every year, 40 years hence. You do have long-term value of any of the samples you bring back. There was nothing brought back from Apollo that was not priceless and highly scientifically satisfying. There are some subsets that were more valuable than others, depending upon which portion of the scientific field you are interested in.*

### D.4 Planetary Defense:

**Tethered satellite was a great example of a demonstration of linear momentum exchange using tethers. Did you look at the possibility of using tethers and then cutting the tether?**
*Well, that idea has come up in discussions of planetary defense. We did not discuss it here today. It has been talked about though and it proved to be very efficient on the tethered satellites, so it may be something to look at.*

**One of your slides called for determining the gravitational field quickly. This is normally done by putting an object into orbit around a planetary body and tracking its position very precisely or carrying a gravimeter across a surface and making surface measurements. I don't see that either of those is a particularly quick way of doing it. Were you thinking of those two or did you have some other way of having that measurement in mind?**

*We don't have a particular technique or solution in mind. It would just be nice if we could do it quicker. One approach you might consider – these are small bodies that rotate relatively rapidly; perhaps you can use the multiple rotations of the small body beside a spacecraft in a rendezvous stand-off position to emulate multiple orbits of the object to do that quicker. Again, we did not know about a specific technique to use, but the ability to deal with that problem earlier would be ideal. The idea would be for the human crew to test two or three techniques.*

**The operational approaches to an actual interception of a near Earth object seem to imply that you know that this is coming a long time ahead of time. Is that a general function that you have to detect the threat a long time ahead of time?**
*The most important component of planetary defense is find them early, find them early, find them early. Unless we are able to find them many years to decades in advance of an impact, we will probably need to resort to the nuclear standoff technique.*

**When we were talking about lunar missions, there was a strong interest in characterization globally of the lunar surface and sending those to different destinations and getting measurements. Is there a similar approach, or has there been, to defining a characteristic payload that we want to send to every NEO to enable comparative analysis of different objects?**
*We didn't talk about what the specific components of such a package might be. It is an idea that has been talked about in other planetary defense discussions. Building up a catalog of characteristics for different types of asteroids so that whenever we are eventually faced with such an impacting object we already have a lot of knowledge about that type of object so we don't necessarily have to do full characterization mission against it before we could do a mitigation campaign.*

### D.5 Synergies with the Moon and Mars:

**Did you have a variety of nuclear power that you focused on? It seems to me that even 20 years ago we talked about how a NEO mission would be a great way to shake down a nuclear propulsion system before you go off to more ambitious destinations. Is that the way you are thinking, a good way to get the system to rung out?**
*Yes, for both. Although a human mission to a NEO probably won't require nuclear power, it would be a good way to prove the capability.*

**Is there any serious discussion about how you get from here, today, in 2010, to that capability?**
*We recognize that it seemed incompatible with the nuclear power development roadmap that exists today, 2025 and we noted that. The current roadmap was not designed to support a NEO mission.*

**I guess I would like to ask if anybody has looked into the amount of risk that is bought down by pre-deploying an ISRU capability in terms of creating a cache of consumables. In case of something like an Apollo 13 type of accident, where they lost one of the fuel cells and other capabilities, oxygen supplies, propellant, etc.**
*That was not discussed but certainly, many Mars mission concepts have considered pre-deploy assets on the surface and you would not launch the humans to Mars until and unless you had validation that the assets were there, and the propellant was mostly or completely in the tanks on the surface before you launched humans. We didn't get into the risk that was associated with that or how you might translate that into decisions about the missions because of risk reduction.*

**There have been several comments in effect that we should essentially wait until we are ready to do a NEO mission the way we would do the Mars mission. One of the attractions of the NEO mission is that we can do it more easily than a Mars mission. If we wait to do it the same way we will do it at the same time, which is not for a very long time from now. Asteroids also give you the opportunity to incrementally work your way into that level of difficulty. Did you talk at all about time phasing? Can you start with the mission that has essentially no new technology and which technologies would you add first? Closed loop life support, and then advanced propulsion, and then a few years later higher speed reentry capabilities?**
*It is a fair question to ask and a way to look at the problem. To start out with your first mission using the existing capabilities that we have today, was not considered a good starting point. You have to make sure that we discuss folding in advanced capabilities. Does it have to be all of them? No, of course not. We can create missions to NEOs that are a more staged sequence of steps. There is a minimum set of capabilities that you must have to be able to send humans there or bring them back safely. It doesn't have to be all of the ones you need to go Mars.*

### D.6 Policy and Public Engagement:

**While it is difficult to flesh out all of these objectives in the absence of a policy context, and the policy is something that has to come from the administration it is not going to be coming out of NASA studies, it has a huge impact on how we prioritize things. How is that policy going to come about to give guidance to the future efforts?**
*When Kennedy decided to go to the moon it wasn't because he was a space cadet, it was because he had a serious political problem at that point in time and to send the man in the in that decade was the answer to the political question he had. A lot of people from the space community asked, including myself, the answer is spaceflight, what was the question? We need to back up and ask what questions we are answering with human spaceflight as opposed to having the answer already in place.*

**Capabilities survive… Programs and architectures, there's a graveyard full of them. The question is where is the focus on buying down program risk? All of these programs haven't failed in buying down mission risk, which has been a tremendous investment, because you need a survivable program. I think it's a function of marketing. You need to go out and sell to the new president that it's not necessarily a good idea to do what others have done. Write a passage for a new president to come in, wipe everything off of the table, and say "I want to do it my way."**
*The answer to that question is to depoliticize the nature of it. Human spaceflight has always been and still is an emotionally fraught and symbolic activity. You will not separate it out from those backgrounds completely. You can try to set up priorities. It is incumbent upon the community to set up these questions. One of the reasons why the congress likes decadal surveys is not because they understand them or read them. It is because the communities have gone and have fought amongst themselves and come up with priority questions that have to be answered. Then NASA is asked within the amount of resources that they are allowed to have, which is decided by political means, as to how many of these questions can you afford. There's a bunch more questions than there ever is resources.*
*However, the priorities set by the community and then the programming put in by the agency is a fairly stable process. Where there are problems, say with overruns on MSL and James Webb, the damage happened to those communities first. There is a sense of equity. However painful it may be, people understand. Congress doesn't have to listen to fighting amongst themselves. There is some stability in these programs because of the pain -- despite the pain and new technology, despite changing questions. That is a process that is much more stable than we have seen before.*

*It gets you away from looking at the development of new launch vehicles. If you look at the history of the Earth observing program at NASA, it developed over time very quietly and in a sustained manner. The second one is the human research program. We worked to understand not just the health and safety of astronauts, but also to look at what the factors are that extend from that research into the broader medical and human factors community. What you have is an extended period of time that was not political. You have a stabilization that occurred in each program. You have a currently understood research trajectory and a technology trajectory that goes along with it. That is, for me, a better example of where we hope to go, rather than looking at prior launch programs.*