NEXT STEPS IN HUMAN EXPLORATION TO MARS AND BEYOND

HEARING

BEFORE THE

SUBCOMMITTEE ON SPACE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

ONE HUNDRED THIRTEENTH CONGRESS

FIRST SESSION

TUESDAY, MAY 21, 2013

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NEXT STEPS IN HUMAN EXPLORATION TO MARS AND BEYOND

TUESDAY, MAY 21, 2013

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON SCIENCE
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Subcommittee met, pursuant to call, at 2:02 p.m., in Room 2318 of the Rayburn House Office Building, Hon. Steven M. Palazzo [Chairman of the Subcommittee] presiding.

LAMAR S. SMITH, Texas
CHAIRMAN

EDDIE BERNICE JOHNSON, Texas
RANKING MEMBER

Congress of the United States
House of Representatives

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Subcommittee on Space

Next Steps in Human Exploration to Mars and Beyond

Tuesday, May 21, 2013
2:00 p.m. to 4:00 p.m.
2318 Rayburn House Office Building

Witnesses

***Dr. Louis Friedman**, Co-Lead, Keck Institute for Space Studies Asteroid Retrieval Mission Study and Executive Director Emeritus, The Planetary Society*

***Dr. Paul Spudis**, Senior Staff Scientist at the Lunar and Planetary Institute*

***Dr. Steve Squyres**, Goldwin Smith Professor of Astronomy at Cornell University*

***Mr. Doug Cooke**, Owner, Cooke Concepts and Solutions*

U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON SPACE

Next Steps in Human Exploration to Mars and Beyond

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2:00 p.m. – 4:00 p.m.
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Purpose

The purpose of this hearing is to examine possible options for the next steps in human space flight and how these options move the United States closer to a human mission to Mars and beyond. In particular, the Committee will explore whether the Administration's proposed asteroid rendezvous mission is a better precursor for an eventual manned mission to Mars compared to Apollo-like follow-on missions to return to the Moon.

Witnesses

- Dr. Louis Friedman, Co-Lead, Keck Institute for Space Studies Asteroid Retrieval Mission Study and Executive Director Emeritus, The Planetary Society
- Dr. Paul Spudis, Senior Staff Scientist at the Lunar and Planetary Institute
- Dr. Steve Squyres, Goldwin Smith Professor of Astronomy at Cornell University
- Mr. Doug Cooke, Owner, Cooke Concepts and Solutions

Overarching Questions

1. Is the proposed Asteroid Retrieval Mission (ARM), a lunar landing mission, or another mission better as a precursor for an eventual human mission to Mars?
2. What things could we learn and capabilities would we develop from a Moon landing that we could not learn from the proposed Asteroid Retrieval Mission?
3. How do different destinations or missions affect a strategic approach with our potential international partners as well as technical architectures?

Background

Following the Space Shuttle *Columbia* accident in February 2003 and the subsequent investigation into its cause, President George W. Bush announced a new "Vision for Space Exploration" on January 14, 2004, to reinvigorate and redirect NASA's human exploration program beyond the International Space Station. The plan focused on the next steps for low-Earth orbit and beyond Earth orbit. It also provided a generalized vision that the Administrator could use to "implement an integrated, long-term robotic and human exploration program structured with measurable milestones and executed on the basis of available resources, accumulated experience, and technology readiness."[1] The plan included four main goals and objectives: to implement a sustained and affordable human and robotic program to explore the solar system; to extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations; to develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.[2] The Constellation Program was born out of the New Vision for Space Exploration and the work for this new program began with NASA's budget request for fiscal year 2005.

After his appointment as Administrator in April 2005, Dr. Mike Griffin ordered a review of NASA's exploration architecture called the "Exploration Systems Architecture Study" (ESAS) to carry out this vision. After the completion of the study, NASA began, with the concurrence of Congress, to restructure the exploration program with an emphasis on acceleration of the development of capabilities to ferry astronauts to the International Space Station.[3] The study recommended the development of a Space Shuttle-derived launch architecture[4] and an exploration vehicle that was capable of carrying cargo and crew to the Space Station as well as crew to the Moon and Mars.[5] Congress codified the majority of the ESAS plan in the National Aeronautics and Space Administration Reauthorization Act of 2005, understanding the milestone schedule was based primarily on the ability to "go-as-we-can-afford-to-pay."

In 2009, President Obama ordered a review of the Constellation program and acting NASA Administrator Chris Scolese established the "Review of U.S. Human Spaceflight Plans Committee" (the Commission), also known as the "Augustine Commission" for its chairman, Norman R. Augustine. The charter for the Commission called for an "independent review of ongoing U.S. human space flight plans and programs, as well as alternatives, to ensure the Nation is pursuing the best trajectory for the future of human space flight—one that is safe, innovative, affordable, and sustainable."[6] The Commission released its final report on October 22, 2009.[7]

The Commission found that "the ultimate goal of human exploration is to chart a path for human expansion into the solar system,"[8] but that "since Constellation's inception, the program has faced a mismatch between funding and program content"[9] and "[d]ifferences between the original Constellation program planning budget and the actual implementation budget, coupled with technical problems that have been encountered on the [programs], have produced the most significant overall impacts to the execution of the Constellation program."[10] The Commission offered five options for the future of the human exploration program, two of which complied with

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[1] National Aeronautics and Space Administration-*The Vision for Space Exploration, February 2004.* Retrieved at http://www.nasa.gov/pdf/55583main_vision_space_exploration2.pdf

[2] *Ibid.*

[3] National Aeronautics and Space Administration Exploration Systems Architecture Study (pg 59). Retrieved at http://www.nasa.gov/pdf/140632main_ESAS_02.pdf

[4] *Ibid.* 3 at pg 717

[5] *Ibid.* 3 at pg 714

[6] Charter of the "Review of U.S. Human Spaceflight Plans Committee". retrieved at http://www.nasa.gov/pdf/354415main_Charter%20-%20Signed%20-%20Clean.pdf

[7] Final Report of the "Review of U.S. Human Spaceflight Plans Committee". Retrieved at: http://www.nasa.gov/pdf/396093main_HSF_Cmte_FinalReport.pdf

[8] *Ibid.* 7 at pg 9

[9] *Ibid.* 7 at pg 58

[10] *Ibid.* 7 at pg 59

the FY2010 budget profile of the Obama Administration for the Constellation program,[11] however, neither of these two options would "permit human exploration to continue in any meaningful way."[12]

As a result of this review, President Obama offered a budget for fiscal year 2011 that proposed to cancel the Constellation program.[13] Later that same year, Congress authorized some of the changes to the human exploration program sought by the President[14] as outlined in a speech on April 15, 2010. In this speech at the Kennedy Space Center he revealed his strategy for the future of human exploration which canceled a return mission to the Moon, saying, "I understand that some believe that we should attempt a return to the surface of the Moon first, as previously planned. But I just have to say pretty bluntly here: We've been there before... Early in the next decade, a set of crewed flights will test and prove the systems required for exploration beyond low Earth orbit. And by 2025, we expect new spacecraft designed for long journeys to allow us to begin the first-ever crewed missions beyond the Moon into deep space. So we'll start -- we'll start by sending astronauts to an asteroid for the first time in history. By the mid-2030s, I believe we can send humans to orbit Mars and return them safely to Earth. And a landing on Mars will follow."[15]

Current Law and National Space Policy

On June 28, 2010 the President announced a new National Space Policy which outlined priorities as well as principles and objectives for the extension of human presence deeper into the solar system.

Although both President Obama and the Administrator have repeatedly said the United States will not be going back to the Moon,[16,17] current law, derived by numerous NASA Authorization Acts over the last decade, requires lunar missions as destinations or at the very least, precursors to other missions. The NASA Authorization Act of 2005 directed NASA to:

> *...establish a program to develop a sustained human presence on the Moon, including a robust precursor program, to promote exploration, science, commerce, and United States preeminence in space, and as a stepping-stone to future exploration of Mars and other destinations.*[18]

Additionally, the 2005 Act required the Administrator to:

> *...implement an exploration technology development program to enable lunar human and robotic operations consistent with section 101(b)(2)including surface power to use on the Moon and other locations;*[19]

[11] http://www.nasa.gov/pdf/345955main_8_Exploration_%20FY_2010_UPDATED_final.pdf. Note the significant change in the budget projection for the Constellation program from the FY 2010 budget profile on page EXP-2.
[12] *Ibid.* 7 at pg 16
[13] President's Budget Request for the National Aeronautics and Space Administration, Fiscal Year 2011. Retrieved at http://www.nasa.gov/news/budget/2011.html
[14] Public Law 111-267: National Aeronautics and Space Administration Reauthorization Act of 2010
[15] Speech by President Obama at Kennedy Space Center on April 15, 2010
http://www.nasa.gov/news/media/trans/obama_ksc_trans.html
[16] *Ibid.*
[17] Oral Testimony of Administrator Charles Bolden before the House Science, Space and Technology Subcommittee on Space, April 24, 2013.
[18] 51 USC 20302
[19] 51 USC 70502

Following the reorganization of the Constellation program, Congress endorsed additional requirements for NASA's human exploration program in the 2008 Act, including a requirement for the Administrator to create a "Stepping Stone Approach" to exploration:

> *In order to maximize the cost-effectiveness of the long-term exploration and utilization activities of the United States, the Administrator shall take all necessary steps, including engaging international partners, to ensure that activities in its lunar exploration program shall be designed and implemented in a manner that gives strong consideration to how those activities might also help meet the requirements of future exploration and utilization activities beyond the Moon. The timetable of the lunar phase of the long-term international exploration initiative shall be determined by the availability of funding. However, once an exploration-related project enters its development phase, the Administrator shall seek, to the maximum extent practicable, to complete that project without undue delays.*[20]

At present, there is no plan for NASA to return humans to the Moon. According to NASA Administrator Bolden, there is no money in the Administration's budget for such a mission.[21]

Next Steps

As NASA prepares to take the next steps in human exploration of the solar system there are many unanswered questions about the correct path to Mars and beyond. The Apollo Program was not a straight shot to the Moon; it included several precursor missions to test new capabilities and gain experience on the way to the Moon including Projects Mercury and Gemini. In much the same way, NASA will need to acquire new capabilities to travel to Mars and beyond.

The two most commonly discussed possibilities for precursor missions to Mars involve manned missions to the Moon or an asteroid.

Lunar Mission

The "Vision for Space Exploration" called for a return to the Moon by 2020 as a stepping stone to other locations and NASA has continued various lunar science projects such as the Lunar Reconnaissance Orbiter (LRO) and the Gravity Recovery and Interior Laboratory (GRAIL). The Constellation program was ideally suited for landing on the Moon with the inclusion of a lunar lander called the "Altair" in the "system of systems" approach to exploration. Since the cancellation of the Constellation program, there is no longer a lunar lander under development.

There are several compelling reasons for using the Moon as a training ground and test bed to prepare for more complex missions. Landing on the Moon would develop technical capabilities for landing on and launching from a large celestial body, something NASA has not done for more than four decades.[22] Establishing a semi-permanent or permanent presence on the Moon such as the lunar outpost referenced in the NASA Authorization Acts of 2005 and 2008,[23] would give astronauts an opportunity to work and live in an environment radically different from Earth, in much the same way explorers on Mars would. Ultimately, operating on another planet will require

[20] 51 USC 70504
[21] Oral Testimony of Administrator Charles Bolden before the House Science, Space and Technology Subcommittee on Space, April 24, 2013.
[22] The last time humans landed on the moon was Apollo 17 on December 7, 1972.
[23] 51 USC 70505

training and preparation, the Moon seems like a logical place to do this training. "On the international front, there appears to be continued enthusiasm for a mission to the Moon."[24]

Asteroid Mission

The National Space Policy issued by President Obama in April 2010, and released formally later that year, envisioned sending humans to an asteroid by the year 2025 beyond lunar orbit into "deep space."[25,26] The National Research Council issued a report last December which stated that "[t]he committee has seen little evidence that a current stated goal for NASA's human spaceflight program—namely, to visit an asteroid by 2025—has been widely accepted as a compelling destination by NASA's own workforce, by the nation as a whole, or by the international community."[27]

The Administration proposed a revised asteroid mission with the FY2014 budget request. The mission concept proposed by the Administration features a robotic capture and redirection of a small near Earth asteroid (NEA) to a deep retrograde lunar orbit for astronauts to visit rather than sending Astronauts to an asteroid in deep space.

The proposed Asteroid Retrieval Mission (ARM) has multiple stages. First, using the Near Earth Observation Program will identify an appropriate asteroid passing near Earth based on size, composition, and orbit while simultaneously developing advanced solar electric propulsion technology. NASA will then need to develop and build a robotic probe to launch to the target asteroid in time to intersect its orbit. This probe will then "dock" with the asteroid while also stabilizing its rotation and ferry it to a retrograde lunar orbit. Finally, NASA will launch a crewed Orion capsule aboard the SLS in order to rendezvous and explore the asteroid, potentially on the initial manned flight of the new vehicle and capsule.

The mission concept is based on a study by the Keck Institute for Space Studies (Keck Study) at the California Institute of Technology in partnership with the Jet Propulsion Laboratory. The Keck Study estimated a mission of this size and scope would cost approximately $2.6 billion.[28] The Administration believes that the mission will actually cost less than this, and NASA plans to provide a revised estimate of the mission's cost this summer. NASA's FY14 budget request also proposes three new initiatives totaling $105 million, but NASA has not identified a budget profile for this mission beyond FY 2014.

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[24] NASA's Strategic Direction and the Need for a National Consensus http://www.nap.edu/catalog.php?record_id=18248
[25] *Ibid.* 15
[26] *Ibid.* 17
[27] *Ibid. 24*
[28] Brophy, J., Friedman, L., & Culick, F. (2012). Asteroid Retrieval Mission Feasibility Study. *Keck Institute for Space Studies*, . Retrieved , from http://www.lpi.usra.edu/sbag/documents/Asteroid percent20Return percent20Feasibility percent2020120530.pdf

Appendix- Reports on Space Exploration

1986 - The National Commission on Space (Paine Commission Report)
http://www.nasa.gov/pdf/383341main_60%20-%2020090814.5.The%20Report%20of%20the%20National%20Commission%20on%20Space.pdf

1987 - NASA Leadership and America's Future in Space: A Report to the Administrator (Ride Report)
http://history.nasa.gov/riderep/main.PDF

1990 – Advisory Committee on the Future of the U.S. Space Program (Augustine Commission Report)
http://www.hq.nasa.gov/office/pao/History/augustine/racfup1.htm

1991 – The Synthesis Group (The Stafford Report)
http://history.nasa.gov/staffordrep/main_toc.PDF

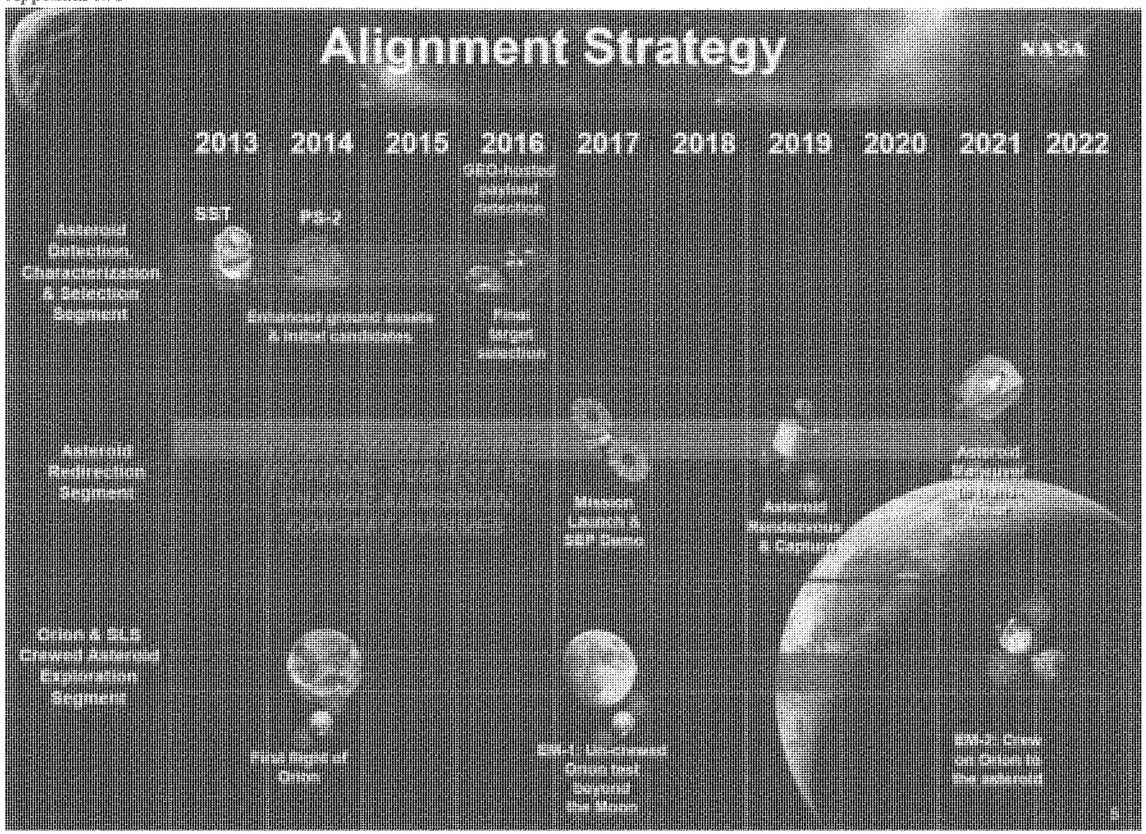
1991 - Office of Technology Assessment: Exploring the Moon and Mars
http://history.nasa.gov/32992.pdf

1993 – The National Space Council Report on the U.S. Space Program
http://history.nasa.gov/33082.pt1.pdf

2004 – President's Commission on Implementation of United States Space Exploration Policy (Aldridge Commission Report)
http://history.nasa.gov/aldridge_commission_report_june2004.pdf

2009 – Review of U.S. Human Space Flight Plans Committee (Augustine Commission Report)
http://www.nasa.gov/pdf/396093main_HSF_Cmte_FinalReport.pdf

Appendix two



Chairman PALAZZO. The Subcommittee on Space will come to order. Good afternoon. Welcome to today's hearing titled "Next Steps in Human Exploration to Mars and Beyond." In front of you are packets containing the written testimony, biographies, and required truth-in-testimony disclosures for today's witnesses.

Before I begin, I do want to take a moment to express our thoughts and prayers on behalf of this Committee for those in Oklahoma who have just gone through the recent tornadoes. As Americans came to their fellow Americans in aid for Hurricane Katrina, Super Storm Sandy, we expect nothing less from us in our friends' time of need.

I recognize myself for five minutes for an opening statement.

I would also like to take a moment and remember Astronaut Sally Ride, the first American woman in space, who was honored last night at the Kennedy Center for her tireless work promoting the Nation's space program and her devotion to STEM education for our Nation's children.

Over the last decade, the human exploration program at NASA has been plagued with instability from constantly changing requirements, budgets, and missions. We can't continue changing our program of record every time there is a new President. This committee is consistent and unwavering in its commitment to human exploration, a tradition that I am confident will continue into the future.

Congress issued steady guidance in the 2005 and 2008 Authorization Acts that directed NASA to base exploration progress on availability of funds. In accordance with the Authorization Act of 2010, NASA is developing the most powerful exploration vehicle and advanced crew capsule since the Apollo era. The SLS and Orion will take our astronauts deeper into space than ever before. I am committed to the success of these assets and ensuring their continued on-time development and appropriate prioritization moving forward.

I, and many on this Committee, are frustrated that the Administration insists on cutting its funding request for the SLS and Orion. Reductions in these programs make me question the Administration's sincere commitment to their success. If nothing else comes out of this hearing, I hope it is clear to those inside and outside the Administration that this Committee is devoted to human exploration and we intend to ensure this year's authorization reflects that commitment.

Numerous studies and commissions have provided Congress with recommendations for purposes and goals for exploring space. We don't need another study, we need action. As we move forward in the next few months with the NASA Authorization Act, Congress must address our path to Mars and beyond so there will be no question as to where we are headed and how we will get there.

As we venture further into the solar system, there must be a plan in place for the capabilities, skills, and technologies needed to land humans on Mars and return them safely to the Earth. Today, we will discuss the best way to take our first steps toward Mars and the path we should follow to get there. The two most commonly referenced possibilities for next steps are an asteroid mission and a lunar mission. We have a panel of experts with us today that will be able to speak to both of these options.

The last three NASA Authorization Acts have created a clear legislative record supporting a return to the Moon with a sustained human presence as a training ground for venturing further into the solar system. There are many advantages to returning humans to the Moon and I look forward to hearing from our witnesses today about what we may gain from a return to the surface of our closest celestial neighbor.

Additionally, this year the Administration proposed to capture an asteroid and move it to a nearby orbit as technology demonstration and exploration training opportunity. Prior to this year, NASA has not presented Congress with any indication such a mission would be in development. I still have many questions about the budget profile, technical plan, schedule, and long-term strategy as NASA has yet to even complete a mission formulation review. I am not convinced this mission is the right way to go and that it may actually prove a detour for a Mars mission.

Today, we have one of the scientists who wrote the study which became the basis of the asteroid mission, and I look forward to hearing his thoughts.

Human exploration has always had its challenges, but the U.S. has always risen to the occasion. This country was built by people who dream big and do hard things. I believe the decisions we make today will determine whether the United States maintains its leadership in space tomorrow. In the future, as in the past, I hope we will be able to focus mission priorities and goals to ensure our best chance of success.

And of course, if I may, I would just like to introduce my friends with the partners with Stennis who are here. I know several of you all may be with the citizens for the exploration of space. Thank you all for being here and it was great to have a little tongue twister while you are in the audience. Just say call it Moon. Why don't we just do that? Lunar, lunar, lunar, okay. I got it.

I now recognize our Ranking Member, the gentlelady from Maryland, Ms. Edwards, for an opening statement.

[The prepared statement of Mr. Palazzo follows:]

PREPARED STATEMENT OF SUBCOMMITTEE ON SPACE CHAIRMAN STEVEN PALAZZO

Before we begin, I would like to take a moment to recognize Astronaut Sally Ride, the first American woman in space, who was honored last night at the Kennedy Center for her tireless work promoting the nation's space program and her devotion to STEM education for our nation's children.

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Human exploration has always had its challenges, but the United States has always risen to the occasion. This country was built by people who dream big and do the hard things. I believe the decisions we make today will determine whether the U.S. maintains its leadership in space tomorrow. In the future, as in the past, I hope we will be able to focus mission priorities and goals to ensure our best chances of success.

Ms. EDWARDS. Well, thank you, Mr. Chairman. And good afternoon and welcome to our distinguished panel of witnesses. I really appreciate, Mr. Chairman, that you called this hearing on Next Steps in Human Exploration to Mars and Beyond. I have to say I don't know what the rest of Congress is doing, but this Subcommittee and our Full Committee have been quite active in our oversight. We have held hearings recently on near-Earth objects, exoplanets, as well as previous hearings that we have held on Mars and planetary science. And these issues have only deepened my enthusiasm for what NASA does and wetted my appetite for the places that our astronauts, our humans, might explore in the future.

Human exploration is indeed a big part of NASA and its inspiring mission. It is also an important catalyst for advancing our Nation's innovation agenda and for demanding the types of skills and educated workforce that contribute to our Nation's economic strength. I want to ensure that others share my enthusiasm and excitement and one day experience the thrill, the absolute thrill, of American astronauts, of humans traveling to and exploring a surface far beyond our Earth and then returning safely home. That is something that the United States of America has not done in four decades and I don't want another four decades to pass before we explore deep space again.

That is why I am delighted to hear that NASA Administrator Charles Bolden speak more often more recently about Mars as an ultimate destination, at least in the next 20 years, for human exploration. Today's hearing will examine potential interim steps en route to that ultimate destination.

Successive NASA Authorization Acts have authorized a stepping-stone approach to human exploration. The Moon, near-Earth asteroids, and other points are among the destinations that can be considered to help prepare for eventual human exploration of Mars. The Administration's recent proposal to capture a near-Earth asteroid, bring it into translunar orbit—lunar orbit, and to potentially send humans there is yet another possible step, but before we look at interim steps, we need first to understand what it takes to get to Mars.

Learning how to deal with extended space travel, protecting ourselves from harmful radiation, and surviving on another planet are a few challenges that come to mind for humans. Is there a plan to get there and to address these and other challenges? What should Congress expect to be included in a credible and measured roadmap to achieve the goals of sending humans to Mars? Such a guide can help us determine whether one or more interim steps make sense and which one—how an interim destination would move us forward along the roadmap and which destination or destinations are most effective in enabling progress towards a Mars goal.

We have an impressive group of witnesses here today, Mr. Chairman, with deep expertise in these issues that we are discussing, and so I thank you for joining us and I look forward to your testimony and to learning from you.

And with that, Mr. Chairman, I thank you and I yield the balance of my time.

[The prepared statement of Ms. Edwards follows:]

PREPARED STATEMENT OF RANKING MINORITY MEMBER DONNA EDWARDS

Good afternoon and welcome to our distinguished panel of witnesses.

Thank you, Mr. Chairman, for calling this hearing today on "Next Steps in Human Exploration to Mars and Beyond."

The hearings this Subcommittee and the Full Committee have recently held on near Earth objects and exoplanets, as well as previous hearings held on Mars and planetary science, have only deepened my enthusiasm for what NASA does and wetted my appetite for the places that our astronauts might explore.

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That's why I'm delighted to hear the NASA Administrator, Charles Bolden, speaking more often about Mars as the ultimate destination for human space exploration.

Today's hearing will examine potential interim steps en route to that ultimate destination.

Successive NASA Authorizations Acts have authorized a "stepping stone approach" to human exploration. The Moon, near Earth asteroids, and Lagrangian points are among the destinations that can be considered to help prepare for eventual human exploration of Mars.

The Administration's recent proposal to capture a near Earth asteroid, bring it into trans-lunar orbit, and to potentially send humans there is yet another possible step. But before we look at interim steps, we need first to understand what it takes to get to Mars.

Learning how to deal with extended space travel, protecting ourselves from harmful radiation, and surviving on another planet are a few challenges that come to mind.

Is there a plan to get there and to address these and other challenges?

What should Congress expect to be included in a credible and measured roadmap to achieve the goal of sending humans to Mars?

Such a guide can help us determine whether one or more interim steps makes sense, how an interim destination moves us forward along the roadmap, and which destination or destinations are most effective in enabling progress toward a Mars goal.

We have an impressive group of witnesses here today with deep expertise in the issues we are discussing, so thank you for joining us and I look forward to your testimony.

Chairman PALAZZO. Thank you, Ms. Edwards. I now recognize the Chairman of the Full Committee for a statement.

Mr. Smith?

Chairman SMITH. Thank you, Mr. Chairman.

Human history is punctuated by great advancements in the exploration of the world around us. We have long sought out the next frontier, which may well be the exploration of our solar system. No doubt humankind will continue to push the boundaries of the known universe.

Not long ago, the exploration of Mars was considered science fiction. Today, with two active Martian robotic missions ongoing, it is no longer science fiction at all. Space exploration goes beyond rockets and avionics; it is about hope for the future. Human space flight represents the aspirations and ambitions of the American people.

Few sights are more inspiring than when a rocket lifts off a launch pad and disappears into the sky. Investments in the Space Launch System and Orion crew capsule manifest the ingenuity of the American people and the next steps in space exploration.

Neil Armstrong and Buzz Aldrin transfixed America and the world when they landed on the Moon in 1969. The Apollo program was proof that we are not permanently tethered to our home planet. It was a reminder that humans will always be explorers.

As our space program prepares for the next step to Mars, Congress must ensure that there is a strategic plan in place. NASA should have a well-thought-out and convincing plan before committing scarce resources. The trip to Mars will not be a direct one. We will need to train for it before we send a crew, much like the Apollo missions.

One option for training would be a set of lunar missions. Congress has a long history of support for lunar landings and exploration. To me, there is no better way for our astronauts to learn how to live and work on another planet than to use the Moon as a training ground. Another option presented by NASA this year is an asteroid retrieval mission. It is difficult to determine what advantages this may offer without a plan to evaluate.

The Administration originally proposed a mission to an asteroid in deep space. A recent National Research Council report found little support for the proposal. Without a consensus for the original plan, NASA haphazardly created a new asteroid retrieval mission. Unfortunately, NASA did not seek the advice of its own Small Bodies Assessment Group before presenting the mission to Congress. If NASA had sought the advisory group's advice, they would have heard it was "entertaining, but not a serious proposal." Maybe that is why they didn't ask.

As this Committee begins to draft the NASA Reauthorization Act, we must be mindful of the impact it will have on the future. The policies we put in place today will affect our capabilities many years from now.

Thank you, Mr. Chairman. I will yield back.

[The prepared statement of Mr. Smith follows:]

PREPARED STATEMENT OF CHAIRMAN LAMAR SMITH

Human history is punctuated by great advancements in the exploration of the world around us. We have long sought out the next frontier, which may well be the exploration of our solar system. No doubt humankind will continue to push the boundaries of the known universe.

Not long ago, the exploration of Mars was considered science fiction. Today, with two active robotic missions on-going, it's no longer fiction. Space exploration goes beyond rockets and avionics; it is about hope for the future. Human space flight represents the aspirations and ambitions of the American people.Few sights are more inspiring than when a rocket lifts off a launch pad and disappears into the sky.

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If NASA had sought the advisory group's advice, they would have heard it was "entertaining, but not a serious proposal." Maybe that's why they didn't ask. As this Committee begins to draft the NASA Reauthorization Act, we must be mindful of the impact it will have on the future. The policies we put in place today will affect our capabilities many years from now.

Chairman PALAZZO. Thank you, Mr. Smith.

I now recognize the Ranking Member of the Full Committee for a statement. Ms. Johnson?

Ms. JOHNSON. Thank you very much and good afternoon. I would like to join the Chairman and Ranking Member Edwards in welcoming our witnesses for today's hearing. It is a distinguished group of experts and I look forward to their testimony.

The topic of this hearing is an important one as it touches directly on the future direction of the Nation's human exploration program. I expect that it will be a lively discussion and that it really should be because it just gives us further evidence that NASA space exploration activity is both human and robotic matter and thus worth discussing, maybe even arguing about.

As my colleagues know, I have long been a supporter of human exploration. It pushes technological innovation, advances our understanding of the universe, challenges our best and brightest, and inspires millions of our young people. It also is a very visible symbol of our commitment to the very peaceful commitment to our outer space. In fact, it is not an exaggeration to say that NASA and its programs provide one of the most positive images of the United States abroad and that is as much as we could hope for.

Yet it is evident that despite clear policy direction and successive NASA Authorization Acts, NASA's human exploration program still has an air of tentativeness about it. For example, the International Space Station, which I strongly support, is currently the lynchpin of our human exploration and spaceflight program. However, we still lack a clear picture of the ways it will be used to advance the Nation's exploration goals.

In addition, the Space Launch System and the Orion crew vehicle are transportation systems that will be needed for whichever path we take in our human exploration program, yet they currently are being funded at levels significantly below the authorized budgets and are being forced to make progress under the funding profile that is anything but typical of challenging development programs. If we—if they are essential to the success of the exploration program, then their priorities should be reflected in the resources they are given.

Finally, of course, if our Nation's exploration program is to succeed, we need to have a clear roadmap to follow. That, too, is lacking at present. Mr. Chairman, we can criticize NASA, we can criticize the current or previous Administrations; the reality is we also need to look at our own actions. I believe that many of our colleagues see the benefits both tangible and intangible that we have reaped from our past investments in NASA and successive Congresses have directed NASA to undertake an exciting and inspiring initiative and human expiration of our solar system with Mars as an obvious and challenging goal. That is as it should be. It is a goal worthy of the great Nation that we are and one that will lead to good things for our country even if its attainment winds up taking longer than some of us would like.

Yet at the same time we appear to be unwilling to make the investments that NASA will need to make it if it is to succeed. And we are even failing to deliver the funding we do provide on any kind of predictable basis. This is unfair to the hard-working men and women of NASA and its contracted team and it is unduly increasing risk and winds up costing us more down the road. Yet I am afraid that we seem poised to repeat that pattern again as we consider this year's authorization and appropriations for NASA. We have just forced NASA to take a significant cut to its Fiscal Year 2013 budget as a result of sequestration, and some of the House seem prepared to extend those cuts into Fiscal Year 2014 and beyond.

If Congress actually carries through with such shortsighted cuts, it will make all of the earnest protestations of support for exploration that we may hear today sound very empty indeed. I hope that as we prepare to move forward with our NASA reauthorization, this Committee at least will make sure that NASA has the resources it will need to carry out the very challenging task that this Nation has given it.

Thank you, and I yield back.

[The prepared statement of Ms. Johnson follows:]

PREPARED STATEMENT OF RANKING MEMBER EDDIE BERNICE JOHNSON

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The topic of this hearing is an important one, as it touches directly on the future direction of the nation's human exploration program. I expect that it will be a lively discussion, and that is as it should be, because that is just further evidence that NASA's space exploration activities, both human and robotic, matter-and thus are worth arguing about.

As my colleagues know, I have long been a supporter of human space exploration. It pushes technological innovation, advances our understanding of the universe, challenges our best and brightest, and inspires millions of our young people. It also is a very visible symbol of our commitment to the peaceful use of outer space. In fact, it's not an exaggeration to say that NASA and its programs provide one of the most positive images of America abroad that we could hope for.

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Finally, of course, if our nation's exploration program is to succeed, we need to have a clear roadmap to follow. That too is lacking at present.

Mr. Chairman, we can criticize NASA. We can criticize the current or the previous Administration. The reality is we also need to look at our own actions. I believe that many of our colleagues see the benefits, both tangible and intangible, that we have reaped from our past investments in NASA. And successive Congresses have directed NASA to undertake an exciting and inspiring initiative of human exploration of our solar system, with Mars as an obvious and challenging goal. That is as it should be-it is a goal worthy of a great nation, and one that will lead to good things for our country, even if its attainment winds up taking longer than some of us would like. Yet, at the same time we appear to be unwilling to make the investments that NASA will need for us to make if it is to succeed. And we are even failing to deliver the funding that we do provide on any kind of predictable basis.

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Chairman PALAZZO. Thank you, Ms. Johnson.

If there are Members who wish to submit additional opening statements, your statements will be added to the record at this point.

At this time I would like to introduce our panel of witnesses. Our first witness is Dr. Louis Friedman, Co-Lead of the Keck Institute for Space Studies Asteroid Retrieval Mission Study and Executive Director Emeritus of the Planetary Society. Our second witness is Dr. Paul Spudis, Senior Staff Scientist at the Lunar and Planetary Institute. Our third witness is Dr. Steven Squyres, the Goldwin Smith Professor of Astronomy at Cornell University and Chair of the NASA Advisory Council. Our final witness is Mr. Doug Cooke, an Aerospace Consultant with Cooke Concepts and Solutions. Prior to his current position, Mr. Cooke served as the Associate Administrator for Exploration Systems Mission Directorate at NASA.

As our witnesses should know, spoken testimony is limited to five minutes each after which Members of the Committee have five minutes each to ask questions. Your written testimony will be included in the record of the hearing.

I now recognize our first witness, Dr. Friedman, for five minutes.

TESTIMONY OF DR. LOUIS FRIEDMAN, CO-LEAD, KECK INSTITUTE FOR SPACE STUDIES ASTEROID RETRIEVAL MISSION STUDY AND EXECUTIVE DIRECTOR EMERITUS, THE PLANETARY SOCIETY

Dr. FRIEDMAN. Thank you very much, Mr. Chairman and Members of the Committee. It is an honor to be here again. The very holding of this hearing on next steps to Mars underscores the point that human exploration has a goal and a direction. Mars is the only human accessible world to study the possibilities of either indigenous past life or potential future life. The asteroid retrieval mission about which I am talking and which was first studied by the Keck Institute for Space Studies creates a first step beyond the Moon, the only one that is now capable—that we are now capable of performing and the only one which we can afford within the current space program budget.

This mission represents an opportunity to sustain American leadership in robotic and human space exploration with technological innovation and engineering prowess. While other nations dream of duplicating the American achievement of a half-century ago, the Administration's new plan has the U.S. looking beyond the Moon on a path that will eventually take humans to Mars later in this century. The new initiative is not a giant-step, Apollo-like crash program; instead, it follows a flexible and cost-effective path using stepping stones into the solar system. The stepping stones are literally and figuratively provided by the near-Earth asteroids.

A robotic spacecraft using solar electric propulsion will rendezvous with a very small asteroid in an orbit that is close to Earth's orbit around the Sun. Redirecting that asteroid to the desired orbit in Earth-Moon space will take several years with the highly efficient but low continuous thrust provided by solar electric propulsion systems. The mission will serve as a key test, a key technological test, for higher levels of power of solar electric propulsion that will be needed for the Moon and Mars.

The asteroid retrieval mission can be done soon with a launch perhaps four or five years from now. It depends of course on finding a good target but this we can do. Hundreds of asteroids this small have already been discovered, although they are hard to see and generally have been ignored and while observers focus on larger objects. Yet we know there are millions of them and a dedicated observation program will find enough candidates and the right combination of traits for attractive targets for this mission. Increases in the observation program, particularly at the Catalina Sky Survey in Arizona and Pan-STAARS in Hawaii are expected to increase the rate of discovery 5- to 10-fold in a few years.

The small asteroids under consideration for this mission pose no danger to Earth. Even if one did impact, it would burn up harmlessly in the atmosphere. In addition, the asteroid would be put on a trajectory that does not intercept Earth even if control of that spacecraft were lost. Nonetheless, the asteroid is big enough to be an interesting object to explore.

Exploring asteroids is important to understand what they are made of and how they hold together. We may someday have to divert one. Exploring them and discovering new ones is also important scientifically because these small bodies of the solar system hold vital clues about the origin and history of the planets. Protection and science are two reasons to explore but these objects offer one more reason for exploration which intrigues many now, and that is prospecting and the potential for possible commercial utilization.

The feasibility of the asteroid retrieval mission caught some in the space community by surprise. But the use of solar electric propulsion technology, the capture of non-cooperative objects in space, the discovery of near-Earth objects, and the application of the clever techniques of celestial mechanics that make up this mission are all developments that NASA has been working—NASA and other space agencies have been working on for years.

The asteroid and lunar orbit may be the first stepping stone on the flexible path to Mars. Asteroids and Sun-Earth Lagrangian points could be the next, then an asteroid further away closer to Mars, then a Martian moon, and then Mars itself. I believe this is the direct and only sustainable way to Mars.

This project will not just unify NASA with science, technology, robotic, and human components, but it will unify many others globally with a great adventure. Europe, Japan, Russia all have asteroid mission plans and solar electric spacecraft in operation. They could join in the mission development. After an asteroid is in place, even private spacecraft developers could be invited to explore and test new prospecting ideas there and maybe create a new commercial industry for utilization of space resources. Meanwhile, NASA again will be leading the world into space moving on to new accomplishments on more distant asteroids, perhaps on the Martian Moons, and then on Mars itself.

Thank you.

[The prepared statement of Dr. Friedman follows:]

Asteroid Retrieval: A Stepping Stone to Mars

Statement of Dr. Louis Friedman to the Space Subcommittee of the U.S. House of Representatives Committee on Science, Technology and Space

Mr. Chairman, Member of the Subcommittee:

Thank you for the opportunity to once again appear before this Committee to discuss the U.S. space program. I am pleased to present a summary of the Keck Institute for Space Studies Asteroid Retrieval Mission study and its implications for the human space exploration beyond the Moon and specifically to Mars.

I applaud the Subcommittee's consideration of this topic. Even though the nation has not taken and cannot afford to take a specific commitment to send humans to Mars at this time, the very holding of this hearing underscores the fact that human space exploration has a goal and a direction. Mars is the only human-accessible world to study possibilities of either indigenous past life or potential future life.

This Subcommittee does not need me to dwell however on the difficulties, costs and exigencies of a human Mars mission. It will require technical developments and scientific understanding which we do not yet have. There are many steps we must take before we can initiate the humans to Mars project. The Asteroid Retrieval Mission creates a first step (beyond the Moon) – the only one we are now capable of performing and the only one which we can afford within the current space program budget.

This mission may be one of the most exciting and interesting one in the history of exploration; certainly, at least, since the Apollo project. It represents an opportunity to sustain American leadership in robotic and human space exploration with technological innovation and engineering prowess. Since the last heroic Apollo mission, no human has ventured beyond low Earth orbit (a distance roughly equal to that from Los Angeles to San Francisco), let alone back to or beyond the Moon. While other nations dream of duplicating the American achievement of a half century ago, the Administration's new plan has the U.S. looking beyond the Moon on a path that will eventually take humans to Mars later in this century. The new initiative is not a giant-step, Apollo-like crash program; instead it follows a flexible and cost-effective path using stepping stones into the solar system. The stepping stones are literally and figuratively provided by near-Earth asteroids. The special cleverness enabling the first step is to use a robot to go out and capture one of these stepping stones and bring it to just beyond the Moon so that we can reach it without building new rockets or crew systems beyond those already now being developed. There is no other affordable way to step onto the path to Mars.

The scheme is audacious, yet both reasonable and feasible. A robotic spacecraft using solar electric propulsion will rendezvous with a very small asteroid (about 25 feet in diameter, but still relatively heavy at about 1.5 million pounds) in an orbit that is close to the Earth's orbit around the Sun. The asteroid would be captured in a large high-strength bag or container deployed once the spacecraft has rendezvoused with the asteroid. Redirecting the asteroid to the desired orbit in Earth-Moon space will take several years with the highly-efficient, but low continuous thrust provided by the solar electric propulsion system. Solar electric propulsion is now frequently used in space missions, scaling it up to the required in this mission is a technology development step that has been planned for many years. This mission will serve as a key test for even higher levels of power and propulsion for spacecraft of the future needed to support human missions to the lunar surface and ultimately to Mars. Using a gravity assist from the Moon, the asteroid will be put into a high lunar orbit that extends beyond the Moon, and in fact, even beyond the Earth-Moon Lagrangian point. It could then be the target for the first trans-lunar human mission, with a goal of doing this by 2025.

This Asteroid Retrieval Mission can be done soon, with a launch perhaps four or five years from now. It depends of course on finding a good target, but this we can do. Hundreds of asteroids this small have been discovered although they are hard to see and generally have been ignored while observers focus on larger objects. Yet we know there are millions of them and a dedicated observation program will find enough candidates with the right combination of traits to be attractive targets for the retrieval mission. Right now, we have a few – enough to be certain we can do the mission, but still looking for more optimal ones. Currently about a dozen asteroids are discovered per year smaller than 10 meters, and of these perhaps 1-3 have orbits which are accessible and characteristics suitable for a retrieval mission target. Increases in the observation program, particular with the Catalina Sky Survey in Arizona and the Pan-STAARS observatory in Hawaii are expected to increase that rate five to ten-fold over the next few years.

In addition to increased discovery rates, steps are being taken to engage the world-wide professional and amateur communities in rapid follow-up observations which permit the accurate characterization of the object's physical properties. The value of this approach was demonstrated recently with the discovery of asteroid 2013 EC20, found by the Catalina Sky Survey on March 7. Within hours the JPL Near-Earth Object program office had calculated a preliminary orbit and requested follow-up through the Smithsonian Minor Planet Center. Within a day a number of observations, including from the NASA Infra-red Telescope Facility, enabled a description of the asteroid's characteristics to be made including its spin rate. During close passage by Earth one week later, radar observations were obtained allowing its size to be determined. That particular asteroid would be fine for a mission to retrieve it by 2021 except that it is smaller than desired – only 2-3 meters, the size of a SUV. But the process of characterizing this object so quickly after its discovery gives us confidence that we will find excellent target candidates before needing to launch the Asteroid Retrieval Mission.

The small asteroids under consideration for the mission pose no danger to Earth: even if one did impact, it would burn up harmlessly in the atmosphere. In addition, the asteroid would be put on a trajectory that does not intercept Earth, even if control of the spacecraft were lost.

While a 5-10 meter asteroid is a small celestial object, it is still a big enough place for astronauts to conduct science measurements and human operations to study its characteristics and determine its potential as a source of resources They can even bring samples back to Earth. After a 50+ year hiatus (1972 to approximately 2025) humans will again be visiting a celestial body and taking new steps deeper into the solar system. In addition to the scientific benefits, the robotic-human synergy will contribute to industrial and technological advances. But, for me, the biggest advantage will be to the popular interest – we will be doing something important and exciting with humans in space again.

Near-Earth asteroids (those whose orbits intersect or pass very close to Earth's orbit) are a subject of increasing attention and importance. The remnant of one that fell in Chelyabinsk, Russia, last month reminded us of the potential danger of an impact, one that could be a lot larger and inflict much more damage. Those are rare – the last noticeable one to inflict damage on Earth was 100 years ago in Siberia, and the most famous one of all that led to the extinction of the dinosaurs (and thousands of other species) was 65 million years ago. But the significance of these objects in Earth's and human history is undeniable.

Exploring asteroids is important – to understand what they are made of and how they hold together. We may someday have to divert one. Exploring them and discovering new ones is also important scientifically because these small bodies of the solar systems (of which the Near-Earth asteroids are the most accessible) hold vital clues about the origin and history of the planets. Protection and science are two reasons to explore – but these objects offer one more reason for exploration that intrigues many now: prospecting. The asteroids are a potential source of water and volatiles for space ventures (perhaps as fuel depots later this century) and possibly of metals and minerals for commercial exploitation. Two private entrepreneurial companies are currently raising money to begin such prospecting, and one more is raising money to observe such asteroids with a space telescope.

The feasibility of the Asteroid Retrieval Mission caught some in the space community by surprise. But the use of solar-electric propulsion technology, the capture of non-cooperative objects in space, the discovery of Near-Earth objects, and the application of the clever techniques of celestial mechanics that make up the mission are all developments that NASA and other space agencies have been working on for years. Even the idea of re-directing a small asteroid was considered in several studies in the past decade. What was new was that recent advances in solar electric propulsion technology make this mission feasible for the first time in history, enabling these ideas to be applied to the flexible path moving humans beyond the Moon recommended by the Augustine Committee and adopted by the Administration for human space exploration. That we could enable the first step on that path with existing systems, deferring the cost and risk of true interplanetary flights until after these achievements, was the surprise. The robotic asteroid retrieval places the risk of human space flight where it belongs: on new exploration.

In our KISS study we quoted a cost, never independently verified, of $2.6 billion. This was the result of a quick study, actually within NASA, with assumptions never vetted by the study team. I actually applaud the group who did this cost – because they made so many conservative assumptions to really test the idea's feasibility. Our KISS study did not have the resources to examine the cost estimate – but I can tell you that many of us thought it was much too conservative. Based on my 40+ years of experience as an aerospace engineer on many planetary projects I believe that the cost estimate for this project will be less than two billion dollars. Without any of the complications of a Mars landing system, entry or descent, or a rover, or a suite of science instruments, surely this mission will cost less than the Mars Science Laboratory. But that is a question for NASA and JPL to answer.

Most space enthusiasts, like me, wish we could jump to Mars. Unfortuantely, we have neither the money nor the knowledge for such a commitment now. But a series of steps, as outlined in The Planetary Society roadmap and similarly described by the Augustine Committee on Human Space Flight in 2009, can steadily increase capabilities to go deeper into interplanetary space. As we achieve longer flight times, more capable crew habitation modules and life support systems, and more knowledge about both the interplanetary and Martian environment we will bring the Mars goal closer. The asteroid in lunar orbit may be the first stepping stone, asteroids in Sun-Earth Lagrangian points could be the next, then an asteroid further away, closer to Mars, then a Martian moon (Phobos or Deimos) and then Mars itself. I believe this is the direct and only sustainable way to Mars.

This project will not just unify NASA with science, technology, robotic, and human components, but also it will unify many others globally, with a great adventure. Europe, Japan and Russia all have asteroid mission plans and solar electric spacecraft in operation. They could join in the mission development. After the asteroid is in place even private spacecraft developers could be invited to explore and test new prospecting ideas there and maybe create a new commercial industry for utilization of space resources. Meanwhile, NASA will again be leading the world into space, moving on to new accomplishments on more distant asteroids, perhaps on the Martian moons, and then on Mars itself.

Dr. Louis Friedman is Co-Lead of the Keck Institute of Space Studies (KISS) Asteroid Retrieval Mission study and is Executive Director Emeritus of The Planetary Society. KISS is a privately funded institute at the California Institute of Technology, supported by the W.M. Keck Foundation.

BRIEF BIOGRAPHY
DR. LOUIS D. FRIEDMAN

Dr. Friedman is a native of New York City. He received a B.S. in Applied Mathematics and Engineering Physics at the University of Wisconsin in 1961, an M.S. in Engineering Mechanics at Cornell University in 1963, and a Ph.D. from the Aeronautics and Astronautics Department at M.I.T. in 1971. His Ph.D. thesis was on Extracting Scientific Information from Spacecraft Tracking Data.

Dr. Friedman worked at the AVCO Space Systems Division from 1963-1968, on both civilian and military space programs. From 1970 to 1980 he worked on deep space missions at the Jet Propulsion Laboratory (JPL) in Pasadena, California. He performed mission analysis and navigation system studies for pre-project definition of Mariner Venus-Mercury, Voyager and Galileo and was the program development leader for Venus Orbital Imaging Radar, which later became Magellan. He led the development and design for the Halley Comet Rendezvous-Solar Sail proposal and was the leader of the post-Viking Mars Program in the late 1970s. In 1979-80 he originated and led the International Halley Watch. He was manager of Advanced Planetary Studies at JPL. Dr. Friedman is the author of more than 20 technical papers on Celestial Navigation, Astrodynamics, Mission Analysis and Design, and Mission Planning. He is the author of the book **Starsailing: Solar Sails and Interstellar Travel,** published by John Wiley, Inc.

In 1978-79, Dr. Friedman was the AIAA Congressional Fellow on the staff of the Senate Committee on Commerce, Science and Transportation. He worked there on Space Policy, Operational Remote Sensing legislation, NASA program oversight and technology innovation on the railroads. He is a member of the American Astronautical Society, the Division for Planetary Sciences of the American Astronomical Society, Sigma Xi and Fellow of the American Association for the Advancement of Science, the British Interplanetary Society and the American Institute of Aeronautics and Astronautics. He is a National Fellow member of the Explorers Club.

Dr. Friedman left JPL in 1980 and co-founded The Planetary Society with Carl Sagan and Bruce Murray. He was Executive Director of the Society for 30 years and remains on the Board of Directors. The Society is a non-profit, popular society seeking to inspire the people of Earth to explore new worlds and seek other life, through research, education and public participation. It is the largest space interest organization in the world. While at the Society he worked on the Mars Balloon development, international Mars rover testing, a Mars microphone, and the joint educational project with LEGO – Red Rover Goes to Mars. He led Cosmos 1, the attempt to fly the first solar sail and was the Principal Investigator of the Living Interplanetary Flight Experiment (LIFE) on the Russian Phobos Sample Return mission was lost in orbit following launch in Nov. 2011. This experiment was to have been the first instance of purposely sending life from Earth to interplanetary space. He has traveled on field expeditions to Kamchatka, the Arctic and Antarctic, tours to observe Halley's Comet, Belize and to several places in the former Soviet Union.

Dr. Friedman lectures in the U.S. and abroad about planetary missions and space exploration programs, has written many popular articles about planetary exploration and space policy as well as op-eds in major newspapers. He has frequently testified to the U.S. Congress about programs and policies in space exploration.

Currently, he is co-leader of the Keck Institute for Space Studies Asteroid Retrieval Mission Study at Caltech. His is also writing a book examining the implications of robotic interstellar precursor missions using nano-spacecraft and solar sails on future human space flight.

May 2013

Chairman PALAZZO. Thank you, Dr. Friedman.

I now recognize our next witness, Dr. Spudis, for five minutes.

TESTIMONY OF DR. PAUL SPUDIS, SENIOR STAFF SCIENTIST, LUNAR AND PLANETARY INSTITUTE

Dr. SPUDIS. Thank you, Mr. Chairman. I thank the Chairman and Members of this Committee for this opportunity to share my thoughts on the appropriate next steps for human exploration of space.

The past 50 years have witnessed some enormous accomplishments of our national space program. We have surveyed the entire solar system and launched hundreds of spacecraft making us more knowledgeable, prosperous, and secure. Despite this history of accomplishment, we lack a clear long-term direction forward and our space program is withering away.

To find a sustainable path forward, we must consider the utility and purpose of human spaceflight. Although much can be accomplished in space using robotics, many tasks require the presence of people who combine high-level cognitive abilities with intricate manual dexterity. I believe our long-term goal should be to possess the ability to go anywhere we choose in space to do whatever job or study we can imagine. Such capability requires an affordable, extensible space transportation system, one built incrementally over variable timescales to prevent fluctuations in funding from preventing its completion.

One can imagine two very different approaches to spaceflight. One conducts a public spectacle, a one-off flags-and-footprints mission to some new and exotic destination. The other approach uses incremental yet cumulative building blocks that enable the gradual extension of human reach beyond low-Earth orbit. The former produces a media event while the latter links capability with progress and creates lasting value. A transportation system that can access the lunar surface can also access all other points of cislunar space, the domain of nearly all the world's satellite assets.

The experience of building International Space Station and the servicing missions to the Hubble Space Telescope have demonstrated that people and machines working together in space can accomplish much more than is possible through the launch of smaller, custom-built expendable spacecraft. Our current template of design, launch, use, and eventual abandonment of space-based assets can be transformed into one of building and maintaining large, extended, and distributed space systems of unprecedented power and capability. This capability will produce enormous economic and societal return. It will create new wealth, not simply consume it.

To achieve these ends, I believe that a return to the Moon to access its—and use its material and energy resources is the next best step for human spaceflight. The Moon is important for three reasons: one, the Moon is close. It is easily and constantly accessible while its proximity permits early development before human return using robots remotely controlled from the Earth. The Moon is interesting. It retains a unique record of its own history and processes as well as those of the Earth-Moon system, the Sun, and the galaxy. This record gives us insights into the past and future of our home planet.

But most importantly, the Moon is useful. Its material and energy resources can break the logistical chains of the Earth. Several recent missions have discovered and confirmed abundant water at the lunar pole, all close to locations of near permanent sunlight. This relationship enables our long-term presence on the Moon where we can extract water for use as life-support consumables, energy storage, and most significantly, to manufacture the most powerful chemical rocket propellant known, hydrogen and oxygen. Water, oxygen, energy, and rocket fuel are vital enabling assets, provisions that will not have to be launched from the surface of the Earth, the deepest gravity well of our solar system. Harvesting these resources from the Moon creates our first off-planet coaling station in space.

We are not capable of sending humans to Mars now or in the near future in either a technical or a financial sense. We need a cohesive intermediate goal, one with specific, scalable activities and benefits that help assemble a permanent space system, a system that will open the way to Mars and all the planets. The Moon affords us this opportunity and the incentive to create such a system, a transcontinental railroad in space. Included with my submitted material is an architecture showing how we can incrementally and affordably develop the system.

We went to the Moon in the 1960s to prove that it could be done. We return to the Moon 50 years later to prove that we can use its material and energy resources to create new capabilities and commerce. A cislunar transportation system, developed and powered with lunar resources, will extend our reach into deep space and revolutionize the paradigm of spaceflight. This effort is not "been there, done that." It is a wholly new, untried, and necessary pioneering enterprise in space.

I thank the Committee for its attention. I welcome your comments and thoughts and I am happy to answer any questions you might have.

[The prepared statement of Dr. Spudis follows:]

Committee on Science, Space, and Technology
Subcommittee on Space

Next Steps in Human Exploration to Mars and Beyond

Testimony submitted by:

Dr. Paul D. Spudis
May 21, 2013

I thank the Chairman and members of the Committee for this opportunity to give you my thoughts on the appropriate next steps for the human exploration of space. This testimony is my personal opinion and does not necessarily represent the views of my employer, the Universities Space Research Association.

The United States has a fifty-year history of accomplishment in space, with a wide variety of satellite and human missions to virtually all of the destinations in this Solar System. We have surveyed the planets from Mercury to Neptune (and soon, Pluto), landed on the Moon multiple times, established a permanent research facility in Earth orbit and deployed a constellation of satellites that have made our lives safer, more productive and interesting. Despite these notable achievements, our civil space program has no long-term focus; it is in disarray, with confusion about objectives and confounded by America's lack of ability to launch humans into space. To confront these issues, I believe that we must step back and address the more basic question of why we undertake human spaceflight and what we hope to achieve by it.

What is the goal of human spaceflight? I believe it is to possess the ability go anywhere, at anytime, to do any job in space that we can imagine. Although much can be accomplished in space with robotic spacecraft, some tasks – including some scientific observation, the repair and maintenance of complex equipment, along with innovative, adaptive problem solving – require the presence of people, who combine high-level cognitive abilities with intricate manual dexterity. Creating the capability to send people and machines wherever necessary requires the development of an affordable and extensible space transportation system, one that can be built incrementally so as to prevent the almost certain future budgetary fluctuations from precluding its completion.

How can such a space capability be created and nurtured? One can imagine two space programs: one being a public relations spectacular, in which some dramatic goal or destination is announced and achieved, and the other being a continuing, gradual and permanent extension of humanity's reach into space. An example of a PR-type program would be the "space race" of the 1960s, with the primary purpose of beating the Soviets to the Moon and not the development a long-term, affordable space faring system. This type of effort may well achieve its immediate goal, but it leaves behind a programmatic and capability vacuum once its objective is satisfied.

The latter program, specifying a gradual human expansion into space, is typified by the Space Shuttle and International Space Station, which – although technically flawed in some ways – retained the basic philosophy that the best approach to creating a permanent space faring system is through the achievement of a gradual and incremental series of milestones. This style of program develops long-term capability and provides practical payback on investment (value for cost) over time, by designing and carrying out shorter, pre-defined milestones. A PR-centered program is most likely to fail in the long-term because typically it delivers on short time scales, lacks continuity and is subject to the whims of the political marketplace.

Since the cancellation of the Vision for Space Exploration in 2010, our national space program has drifted, guided by no long-term strategic direction beyond a vague statement of a nebulous goal of a human Mars mission sometime in the next 30 years. The so-called "Flexible Path" for human exploration, in which we abandon specific destinations and goals for the supposed development of the technology and ability to go anywhere, has in fact taken us nowhere. Technology development as a goal unto itself has not produced anything of enduring value – we *will* get new technical development and lasting public benefit by satisfying the requirements of going somewhere and doing something.

Because we do not possess even the rudiments of a true space transportation system, a human mission to Mars will be decades – not years – away, and as such, Mars should not be characterized as our "ultimate goal." Our long-range ambition is to go everywhere, not simply to Mars. To do so, we must think in terms of building the permanent and adaptable systems needed to become "space faring." Contra the Augustine (2009) report, this is best accomplished through the selection of concrete and distinct intermediate objectives – space destinations nearer to Earth than Mars – where specific and useful activities can be undertaken that will help us to develop and extend the new capabilities needed to sail on the ocean of space. To accomplish this goal, we need a significant destination that is achievable on realistic time scales (10-20 years). To check and assure our progress, and to provide the necessary motivation for continuation of the program, the path we select must have a number of intermediate milestones.

The Moon is the next logical goal for America in space.

We are fortunate to have in our own space "backyard" a miniature planet of surprising complexity and utility. I believe that the Moon offers three principal benefits as the next destination for human spaceflight.

The Moon is close: At 400,000 km away, the Moon is the celestial object closest to our home planet. Moreover, because it orbits the Earth, is it also the most accessible body in space. There is a launch opportunity to the Moon every day of the year, an attribute shared only with getting to low Earth orbit. Planning trips to near Earth asteroids is very difficult, as launch windows open for very short time periods and if the window is missed, the mission must be delayed, typically for many months.

The Moon is also easy to get to: transit times are short (typically, around 3 days), there is the capability for mission abort (in case problems develop on the spacecraft), and it requires less energy to get to the Moon than to go to any other planet.

Because the Moon is only 1.5 light-seconds from Earth, we can remotely operate machines and robots on the lunar surface from control centers on Earth, uniquely permitting us to deploy and operate a substantial robotic presence there prior to human arrival. We can pre-deploy habitats and fuel depots using telerobotics, allowing us to go the Moon with less restrictive logistical constraints than were possible during the Apollo missions of the previous century. We need no new technology to go to the Moon; existing systems can be adapted with minimal modification to return us to the lunar surface. Thus, we can focus technology development efforts on systems designed to perform new tasks and accomplishments never before achieved.

The Moon is interesting: The Moon is a natural laboratory to study the processes involved in creating the rocky planets of our Solar System. It has been shaped and molded by the processes of impact (the collision of solid bodies), magmatism and volcanism (heating, melting and re-melting of the interior) and tectonism (the deformation of solid surfaces). These processes occur on all planets, including the Earth, and study of lunar geologic history over the last 40 years has greatly illuminated our understanding of Earth's history and planetary evolution.

Unique among all space objects, the Moon preserves facets of the history of the Earth-Moon system, specifically by acting as a "witness plate" to record our impact bombardment. By studying the impact record of the Moon, we reconstruct that history for the Earth as well, including the possible preservation of evidence for impact-caused mass extinctions evident in the terrestrial fossil record. A comparable record is not present on any other object of the Solar System. Because the Moon has no atmosphere or global magnetic field, it also retains a record of particles emitted by the Sun and galaxy over the last four billion years, permitting us to better understand the solar and galactic output of radiation and particles through time – phenomena that greatly affect Earth's climate and habitability.

The Moon is a valuable platform for observing the universe. It is a geologically stable base on which extremely sensitive instruments can be emplaced, with a dark, clear sky that affords us one of the best views of the universe, and a place where Earth's radio noise is perpetually silenced on the lunar far side. The Moon also offers a unparalleled surface environment for laboratory study, with its partial-gravity (1/6 that of Earth), hard vacuum ($\sim10^{-7}$ Pa, a trillion times less dense than atmospheric surface pressure on Earth) and thermal extremes difficult to achieve on Earth (dark, cold areas near the poles are only 25 degrees above absolute zero, colder than the surface temperature of Pluto). Such an environment permits a wide variety of experiments to be conducted that would be impossible or extremely difficult to accomplish elsewhere, on Earth or in space.

The Moon is useful: In the past few years, we have made new and astounding discoveries about the material and energy resources of the Moon. A fleet of international spacecraft have orbited and hit the Moon, revealing that areas near the lunar poles contain abundant quantities of water ice and other useful, volatile substances. Additionally, these valuable deposits are located next to zones of near-permanent sunlight, illuminated for more than 90% of the year, permitting the near-constant generation of electrical power from solar arrays. Thus, we have discovered areas on the Moon that permit us to stay on its surface for extended periods of time.

Water is the most useful and enabling substance for space faring. It provides critical life support consumables (drinking and eating), it may be used as radiation shielding (by jacketing habitats with water-filled enclosures), and can be cracked into its component gases (hydrogen and oxygen) for breathing. Water is also a medium for energy storage – reversible electrical generation, a process in which water is cracked into its component gases using electricity provided by solar power during daylight, and is then re-combined into water, generating electricity during the night. Finally, if water is separated into its component gases and these gases are cryogenically converted into liquid form, we create the most powerful chemical rocket propellant known, LOX-hydrogen. This use of water allows us to re-fuel spacecraft on the Moon and eventually, export rocket propellant to space. As the Moon's gravity well is much shallower than Earth's, requiring far less energy to launch, lunar propellant production and export can be used to create a permanent space-based transportation infrastructure.

What is our "mission" on the Moon? The principal goal is to *use the Moon* to create new space faring capability. The discovery of hundreds of millions of tons of water ice at the poles indicates that large-scale harvesting of lunar water is possible. Such a development would create the first off-planet fueling depot, a coaling station for our space fleet. This is a paradigm shifting development for space logistics. By learning how to use the material and energy resources of the Moon, we will take our first steps towards space permanence, developing the ability to go elsewhere in the Solar System. Instead of single shot, one-off missions to some destination, after which the program and all of its valuable developments are abandoned, we build an extensible, maintainable and reusable space transportation system. We went to the Moon in the 1960s to prove that it could be done; we return to the Moon 50 years later to use its material and energy resources to create new capabilities and commerce. This effort is *not* "been there, done that" – it is a wholly new, untried, *pioneering* enterprise in space.

The Moon is reachable under a variety of budgetary environments and constraints. We can structure a lunar return to incrementally build capability over time. There should not be a "large pill" that must be swallowed whole immediately; the key to such development is to craft a program that uses small, incremental steps that work together as an extended, large-scale system. An example of such an architectural approach is described in the supplementary materials that I attach to my testimony. This approach not only achieves the goals I advocate with the flexibility desired, but fits under a reasonable projection of the existing civil space budget.

A space transportation system that can go to the lunar surface and re-fuel there can reach any other point in *cislunar space* (the volume of space encompassing Earth and Moon). This region is the "pay zone" of space, the place where virtually all our scientific, economic, and national security satellite assets reside. The most useful satellites are located in regions of space well above the altitude of low Earth orbit (~200 km). Weather and communications satellites are found in geosynchronous orbit, about 36,000 km high. National security satellites need a variety of high-energy orbits, many of them above LEO. None of these orbits are reachable by humans, with either existing or projected spacecraft.

A return to the Moon to produce rocket propellant from lunar ice creates a refuelable, space-based transportation system that can access not only the lunar surface, but all of the points of cislunar space as well. Such a development would revolutionize spaceflight. Satellites would no longer be limited in power and capability. We could assemble large, powerful distributed space systems in these high orbits using people and machines, transported there by our expanding permanent space transportation system.

The experience of building the International Space Station, as well as missions sent to service and extend the life of the Hubble Space Telescope, show that people and machines working together in space can build systems much larger and more capable than those launched on a satellite from the Earth, even on the largest launch vehicles. As long as we are restricted to what we can lift up from the surface of Earth – the deepest gravity well in the inner Solar System – we will always be mass- and power-limited in space and thus, capability-limited. By developing the resources of the Moon, we greatly mitigate the high cost and difficulty of bringing everything with us from Earth. We become capability-***un***limited, permitting the development of new, and as yet undreamed of capacities. And we gain the means to go the planets – not only to Mars, but to all the interesting destinations that our Solar System offers.

I thank the Committee for its attention, I welcome your comments and thoughts and I am happy to answer any questions that you might have.

Attachments

These papers can be downloaded from: http://www.cislunarnext.org/Site/Home.html

1. Using the Resources of the Moon, Space 2011 paper
2. The Moon, National Defense University paper
3. Cislunar brochure
4. Develop Cislunar Space Next

The following is available from: http://blogs.airspacemag.com/moon/2011/08/destination-moon-or-asteroid/

5. A Comparison of Human Lunar and Asteroid Missions

PAUL D. SPUDIS is a Senior Staff Scientist at the Lunar and Planetary Institute in Houston, Texas. He received his education at Arizona State University (B.S., 1976; Ph. D., 1982) and at Brown University (Sc.M., 1977). His research focuses on the processes of impact and volcanism on the planets and studies of the requirements for sustainable human presence on the Moon. He was Deputy Leader of the Science Team for the Department of Defense *Clementine* mission to the Moon in 1994, the Principal Investigator of the Mini-SAR imaging radar experiment on India's Chandrayaan-1 mission in 2008-2009, and a team member of the Mini-RF imaging radar on NASA's Lunar Reconnaissance Orbiter mission (2009-present). He was a member of the White House Synthesis Group in 1990-1991, the President's Commission on the Implementation of U. S. Space Exploration Policy in 2004 and was presented with the NASA Distinguished Public Service Medal that same year. He is the recipient of the 2006 Von Karman Lectureship in Astronautics, awarded by the American Institute for Aeronautics and Astronautics and a 2011 Space Pioneer Award from the National Space Society. He is the author or co-author of over 100 scientific papers and five books, including *The Once and Future Moon*, a book for the general public in the Smithsonian Library of the Solar System series, and (with Ben Bussey) *The Clementine Atlas of the Moon*, new edition published in 2012 by Cambridge University Press.

Chairman PALAZZO. Thank you, Dr. Spudis.

I now recognize our next witness, Dr. Squyres.

TESIMONY OF DR. STEVEN M. SQUYRES, GOLDWIN SMITH PROFESSOR OF ASTRONOMY, CORNELL UNIVERSITY

Dr. SQUYRES. Thank you, Mr. Chairman. Mr. Chairman, Members of the Committee, thank you for the opportunity to appear today.

The topic of this hearing is the Next Steps in Human Exploration to Mars and beyond. My recommendations to the Committee today are as follows: first, affirm that Mars is and will continue to be NASA's long-term goal for human exploration of space; second, at all future milestones on the road to Mars, direct the Agency to focus on activities that clearly serve the goal of landing humans on Mars, operating there, and returning them safely to Earth; third, adopt cislunar space as the next milestone whether ongoing studies show that it is possible to direct a small asteroid there or not; finally, dictate no milestones beyond cislunar space without first assuring ample funding to achieve them. I will address each of these in turn.

The NASA Authorization Act of 2010 stated that "a long-term objective for human exploration of space should be the eventual international exploration of Mars." I agree. In fact, in my view Mars should be the long-term objective for human exploration of space weather carried out internationally or by NASA alone.

Alone among the planets, Mars is enough like Earth that we can imagine life once taking hold there, as a vast and growing body of scientific knowledge shows that the Martian surface once possessed many of the essential ingredients that are required for life. So sending human explorers to Mars to learn whether life ever emerged there is a goal that is worthy of a great national space agency.

The most useful milestones on the way to Mars are the ones that, when met, help retire risks that will be faced on the way to the Martian surface and back. In the 1960s we didn't go to the Moon all at once. Instead, the capabilities to land humans on the surface of the Moon and return them safely to Earth were built up systematically over a series of Mercury, Gemini, and early Apollo missions. I am convinced that the even more challenging capabilities that will be necessary to achieve a similar goal of Mars must also be built up step-wise. And at each step along the way it will be crucial to examine all the activities that might be conducted critically and pare them down to the minimum necessary to assure progress towards Mars.

Many of the most important capabilities that are going to be necessary for human missions to Mars can be developed in cislunar space. This work can be done far enough from Earth to progress towards a true deep space capability can be demonstrated but close enough to Earth that a safe return in the event of an anomaly is facilitated. Moreover, given the performance capabilities of the Space Launch System and the Orion crew capsule, cislunar space is the only significant destination below low-Earth orbit that can be reached for the foreseeable future. It is the sensible next step simply by process of elimination. And I reach this conclusion whether NASA's ongoing efforts to study redirection of a small asteroid to lunar orbit bear fruit or whether they do not.

After cislunar space, the choice of the next milestone becomes more difficult. Personally, I am not persuaded that any physical destination like the lunar surface, an asteroid, or a Martian Moon is truly necessary to get to Mars, function there effectively, and return safely. Others on this panel may disagree. But while we can debate the relevant merits of such destinations, my most important message to this Committee today is that I believe that no realistic step beyond cislunar space should or can be usefully identified right now.

The fundamental barrier to making an intelligent choice today is that NASA is being asked to do too much with too little. This overtaxing of the Agency is chronic, it is severe, and it is getting worse. It is manifested clearly even in NASA's near-term plans.

To be more specific, the current development schedule for SLS and Orion calls for a flight rate that is so low that I believe it is a cause for serious concern. In a fiscal environment where even next step to cislunar space cannot be carried out at an adequate pace, I feel that for Congress to dictate any subsequent milestones today would be unwise. Unless NASA's funding is increased substantially, any attempt to specify milestones beyond cislunar space today would amount to an unfunded mandate, and if NASA is directed to do something it is not funded to do, I predict that the result will be wasted effort and a delay in achieving the ultimate goal of humans to Mars.

I would like to conclude my opening remarks today on a positive note by pointing out that the solution to the mismatch between NASA's aspirations and its budget may be international partnerships. This was the case for establishment of a permanent Earth-orbiting laboratory and the International Space Station that resulted is a magnificent example of what space agencies can accomplish when they work together.

If no major funding increase for NASA can be found, then I believe that the Agency should aggressively seek out international partners for the human exploration to Mars, but if that happens, I feel that neither Congress nor the Administration can expect to dictate what the next milestone after cislunar space should be unilaterally. Instead, that milestone will have to be negotiated fairly and equitably with those international partners.

Again, thank you for the opportunity to appear today.

[The prepared statement of Dr. Squyres follows:]

Statement of Steven W. Squyres
Goldwin Smith Professor of Astronomy
Cornell University

Before the Subcommittee on Space
United States House of Representatives

May 21, 2013

Mr. Chairman and Members of the Committee, thank you for the opportunity to appear today. My name is Steven W. Squyres, and my title is Goldwin Smith Professor of Astronomy at Cornell University. I have participated for the past thirty years in a number of NASA solar system exploration missions. Recently I chaired the planetary decadal survey for the National Research Council, and I am currently the Chairman of the NASA Advisory Council. The views that I express today are my own, and do not represent the opinions of the National Research Council, the NASA Advisory Council, or any other organization.

Recommendations to the Committee

The topic of this hearing is the next steps in human exploration, to Mars and beyond. My key recommendations to this committee today are as follows:

- Affirm that Mars is and will continue to be NASA's long-term goal for human exploration of space.

- At all future milestones on the road to Mars, direct the Agency to focus narrowly on activities that clearly serve the goal of landing humans on Mars, operating there, and returning them safely to Earth.

- Adopt cis-lunar space as the next milestone, whether ongoing studies show that it is possible to redirect a small asteroid there or not.

- Dictate no milestones beyond cis-lunar space without first assuring ample funding to achieve them.

I will explain my rationale for each of these recommendations in the sections below.

Why Mars?

The NASA Authorization Act of 2010 stated that "A long term objective for human exploration of space should be the eventual international exploration of Mars." I agree. In fact, **I believe that Mars should be *the* long-term objective for human exploration of space, whether carried out internationally or by NASA alone.**

Mercury, Venus, and the giant planets and their moons present environmental obstacles to human exploration that will be insurmountable for decades to come. But what makes Mars unique is not just its relative accessibility. Alone among the planets, Mars is enough like Earth that we can imagine life once taking hold there. A vast and growing body of scientific knowledge shows that the martian surface once possessed many of the essential ingredients required for life. If by exploring Mars we could show that life emerged there -- and therefore that it emerged twice in just this one solar system – it would take no great leap of faith, logic, or anything else to conclude that life may be commonplace throughout the cosmos.

One could ask whether it is necessary to send humans to Mars to answer this question. Despite having devoted my career to exploring the solar system with robots, I am a strong advocate of human exploration, particularly at Mars. Humans have an extraordinary ability to function in complex environments, to improvise, and to respond quickly to new discoveries. Robots, in contrast, do best when the environment is simple and well understood, and the scientific tasks are well defined in advance. Because the capabilities of humans most surpass those of robots in complex environments, the exploration value that humans add is in proportion to the complexity of the environment to be explored. And there is no planetary environment where humans can operate in the foreseeable future that is more complex than the martian surface.

We also must not underestimate the inspirational value of human explorers on Mars. I can tell you from personal experience that NASA's long-lived Spirit and Opportunity Mars rovers were designed and built by people like me who grew up watching the Apollo lunar landings on television, and dreaming of sending spaceships to Mars one day. Sending humans to Mars would surely provide an even more compelling inspirational spark for the next generation of scientists, engineers, and explorers.

To put it simply, **sending human explorers to Mars to learn whether life ever emerged there is a goal worthy of a great national space agency.**

Why Intermediate Milestones?

It is not hyperbole to say that sending humans to Mars and returning them safely to Earth will be the most technically difficult task in human history. When attempting something so difficult, there is great value in setting intermediate milestones against which progress can be measured and demonstrated.

The most useful milestones are ones that, once met, help retire some of the many risks that will be faced on the way to the martian surface and back. In the 1960s, we didn't go to the Moon all at once. Instead, the capabilities necessary to land humans on the lunar surface and return them safely to Earth were developed systematically over a series of Mercury, Gemini, and early Apollo missions. I am convinced that the even more challenging capabilities that will be necessary to achieve a similar goal at Mars must also be built up stepwise.

A more difficult question is whether any of these intermediate milestones must involve a physical destination – a solid solar system body that astronauts can visit and where they can work. Physical destinations have intrinsic appeal; indeed, they are integral to our notion of what exploration means. But if our real goal is the surface of Mars, then we must critically examine the idea that milestones along the way must involve specific bodies where we can plant a flag or leave a mark in the soil.

Possible Intermediate Milestones

A number of possible intermediate milestones on the way to Mars have been discussed over the years. These include:

- Cis-lunar space
- The lunar surface
- A near Earth asteroid
- Mars orbit
- The martian moons Phobos and/or Deimos

I will address the prospective merits of each of these in turn.

Cis-lunar space: Many of the capabilities and systems necessary for eventual human missions to Mars can be tested and validated in cis-lunar space. These include deep space life support and habitability systems, advanced propulsion, complex ground and space operations, and rendezvous in a variety of gravitational settings. All of these can be exercised far enough from Earth that progress toward a true deep space capability can be demonstrated, but close enough to Earth to facilitate a safe return in the event of an anomaly.

The lunar surface: Others on this panel will argue persuasively for the merits of a return to the lunar surface, so I will not dwell on it here. Most significantly, the Moon is the only potential destination on the way to Mars with sufficient gravity to permit anything resembling Mars-like surface operations. If we truly require an intermediate milestone where astronauts can walk, the Moon is the only choice. I am not convinced, however, that such a milestone is absolutely necessary. It was not for Apollo, and we actually know much more about the surface of Mars today than we did about the surface of the Moon before Apollo 11.

Near Earth asteroids: NEAs are important targets for scientific exploration. Asteroids contain clues regarding the formation and earliest evolution of the solar system. Practically, NEAs present both an opportunity and a threat. Mining of asteroids could yield raw materials of considerable value for use in space, because they need not be lifted from the Earth's gravity well. And we know that asteroids have impacted the Earth in the past with devastating effects, and will do so again in the future unless we develop an understanding of these bodies sufficient allow us to prevent such an event.

The relevance of NEA exploration to the ultimate goal of sending humans to Mars must be questioned, however. Certainly a mission to such a body would require operations for long periods of time in deep space, well beyond the Earth-Moon system. The same can be said, however, for any flight far into deep space, whether an asteroid is present along the trajectory or not. Perhaps more persuasively, proximity operations techniques that could be developed and demonstrated at small asteroids would also be useful for exploration of Mars' two small moons, Phobos and Deimos.

Mars orbit: Just as the ability to operate in lunar orbit was necessary for Apollo, the ability to operate in Mars orbit will be necessary for a mission to and from the martian surface. Like Apollo 10, a mission to Mars orbit could demonstrate all elements of a Mars surface mission other than landing, surface operations, and ascent. Mars orbit is also an ideal location for real-time operations of robotic assets on the martian surface, dramatically increasing their potential science return. So clearly Mars orbit is a valuable potential milestone on the way to the martian surface.

Phobos and Deimos: Operations in Mars orbit would also permit exploration of the martian moons Phobos and Deimos. These objects, which are probably captured asteroids, are scientifically interesting in their own right. More importantly, we can expect their surfaces to be littered with martian rocks, particularly ones ejected from the planet during the early, more Earth-like phase of its history. So they present a scientific opportunity that is complementary to what can be achieved on the planet. Again, however, it is not clear that they represent a truly necessary step on the way to the martian surface.

NASA's New Asteroid Initiative

NASA has recently announced a particular variant of the cis-lunar space milestone that would include rendezvous with a very small asteroid that has been redirected to lunar orbit. Because this initiative is part of the President's FY '13 budget request, it is worth particular consideration by this committee.

To evaluate the merits of this initiative, it is useful to break it down into its constituent parts. It has three elements:

- Searching for a potential target asteroid
- Capturing a small asteroid and redirecting it to lunar orbit
- Rendezvous with the redirected asteroid in cis-lunar space

In my opinion, **the first element, searching for a target asteroid, has great value.** I have already described how NEAs pose potential threats, resources, and opportunities for scientific study. The search for a target asteroid for this initiative will inevitably lead to discovery and characterization of many objects. In my opinion, the goal should not be to find a single target whose properties potentially allow it to be redirected. Instead, **the net should be cast widely, using assets that are capable of finding such a target to characterize the population of NEAs as fully as possible.**

Moving on to the third element, I will argue below that **cis-lunar space is the logical next place to send humans beyond low Earth orbit.** My conclusion is dictated by practical considerations and by a long-term focus on Mars, and is independent of whether a small asteroid has been redirected there or not.

The second element, asteroid capture and redirection, is where important questions and concerns lie. Despite some encouraging preliminary studies, **we do not know how to capture and redirect an asteroid**, even a very small one. To their credit, in all of the briefings I have seen on this topic, NASA has described existing concepts for redirecting a small asteroid as "notional". The President's FY'13 budget request includes funds to study these concepts, and to assess their feasibility. The results of this assessment must be examined critically, and **NASA should not be afraid to abandon the idea if the results are not favorable**. The first and third elements of the initiative each have sufficient value on their own even if the second element proves infeasible.

Concerns

Sending humans to Mars will be extraordinarily difficult and costly. With such a challenging long-term goal in a budget-constrained environment, I feel that it is crucial that the milestones on the road to Mars be true milestones, not off-ramps. Stating it differently, the activities we engage in on the way to Mars should be ones that enable reaching that goal, not delay reaching it.

Again, Mercury, Gemini, and the early Apollo flights provide a good model. The tasks carried out on those flights were aimed very directly at preparation for the eventual Apollo landing missions. None of their major activities were superfluous. I believe that the goal of sending humans to Mars will be best served by milestones that maintain a similar focus. So at each step along the way it will be crucial to examine proposed flight activities critically, and to pare them down to the minimum necessary to assure progress toward Mars.

As I noted above, any of the potential candidate milestones could make at least some useful contributions to the long-term goal of Mars. Choosing among them becomes a matter of practical implementation and budget considerations.

In my opinion, **the first milestone should be to return humans to cis-lunar space**. Of course, such a milestone has only modest value in and of itself; it would serve largely to re-assert capabilities we had forty years ago. But if we really are going to Mars, I believe it is an essential next step.

My conclusion is based as much on simple practicality as it is on the work that can be accomplished there. The only vehicles currently in development by NASA to support human exploration beyond low Earth orbit are the Space Launch System (SLS) and the Orion crew capsule. Given the performance capabilities of these vehicles, cis-lunar space is the only significant destination beyond low Earth orbit that can be reached. It is the next step in part simply by process of elimination.

If a small asteroid can be redirected to lunar orbit by the time astronauts get there, the rendezvous possibilities it would offer would make a lunar orbital mission more interesting and challenging. The relevance of such a rendezvous to the goal of putting humans on the surface of Mars remains to be demonstrated, in my opinion, and should be scrutinized. But I believe that **lunar orbit is the sensible next step beyond low Earth orbit whether a small asteroid has been redirected there or not.**

After cis-lunar space, the choice becomes more difficult. **I am personally not persuaded that any physical destination like the lunar surface, an asteroid, or a martian moon is truly necessary to get to Mars, function there effectively, and return safely.** Others on this panel may disagree. But while we can debate the relative merits of such destinations, my most important message to this committee is that **I believe that no realistic next step beyond cis-lunar space can or should be identified today.**

The fundamental barrier to making an intelligent choice of a milestone beyond cis-lunar space now is that **NASA is being asked to do too much with too little**. This overtaxing of the agency is chronic, severe, and getting worse. It is manifested clearly even in NASA's near-term plans.

To be more specific, the current cost-constrained development schedule for SLS and Orion calls for:

- In 2014, an orbital test flight of an Orion capsule with no crew, to be launched on a Delta 4 Heavy.
- In 2017, a lunar flyby test flight of an Orion capsule with no crew, to be launched on a 70-metric ton SLS.
- In 2021, eight years from now, the first flight of a crew in an Orion capsule, again launched on a 70-metric ton SLS, on a mission to orbit the Moon.

Subsequent missions would occur on a "pay-as-you-go" basis, with a launch roughly every two years.

I believe that **the low flight rate projected for SLS and Orion is a cause for serious concern.** No human-rated launch system in NASA's history has flown so infrequently. With such a low launch rate it will not just be difficult to maintain program momentum; it will be difficult to keep flight teams sharp and mission-ready.

In a fiscal environment where even the next step to cis-lunar space cannot be carried out at an adequate pace, I feel that it would be unwise for Congress to dictate any subsequent milestones. Unless NASA's funding is increased substantially, any attempt to specify milestones beyond cis-lunar space today would amount to an unfunded mandate. Unfunded mandates are the bane of any government agency. They can be particularly crippling for an agency like NASA that is tasked with attempting things that have never been done before, with the uncertainties regarding schedule and budget that invariably result. If NASA is directed to do something it is not funded to do, I predict that the result will be wasted effort and a delay in achieving the ultimate goal of humans on Mars.

A Possible Long-Term Solution

I would like to conclude my testimony on a positive note, by pointing out that **the solution to the mismatch between NASA's aspirations and its budget may be international partnerships.** This was the case for establishment of a permanent Earth orbiting laboratory, and the International Space Station that resulted is a magnificent example of what space agencies can accomplish when they work together.

If no major funding increase for NASA can be found, then I believe that the Agency should aggressively seek out international partners for the human exploration of Mars. But if that happens, I feel that neither Congress nor the Administration can expect to dictate what the next milestone after cis-lunar space should be unilaterally. Instead, **that milestone will have to be negotiated, fairly and equitably, with those international partners.**

Steven W. Squyres is Goldwin Smith Professor of Astronomy at Cornell University, and is the Principal Investigator for the science payload on the Mars Exploration Rover Project. He received his Ph.D. from Cornell in 1981 and spent five years as a postdoctoral associate and research scientist at NASA's Ames Research Center before returning to Cornell as a faculty member. His main areas of scientific interest have been Mars and the moons of the outer planets. Research for which he is best known includes study of the history and distribution of water on Mars and of the possible existence and habitability of a liquid water ocean on Europa.

Dr. Squyres has participated in many of NASA's planetary exploration missions, including the Voyager mission to Jupiter and Saturn, the Magellan mission to Venus, and the Near Earth Asteroid Rendezvous mission. Along with his current work on MER, he is also a co-investigator on the Mars Express, Mars Reconnaissance Orbiter and Mars Science Laboratory missions, a member of the Gamma-Ray Spectrometer Team for the Mars Odyssey mission, and a member of the imaging team for the Cassini mission to Saturn.

Dr. Squyres chaired the most recent planetary decadal survey for the National Research Council. He has also served as Chair of the NASA Space Science Advisory Committee, and is currently Chair of the NASA Advisory Council. His awards include the American Astronomical Society's Harold C. Urey Prize, the Space Science Award of the American Institute of Aeronautics and Astronautics, the American Astronautical Society's Carl Sagan Award, the National Space Society's Wernher von Braun Award, and the Benjamin Franklin Medal of the Franklin Institute. He is a fellow of the American Academy of Arts and Sciences.

Chairman PALAZZO. Thank you, Dr. Squyres.
I now recognize our final witness, Mr. Cooke.

TESTIMONY OF MR. DOUGLAS COOKE, OWNER, COOKE CONCEPTS AND SOLUTIONS

Mr. COOKE. Thank you, Mr. Chairman and Members of the Committee, for the opportunity to discuss this exceedingly important subject. I strongly believe that an enduring, long-term strategy for human spaceflight should be developed now with the carefully defined missions that significantly contribute to long-term goals. This strategy does not exist today. Once developed, national will is crucial to sustain the strategy with budget stability; otherwise, we may watch other space-faring nations pass us by when the United States should have led the way.

We first need to address the questions initially without regard for specific budget. What are the geopolitical goals that we want to achieve with human spaceflight? What is this country's long-term vision for future human space exploration? And how do we collaborate with international partners to achieve this vision? If crafted properly, an organized process would obtain and prioritize the exploration objectives from a spectrum of stakeholders. The strategy would then address appropriate objectives for each destination, including those for advanced scientific discoveries, development of critical technologies, and preparing for Mars exploration and others. A widespread advocacy for the strategy would occur with stakeholder participation in the process.

There is a broad international consensus that Mars is a human exploration destination that we should ultimately aspire to. To develop this strategy, we should ask: what is needed to send people safely to Mars in capabilities, technologies, human research, et cetera? A preferred path could then be chosen through a series of carefully selected missions and destinations that must effectively address these exploration goals and objectives.

Regardless of the actual sequence of missions, the current development of the Space Launch System and Orion MPCV are critical to success for the strategy. The strategy must be flexible with the anticipation that it should be responsive to discoveries, budget realities, and emerging technologies.

Asteroids are certainly very interesting objects for scientific study. They can provide information on the formation of our solar system, and cataloging them is important to understand their threat to Earth. The current President budget request included a challenge to retrieve an asteroid and move it to near-Earth space to be investigated by astronauts. It is a clever concept and such a mission would undoubtedly demonstrate technologies and capabilities. However, there is not a recognizable connection to a long-term strategy. It does not appear to be based on consultation with stakeholders, nor are there visible opportunities for international participation, although I am told these are in work. It appears to be a very complex mission with the potential for growing more complex and more costly. As currently defined, the mission definition does not convey a mature concept that should be supported with significant funding without further understanding of its value to long-term human exploration strategy competing with other mission destinations. I believe that robotic missions are currently a more cost-effective way to study asteroids.

In preparing for Mars, the next generation of explorers must learn how to survive in other hostile environments. The Moon is an alien world with partial gravity like Mars, yet is only a 3-day journey from Earth. Human lunar exploration will provide opportunities to test technologies, to experience living and working on another planetary surface, to use lunar resources, and to identify commercial opportunities. The Moon is a truly unique nearby destination where scientists can learn about the history of the inner solar system over the past 4.5 billion years. We now have incredible new information derived from recent robotic missions—LCROSS, LRO, and GRAIL—that can help guide further lunar exploration. I believe the United States should provide leadership in exploring the Moon as an important step in any long-term exploration strategy.

Relevant, near-term missions to Mars may be closer than previously thought. For instance, the mission proposed byInspiration Mars, while I think it is very challenging, may provide such an opportunity, more difficult but on the order of what would be needed for a mission to one of the more difficult-to-reach asteroids, a mission to the fascinating Moons Phobos and Deimos are possible. Mars surface exploration is the ultimate goal that can be reasonably envisioned today.

I propose that the following steps be taken to develop a unified and enduring U.S. human space exploration strategy: conduct an open process including stakeholders to develop the strategy and exploration objectives; reestablish lunar exploration as a valued near-term part of the strategy; identify other near-term mission opportunities that most effectively contribute to long-term exploration goals; identify opportunities to combine resources and capabilities with international partners to achieve these objectives; and endeavor to ensure U.S. leadership in human space exploration.

Once again, I thank you for inviting me here to get my views. I also want to thank this Committee and the Subcommittee and your staff for a continued bipartisan support for human spaceflight. I welcome your questions.

[The prepared statement of Mr. Cooke follows:]

Hearing of the House Committee on Science, Space, and Technology
Subcommittee on Space

"Next Steps in Human Exploration to Mars and Beyond"

Tuesday, May 21, 2013

Testimony of Douglas R. Cooke
Cooke Concepts and Solutions

Thank you Chairman Palazzo, Ranking Member Edwards, and members of this Subcommittee for this opportunity today to discuss the exceedingly important subject of our Nation's future in human space exploration. This is a topic close to my heart, and one I am privileged to be here today to discuss. Congress has an important role to play in helping to establish U.S space policy, so I thank this Subcommittee and indeed the full House Committee on Science, Space and Technology for its continued support for our Nation's space program.

Before I begin, let me be clear that my testimony today is based on my personal views and experience. Although I have business affiliations as disclosed to this Subcommittee, I am not representing anyone other than myself during today's hearing. My testimony is based on my perceptions and programmatic experiences as well as past engineering studies and the collective knowledge from many exceptional colleagues over the years, including my colleagues testifying here today.

Throughout history, great nations and societies have been at the forefront of exploring the frontiers of their time. Egypt, Greece, Rome, Scandinavia, China, Spain, Portugal, France and England were leaders in exploring our world and consequently were viewed as the leading world powers of their eras. Then they retreated from exploration and prominence in the world. What decisions did they make and where are they now? In the case of China, what decisions are they currently making? Britain became great in the 17th century through its exploration and mastery of the seas. America's greatness in the 20th century was evidenced in its mastery of the air and initial steps space exploration. Great nations have always led exploration. For this and future generations, the frontier is space. Other countries will explore the cosmos, whether the United States does or not. Those nations will be the great global economic powers in the years and centuries to come. I believe America should look to its future – and our leaders should consider what that future will look like if we choose not to lead space faring nations. For the foreseeable future, space travel is going to be difficult and dangerous. Critics often claim it is too expensive, but this is the United States of America, and human space exploration is an important strategic component of maintaining leadership in the world. It is one I have dedicated my entire career to supporting.

A long-term strategy for U.S. human space exploration based on discussions like these today can have a momentous effect on the future of the United States and our global partnerships. American leadership in space technology and exploration will ensure that the United States maintains stature in the world, developing and maturing innovative 21st century technologies that are vital to the industries, which will contribute to the health of our economy. If crafted properly with the input from a spectrum of U.S. stakeholders, including the government, industry, private and academic communities, as well as the international space community, the strategy for human space exploration can identify and achieve many important national objectives including advanced scientific discoveries, development of critical technologies and capabilities, technically preparing for Mars exploration, continued sustained human presence in space, economic expansion, strengthening and enhancing global partnerships, and inspiring our people. Our Nation needs a unified and broadly-agreed upon long-term strategy for human space exploration – a strategy that does not exist today.

Developing an enduring U.S. long-term strategy for human space exploration is extremely important to me personally, because human space flight has been my lifelong passion, beginning with the earliest flights of Yuri Gagarin, Alan Shepard, Gus Grissom, John Glenn and all those who followed. I was fortunate to have been given meaningful and significant opportunities during my 38 years at NASA, contributing to Space Shuttle, Space Station, Human space Exploration and other programs. I had significant leadership roles in planning for the future of human space flight for over 20 years. I make these points to reinforce the importance that I give this subject and the needed direction that should come from serious planning efforts.

By holding this hearing, Members of this Subcommittee recognize that the Nation's vision and strategy for human space flight needs to be more clearly defined if our efforts are to result in a meaningful and desirable future. In my opinion, the current strategy continues to be ill-defined, hostage to frequent policy shifts over recent years and the lack of a widely accepted long-term strategy. Individual missions proposed in this environment have no apparent context.

Today, NASA **is** building the capabilities and technologies needed to send humans further from our home planet than ever before. In terms of a long-term strategy, there is a broad international consensus that Mars is a destination that we should ultimately aspire to for human space flight. It is a destination that we are reasonably certain is achievable with further preparation. However, currently there is **not** a long-term strategy for the steps to get there.

Any near-term mission that enables future travel to Mars must be couched in terms of how it fits into a long-term strategy, and it should have clearly defined rationale and objectives. It should be the most efficient and effective solution for how to achieve those objectives.

NASA's human exploration programs need stability in budgets and direction to make efficient progress in critical vehicle developments. It is counterproductive for NASA scientists and engineers, who are working to build the vehicles and support structures needed to get to our ultimate destination of Mars, when they are frequently told to switch gears and develop new transportation systems and technologies for changing missions and destinations. What is truly needed is a national consensus about what our long-term national space strategy should be and the destinations we will go to, as well as the precursor missions that are needed to succeed. We need to coalesce around a unified vision and the strategy needed to achieve it. We need to find the national will to sustain pursuit of that strategy over many years, regardless of changing political winds. Otherwise we will never get out of low-Earth orbit (LEO) and we will watch other space faring nations pass us by, with missions to the Moon and planets where the United States should have and could have led the way.

And let me be clear, I believe developing a national space strategy is the responsibility of the President and his Administration and equally the responsibility of this Congress giving consideration to ideas from vital stakeholders in many communities, including industry, academia and international realms. More importantly, any strategy needs to inspire the American public to participate in the journey for greatness.

Therefore, in my testimony today, I will discuss an approach to reaching consensus on a long-term exploration strategy, and I will discuss meaningful first steps that I believe can be supportable by the international space community and the public. I will also address the questions you outlined in your invitation for me to appear before you today.

Current State in Human Space Flight Planning

Today, NASA's human space flight programs include the International Space Station (ISS), the Space Launch System (SLS), the Multipurpose Crew Vehicle Orion (MPCV), and their supporting programs.

In terms of a human exploration program, the ISS is a unique capability that is utilized for research needed to better understand human health and safety on long space missions. It is also to be used to demonstrate needed technologies and reliability of systems for exploration missions. Since the retirement of the Space Shuttle we are solely reliant on the Russians until future "commercial crew" suppliers develop the capabilities needed to provide that service to NASA. In turn, NASA has turned its focus to developing the next-generation human space flight transportation systems. These next-generation systems, developed by NASA, are what will advance the Nation's knowledge and capabilities in space.

Currently, NASA is developing the SLS to provide the required heavy-lift payload capacity (mass, volume and diameter) necessary to launch the large spacecraft for human exploration missions beyond LEO. A heavy-lift launch capability has other potential uses for science missions, and other national security government customers. The Orion MPCV is being developed as a deep-space crew transportation vehicle (capsule) with systems required to support astronauts for those missions, whether they are backup capabilities for ISS transportation or more importantly longer-term missions to destinations beyond LEO. The design and systems are necessarily much more complex than those needed for transportation to and from LEO. An important point to make is that regardless of the uncertainty of the long-term strategy, a heavy-lift vehicle (SLS) and an interplanetary capable crew vehicle (MPCV) are essential to any human space flight strategy, regardless of the exact beyond-LEO destinations

While these programs continue to make progress in development, I strongly believe that a long-term strategy for human space flight should be developed now to lay out a preferred path for the future of U.S. human space flight and that time is of the essence.

Good Examples of Exploration Strategies

There are good examples that exist for laying out long-term space flight programs. The Apollo Program, the Mars Science Program, and the NASA Science Directorate have benefitted from clear objectives being set to achieve ultimate goals.

The Apollo Program consisted of a number of objectives that led to the human lunar landings. In simplified form, these included:

- Ranger Program: Obtain first close-up lunar images to characterize the surface
- Lunar Orbiter Program: Obtain lunar maps from orbit to provide Apollo landing site data
- Surveyor Program: Achieve first lunar controlled landings to demonstrate soft landings and further characterize the lunar environment
- Mercury Program: Determine whether humans could survive and work in the space environment
- Gemini Program: Demonstrate rendezvous and docking. Demonstrate ability to conduct space walks and work in an EVA suit
- Apollo Program: Perform final Saturn, Apollo capsule and lander tests; and demonstrate operational capabilities leading to lunar landings

The Mars Science Program has been planned for years based on inputs and objectives from Decadal surveys and forums such as Mars Exploration Program Analysis Group (MEPAG), which assemble objectives from constituents of the science communities, technologists, and human space flight. It has laid out meaningful missions to achieve these objectives. Measurements for each mission are developed in formulation committees made up of these constituents. Instruments for each objective on a mission are competed. An important feature is that the Mars program strategy is flexible, in that it is adaptable, changing with compelling discoveries from ongoing missions.

Developing a Rational Long-Term Exploration Strategy

Learning from these experiences and others gained through years of planning for the future of human space flight, leads me to advocate the following approach.

To begin with, the strategy's ultimate long-term goals need to be widely accepted within the broad space flight community. These ultimate goals should include answering fundamental questions:
1.) What are the large geo-political goals that we want to achieve with human spaceflight?
2.) What should be our country's long-term vision for future human space exploration? and,

3.) How do we envision collaborating with international partners, considering their aspirations and strategies to achieve this vision?

I believe the first 2 questions, at a minimum, should initially be answered without the constraints of specific budgets and schedules. Instead, we should acknowledge our ultimate aspirations.

The title of this hearing includes the words "...Mars and Beyond." Any long-term human space flight strategy that speaks to "and beyond" will certainly include missions to Mars. Mars is globally accepted as an ultimate human space flight goal based on the fact that it is the planet most like our own; habitable with known systems, and can be reached within foreseeable technological capabilities. Once achieved, going "beyond" Mars may be less daunting.

The next step is to determine what we need to learn in order to send people safely to Mars. In other words, first work backwards from Mars.

- What are the science and exploration objectives?
- What are the critical technologies and capabilities needed for travel to Mars and back?
- What are the human frailties and how do we address them?
- What are the environments we will encounter and how do we protect for them?
- What performance is required of systems?
- What are the optimal destinations for testing and demonstrations to prove out capabilities and new technologies
- Which intermediate destinations produce the best potential for exploration and science return/discoveries in their own right?
- What precursors are required, including robotic and human missions, testing and potentially other programs?

Second, it is essential to develop the most logical strategy based on collaboration with international partners, with whom the United States would work to develop complementary aspirations, capabilities and needs. Solicitation of inputs and collaboration with interested stakeholders through an organized process would also be required. Decision makers would thus become better informed and better able to assemble important mission objectives, and envision greater potential for achievements at each potential destination. These objectives would be solicited from stakeholders, including the science community (all disciplines), applied science experts, Congress, the Administration, exploration advocates and experts, academia, international partners, private industry, media, education specialists, public affairs experts, etc. If leaders were aware of the entire spectrum of possible objectives, missions could be designed to be more effective, by satisfying as many important objectives as practical. Based on this process, options would then be developed for mission sequences to destinations; options, which most effectively address the established needs, goals and objectives. This consultative process would likely result in more widespread advocacy for the strategy by enabling a broad spectrum of stakeholders to be a part of the process as they provide valued input into key mission decisions.

Third, it is important develop a long term-budget strategy for the United States' human space flight exploration plan. In my view, the budget strategy should not initially be tied strictly to dates for missions, since the timeline for some intermediate missions and human Mars missions extend too far beyond a near-term 5 year budget run-out, thereby making budget projections unrealistic and subject to criticisms of "cost growth" in later years. NASA programs, even internal to NASA, are often forced to make such unrealistic budget estimates. These complex developments are "rocket science." Inevitably technical unknowns are discovered and the programs are forced to develop alternatives – usually with success, but frequently with "cost growth". More importantly, budget instability, including budget cuts cause the development schedules to slip, which can contribute to significant "cost growth." We have seen these factors affect overall cost and schedule too often in the past. The current flat budget without built-in inflation, changing policy and budget priorities, and instability therefore make any long-term budget estimation for a Mars mission, for example, self-defeating and unrealistic. Instead, a better approach is to evaluate NASA long-term budget priorities, including evolution and completion of programs to get a sense of how to proceed. There is a tendency to continue programs, because they have momentum and constituency. However, for progress to be made on the long-term path, decisions have to be made to end programs when they reach a point of diminishing returns in achieving planned objectives. This is necessary to free funds for the important next steps on the exploration path. This needs to be accounted for in planning.

Finally, based on the shorter budget horizon of five years, the United States must rank order its mission objective priorities, choosing only those missions which contribute most effectively to the nation's long-term strategy goals. Considering both the look-back from Mars and the near-term path forward, the United States must choose a preferred path through a series of missions and destinations that most effectively address the nation's agreed-upon exploration goals and objectives. In executing this strategy, NASA must take advantage of existing capabilities (Examples: ISS, SLS, Orion, applicable science mission developments and operational approaches), as well as existing technologies if practical. NASA should not lock-in every possible new technology, instead concentrating on developing the most enabling technologies. Like the Mars Science Program, the human space flight strategy should be flexible with the anticipation that it should be driven by exploration and science discoveries as well as budget realities and emerging technologies.

Figure 1 illustrates notional decision paths that could be options in this process. A key point is that the heavy-lift SLS and the long-duration Orion MPCV are necessary capabilities, regardless of the path that is ultimately taken– visiting an asteroid, cis-lunar exploration, or traveling to Mars.

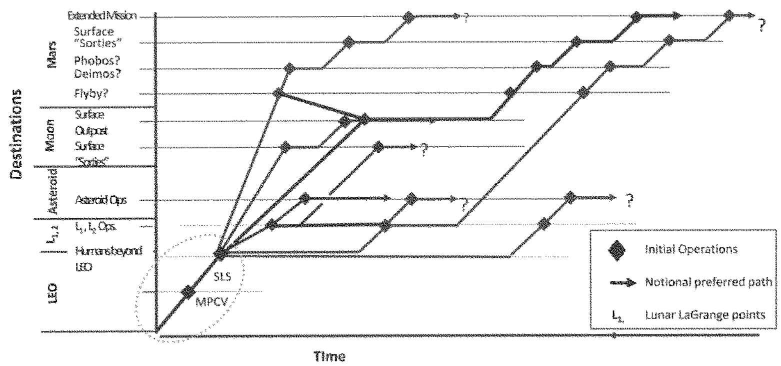

Figure 1-Possible Strategy for Architecture Pathways

<u>Initial Destination Possibilities</u>

Asteroids

The President's FY 2014 budget proposal included a challenge to send humans to an asteroid by 2025. The mission currently being proposed includes three separate elements: the detection and characterization of candidate near-Earth asteroids; the robotic rendezvous, capture, and redirection of a target asteroid to the Earth-Moon system; and the crewed mission to explore and sample the captured asteroid using the SLS and the Orion crew capsule. Each mission element is supposed to contribute to a human Mars mission in the 2030s, and the intent is to leverage on-going exploration, scientific and technology development activities across the Agency.

In my opinion, the publicly discussed rationale for this mission has not been compelling or convincing, nor does there seem to be a recognizable connection to a long-term strategy or supporting stakeholder support. It would seem that the science community should be one of the primary beneficiaries of such a mission. However, in researching this, published news articles have indicated that there is not an apparent expectation for significant scientific return from planetary scientists.[1] At a panel of the recent Humans to Mars Summit, the NASA Science Mission Director is quoted as saying, "We've been very clear that this is not a science-driven mission."[2] Therefore to me and others, it is not apparent that the Administration's asteroid retrieval proposal was developed based on consultation with stakeholders in the broader space community. It is also not apparent that there are meaningful opportunities for international participation. For example, were potential international partners consulted about this new

[1] View relevant article: http://www.sciencemag.org/content/340/6133/668.summary
[2] View source of quote: http://www.thespacereview.com/article/2294/1

mission? Personally, I do not know of any prior consultations. The problem this creates is that NASA spent many years persuading international partners to join the Agency in its lunar mission, encouraging them to take lead roles on certain elements of a lunar architecture, and now NASA is telling them a completely different story.

As for the cost of this new near-term mission, my impression is that the only cost estimate available is a $2.6B estimate that was included in a Keck Institute study. The problem is that this estimate is not NASA owned. However, a commitment to significant near-term funding and diverted resources to study this mission is expected without understanding the impact or understanding how the mission fits a long-term strategy. The President's FY 2014 budget request included $105M for this mission in order to further evaluate costs, technology needs etc. – funding that is certainly being diverted from somewhere else in the NASA's already tight budget. Therefore, in my view, the mission objectives, definition, and rationale for an asteroid retrieval mission, as currently envisioned, do not convey a mature concept worthy of acceptance without further understanding as to value to the future of human space flight as compared to other options/destinations before diverting significant funding.

Additionally, I believe there are potential technical issues with the proposed mission. The yet-to-be-chosen asteroid must be relatively small, on the order of 7 to 10 meters, according to the NASA mission description. As I understand it, a small asteroid is difficult if not impossible to characterize from Earth. The makeup and stability of the object may not be known in advance. If it is tumbling, it may not be retrievable. Additionally, the spacecraft needed to retrieve the asteroid will be complex. Although NASA is working to understand this, the complexity of such a spacecraft and mission will undoubtedly increase as time goes on, and with complexity, costs will rise. In fairness, this is the norm for most complex space development programs, especially those that tackle so many "unknowns." In my view, this mission, as currently envisioned, has many more unknowns than a human lunar mission would have.

Furthermore, I point to the 2012 National Research Council's (NRC) report "*NASA' Strategic Direction and the Need for a National Consensus*" which noted the following:

> "Finding: *Human Exploration*. The committee has seen little evidence that the current stated interim goal for NASA's human space flight program -- namely, to visit an asteroid by 2025 -- has been widely accepted as a compelling destination by NASA's own workforce, by the nation as a whole, or by the international community. Although asteroids remain important subjects for both U.S. and international robotic exploration and study, on the international front there appears to be continued enthusiasm for a mission to the Moon but not for an asteroid mission. This lack of national and international consensus on the asteroid-first mission scenario undermines NASA's ability to establish a comprehensive, consistent strategic direction that can guide program planning and budget allocation. The current program has significant shortcomings in the pursuit of the stated goal of the asteroid mission. There has been a long-standing general agreement that a human mission to Mars should be the long-term goal of the

human space flight program, even though a near-term commitment to such a program is still pending. "

This finding is consistent with my observations, and one that I trust this Subcommittee will take under advisement given the Committee's long-held trust in the work and value of the NRC. Although the NRC's report was published prior to the President's announcement of the current asteroid retrieval mission, the shortcomings and issues cited in the above excerpt are still relevant in my view.

After the President first proposed a human asteroid mission in April 2010 – which is not the same mission as has been proposed in the FY 2014 request -- the NASA Explore Now Workshop was conducted in August, 2010 to develop objectives for human asteroid missions. A finding of this workshop was that a survey telescope is needed, positioned in orbit around the Sun between the orbits of Venus and Earth in order to increase the number of catalogued objects. The activities outlined in this workshop for human missions are as follows:

- Test Hardware Systems: High Performance Propulsion, Long Duration Habitats, Radiation Mitigation, ISRU
- Sample Handling and Curation
- Deploy Scientific Instruments for On-going Operations (Subsurface Drilling, Core Sampling)
- Test potential threat mitigation techniques
- Characterize Physical and Chemical Properties of near-Earth objects: Mass, shape, density, porosity, spin, strength, mineralogy

This workshop was organized to develop mission objectives from interested stakeholders according to the process outlined earlier.

The study of asteroid missions over the subsequent years has led to an understanding of the difficulty of human missions travelling to an asteroid in its natural orbit. This includes the need to identify interesting targets, characterize the targets as to what could be learned scientifically as well as to whether the object is safe to visit with a human crew. Due to the difficulty of characterizing asteroids from Earth, my understanding is that a robotic mission may be needed in advance of any human mission to characterize the candidate asteroid – leading to yet another cost for this mission. Also problematic is the fact that opportunities to visit given asteroids can occur infrequently due to their specific orbits. Therefore, the time between a robotic characterization mission and a human mission to a specific asteroid could take years, and even then the robotic mission could find that the asteroid is not a good candidate. Granted, an asteroid mission would offer the chance to test the SLS and Orion vehicles and human factors during the mission. However, the question is whether this is the most cost effective way of accomplishing these objectives or whether similar testing of SLS/Orion capabilities would be better served with other missions, tests, and destinations.

Asteroids are certainly very interesting objects for scientific study. They can provide key information on the formation of our solar system, and cataloguing of these objects is important to understand their threat to Earth. However, I believe that robotic missions are currently a more cost-effective way to study asteroids. That is not to say that the proposed asteroid retrieval mission is uninteresting. Rather, it is a clever concept, and it would make for a good public affairs event. Such a mission could undoubtedly demonstrate technologies such as solar electric propulsion and orbital mechanics techniques. But I question whether this mission represents the most effective expenditure of precious funds in demonstrating these capabilities. The cost ($2+ billion?) would likely be funded largely at the expense of other human space flight needs. These needs include the fully developed SLS, including the upper stage that provides the needed capacity for beyond-LEO exploration. These funds could potentially help fund an internationally developed lunar lander, whereby NASA could collaborate with other countries which have shown interest in a human lunar mission. In the end, Congress and this nation must ask whether this proposed asteroid mission really represents the best next step in reaching the goal of human exploration of Moon, Mars and other known human exploration goals.

The Moon

I believe there is great value in returning to the Moon and establishing at least a modest outpost there as a first major precursor to a human Mars mission.

If humans are indeed going to go to Mars, the next generation of explorers is going to have to learn how to survive in other forbidding, faraway places across the vastness of space. The Moon is a crucially important stepping stone along that path – an alien world with partial gravity, like Mars, yet one that is only a three-day journey from Earth. Human lunar exploration will provide opportunities to test new technologies, experience living and working on extraterrestrial surfaces and learn ways to use resources found in space – all with the goal of safely preparing crews for missions to Mars and beyond.

It is also clear that human space exploration will be most successful when the shared aspirations of the international community are realized. A global exploration strategy maximizes resources and talent applied to the endeavor, benefitting all of us in space and on Earth. For this reason, the lunar mission which is already broadly agreed upon amongst our international partners is the logical next major step in our long-term U.S. space strategy.

Human missions to the Moon have been studied in detail for many years. For example, a workshop was conducted in April, 2006 to develop objectives for lunar exploration. The workshop's invited 166 attendees consisted of many of the listed space constituencies as described in the process I proposed earlier in this testimony. They generated hundreds of lunar objectives which were then vetted with over one thousand subject matter experts worldwide in various stakeholder organizations and forums, including international conferences and domestic forums, the 10 NASA Centers, NASA HQ Mission Directorates, the NASA Advisory Council, the Lunar Exploration Advisory Group (LEAG), Mars Exploration Program Analysis Group (MEPAG), the Lunar Commerce Roundtable, the U.S. Chamber of Commerce, Next Generation

Space Explorers Conference, the NewSpace 2006 Conference, etc. These objectives were consolidated into 188 objectives and organized into themes.

The subsequent themes and objectives were adopted and tailored by 14 international space agencies, including NASA, becoming the foundation of the current international interest in exploring the Moon. Representatives from these agencies organized initially to develop the Global Exploration Framework and Global Exploration Strategy. This group has evolved into the International Space Exploration Coordination Group, which is developing the Global Exploration Roadmap. They are continuing to assess exploration options as a part of that roadmap.

Through the process of developing lunar objectives beginning with the 2006 workshop, the following example objectives give a sense of what lunar exploration can offer:

- Compelling scientific questions:
  - What is the history of the Sun from solar wind particles deposited in the regolith?
  - What is the history of the inner solar system and Earth-Moon system over 4.5 billion years
    - Impact history correlation with extinctions and changes on Earth
    - Planetary processes and geological characteristics of the Moon: volatiles, volcanism, plate tectonics
  - What is the accessibility of useful resources? What are the processes to extract them and potential uses in missions?
    - Water/ice at the poles, other volatiles and materials
    - In Situ Resource Utilization (ISRU) process development and use
  - What can be learned of the universe from the Moon?
    - Far side radio astronomy shielded from Earth's radio noise
    - Astrophysics and astronomy
    - Stable platform/ no atmosphere for space/ Earth observations
    - Large lunar disc diameter to achieve large apertures for phased arrays
- Monitoring space weather away from Earth's environment and magnetic field
- People learning skills to live and work on another planetary body
- Opportunities for significant commercial and international collaboration
- Using, testing, and maturing of planetary systems that will benefit Mars exploration (habitation, life support, power, thermal, Extra Vehicular Activity (EVA), mobility, etc.)
- Development of surface operational approaches and techniques
- Development and use of surface mobility and EVA capabilities
- Human health and safety in a hazardous planetary environment, including temperature, dust, radiation, partial gravity, no atmosphere, meteoroid, etc.
- Characterize environments
- Measure human response and performance
- Yet unknown opportunities for exploration and discovery

The Moon is a truly unique destination due to its size and diversity and the fact that it is undisturbed by wind and water. As a result, scientists can learn about the history of the inner/near Earth solar system over the past 4.5 billion years. Informed by the vetted lunar objectives described above, NASA studies were performed to choose potential landing sites and mission scenarios to obtain the greatest possible return towards those objectives. This is a major reason for having well-established objectives.

Adding to this information we now have incredible new information on the Moon derived from the Lunar Crater Observation and Sensing Satellite (LCROSS), Lunar Reconnaissance Orbiter (LRO), and the Gravity Recovery and Internal Laboratory (GRAIL). The following and other achievements have been possible:

- Lunar water-ice and other volatiles and minerals were identified and mapped
- Three dimensional lunar maps have been generated
- To enable safe landings, high resolution images have been made of the most compelling potential landing sites, which were requested by lunar scientists and exploration experts
- Knowledge of the Moon's irregular gravitational field

These and other data are now available to inform future human lunar exploration missions. Objectives developed over the past seven years should be updated based on this new knowledge. Far more compelling landscapes and locations than visited by Apollo astronauts are possible based on this combined detailed information. Modern technologies can enable astronauts to safely land in more hazardous, but more scientifically interesting terrain than was possible 40 years ago. The Moon therefore provides a unique nearby opportunity which I believe should be an exceptionally important step in any long-term human space flight strategy.

I believe the United States should provide leadership in this endeavor.

In Moscow last June, the International Space Station Advisory Committee received a Russian briefing on Russia's human exploration strategy, with Russia space officials actually making a plea with the United States representatives to partner with Russia in leading lunar exploration. While the other international agencies support human exploration of the Moon, the United States / NASA has now reversed course, backing out of previous international collaboration in such a venture. The current NASA position, as stated publicly, is that if there ever is an international lunar mission, NASA will not lead the mission, but will participate.

Mars

Mars has always been a source of inspiration for explorers and scientists. Robotic missions have found evidence of water, but whether life exists beyond Earth still remains a mystery. Robotic and scientific robotic missions have shown that Mars has characteristics and a history similar to Earth's, but we know that there are striking differences that we have yet to begin to understand. Humans can build upon this knowledge and look for signs of life and investigate Mars' geological evolution, resulting in knowledge applicable to the evolution of our home planet, Earth.

Mars missions have also been studied for many years. Mars robotic missions continue to provide incredible information that makes the planet an ever more compelling location for people to travel to and advance the science knowledge that is accessible with human capabilities. However, Mars missions where a human actually lands on the Martian surface will require advances in a number of technologies and capabilities to significantly reduce the mass and improve success of the mission -- technologies I am confident will be developed over time.

Relevant nearer-term Mars human missions may be closer than previously thought. For instance, the mission proposed by "Inspiration Mars," while very challenging, can potentially provide a nearer-term mission, which could demonstrate the ability to send people out to Mars distances with a Mars flyby trajectory and a non-propulsive free return to Earth. This mission could demonstrate a subset of the needed technologies for a full Mars mission. It would require much less mass and hardware launched from Earth than a full Mars mission.

More difficult, but on the order of what would be needed for a human mission to one of the more difficult to reach asteroids, is a mission to Mars' moons, Phobos and/or Deimos. These are destinations in the Mars vicinity, with the opportunity to collect samples from these moons and potentially Mars samples ejected through impacts over their history. Tele-operating robots on the surface of Mars with short communication times as compared with robotic missions controlled from Earth would also be an important opportunity. These preliminary missions could enhance the public and stakeholder interest to pursue the actual landed missions on Mars.

Landing of crews on the surface of Mars is the ultimate goal for the U.S. human space flight strategy – at least the ultimate goal that can be reasonably envisioned today. Landing on Mars will be a significant step beyond a Mars flyby and missions to Mars' moons, but it is a goal I believe we must ultimately aspire to achieve successfully. Perhaps the progression from a Mars flyby mission, to exploration of Mars' moons, to Mars surface landings is the sequence of Mars missions that should be pursued in a long-term strategy.

Moving Forward

In my personal opinion, the following steps should be taken as soon as possible to develop a unified and enduring U.S. human space exploration strategy:

- Conduct an open process including stakeholders as outlined above to develop a long-term human and robotic space exploration strategy;
- Reestablish lunar exploration as a valued near-term part of that strategy;
- Identify other near-term opportunities that can effectively contribute to long term needs, goals and objectives to achieve missions to the Mars surface;
- Engage international partners and identify opportunities to combine resources and capabilities in achieving these goals; and
- Endeavor to maintain U.S. leadership in human space exploration.

Conclusion

The preceding is a brief discussion of a process and examples of supporting information that I believe need to be a part of the development of an informed long-term human exploration strategy. Much more supporting information exists from years of studies at NASA and external to NASA. This is just a sample. My hope is from this testimony one can envision what should be considered in the path forward, leading to decisions for a long-term exploration plan. The fact that this Subcommittee is conducting this hearing with this panel illustrates the perceived need and an initial step on a small scale of beginning the process I am proposing.

My fear is that although based on an interesting external study, the current asteroid retrieval mission was apparently chosen in isolation without the benefit of a process involving stakeholders and without the perspective of a long-term exploration strategy. Such a significant shift in near-term focus/destination also risks offending some of our long-term international partners who were already onboard with a lunar mission. Only time will tell if they are willing to join us on the asteroid retrieval mission if that idea persists– or if roles unique to their capabilities can be identified and negotiated. Based on experiences during the Space Station redesign in the early 1990's and observing reactions from retiring the Space Shuttle without a replacement, I believe that imposing a solution with minimal input or communication with key stakeholders and partners does not provide a satisfactory or supportable approach.

Although I have stated my specific views here, I too am only one constituent of the space community. Therefore, if the United States and NASA does what I think is the right thing in soliciting feedback on a long-term strategy from the broader space community; I would gladly submit these same views as part of that inclusive process.

Once again, thank you Chairman Palazzo, Ranking Member Edwards, and members of this committee for inviting me to give my views. I also want to thank this committee and your staff for your continued bipartisan support for human space flight, even through difficult times. I welcome your questions.

Douglas R. Cooke

Douglas R. Cooke is an aerospace consultant for Cooke Concepts and Solutions. In 2011, he retired from NASA after a 38-year career at Johnson Space Center and NASA Headquarters. He advises on company strategies, program management, proposal development, program strategies, and technical matters. His experience at NASA was in engineering and senior level program management positions in the Space Shuttle, the ISS, and Human Exploration Programs. During his career, Mr. Cooke has held major leadership responsibilities and had achievements during critical periods of each of these human space flight programs. In Mr. Cooke's last three years at NASA, he served as the Associate Administrator of the Exploration Systems Mission Directorate at NASA Headquarters. In his last year at NASA, he led efforts within NASA to adopt the current vehicle designs for the Orion and the SLS. As Associate Administrator, Mr. Cooke was also responsible for the Lunar Reconnaissance Orbiter, Lunar Crater Observation and Sensing Satellite, Commercial Cargo and Crew, Human Research and Exploration Technology Programs. Prior to this he was deputy of the same directorate, since it was formed in 2004. He has been in leadership positions for most of NASA's advanced studies in human space exploration since 1989, including the White House studies "The 90 Day Study" in 1989 and the "Synthesis Group Report, America at the Threshold" in 1990. He also had several high priority detail assignments to other NASA centers and NASA Headquarters. Mr. Cooke was NASA technical advisor to the Columbia Accident Investigation Board in 2003. Mr. Cooke has also been a member of the ISS Advisory Committee.

Mr. Cooke has received the Presidential Distinguished Rank Award, Presidential Meritorious Rank Award, NASA Distinguished Service Medal, three NASA Exceptional Achievement Medals, NASA Outstanding Leadership Medal, NASA Exceptional Service Medal, two JSC Certificates of Commendation, a number of NASA Group Achievement Awards, and the Space Transportation Association Lifetime Achievement Award. Most recently he was awarded the Texas A&M Outstanding Aerospace Engineer Alumni Award. Mr. Cooke received a B.S. in aerospace engineering from Texas A&M University.

Chairman PALAZZO. Thank you, Mr. Cooke.

A vote has been called. The Committee will recess until ten minutes after last vote. The Committee stands at recess.

[Recess.]

Chairman PALAZZO. The Subcommittee on Space will come back to order. I want to thank again the witnesses for being here and being available for questioning today. I also want to remind Members that Committee rules limit questioning to five minutes.

The Chair will at this point open the round of questions. The Chair recognizes himself for five minutes.

Mr. Cooke, Congress has consistently affirmed that NASA should develop an exploration architecture to go to the Moon, Mars, and beyond on a timetable determined by available funding. NASA receives roughly 17 billion a year and approximately 3–1/2 billion of that is devoted to exploration systems and support infrastructure and even more under the previous Administration. Last month, the NASA Administrator indicated that we cannot return to the Moon because NASA does not have the funding to do so, arguing that NASA has no money for a lunar lander. My question is: could NASA establish an exploration architecture and development profile that could accommodate a lunar architecture under the current funding profile if schedule was not a driver?

Mr. COOKE. There are a couple of factors that I would like to bring up. One, the existing profile is a flat profile as I understand it still with no inflation, which is problematic. So I think the situation would be improved if there were even inflation. And I think we were seeing that back when I was at NASA. I think NASA can definitely put together architectures that fit a funding profile. We have done it—we have always done it.

I guess a question I would have is if an asteroid retrieval mission is going to cost $2 plus billion according to the Keck study, where is that money coming from? Is that new money? If it is not new money, it is coming from somewhere, and so is it coming out of existing human spaceflight programs? Is it coming out of technology? And if $2 billion—plus billion is available, could it be better spent? Could it be better spent on an upper stage for SLS that brings it to full capability or could we partner with internationals to develop—collaborate and develop a lander for the Moon?

If we have a long-term exploration plan, as I was making a plea for, you understand—you can understand how those things fit into it and what is the best expenditure of funds. So I don't know specifically what the plans are and where the money is coming from for the asteroid retrieval mission, but it seems that an alternative would be to do—would be to put that money toward lunar exploration.

Chairman PALAZZO. Do you believe it is necessary to develop a lander in parallel with the development of SLS and Orion or could the lander be developed at a later date?

Mr. COOKE. I believe that in everything we do we phase our spending, and in fact even in the SLS program as we initially laid it out in 2011, things were phased. We chose the components that we did. We knew we had to get the core stage built, which was new. We—everything—every choice that we made in terms of the engines and boosters and that sort of thing were phased in order to fit under the funding profile. So we—that is something that is always done is you phase your developments to fit under that line. So certainly, as some of the costs come off of development on a rocket or efficiencies are found in space station operations, for instance, money like that could then be phased into development of a lander. It doesn't have to be at the same exact time. We don't—I mean we phased money and spending to develop as we could.

So driving towards your point, you can phase your developments within a funding line to achieve long-term what you are looking to do.

Chairman PALAZZO. Now, Exploration Systems Architecture Study has considerable international input. The witnesses before us today agree that international cooperation will be necessary for any mission. Understanding that you no longer work for NASA, do you know whether international input was sought for the asteroid retrieval mission?

Mr. COOKE. I am not aware that it was. In fact, one of the concerns I have is that it seems like the process is reversed on this asteroid retrieval mission where the mission is announced and then you go figure out the rationale and how to partner on it. And so I am not aware or have seen evidence that there was international consultation going into the announcement.

Chairman PALAZZO. And my last question for Mr. Cooke, the cancellation of the Constellation Program was a huge blow to our Nation's exploration program and created a significant uncertainty for our industry partners. How can Congress ensure that the SLS and Orion are not political footballs in the next Administration and are part of a stable, long-term plan for exploration?

Mr. COOKE. In my written testimony I made the point and I made it briefly in my oral today that we have looked at various scenarios and what steps could be taken in destinations and missions in achieving Mars landings down the road. The SLS and Orion are critical components no matter what that path ends up being. If we are going to travel beyond Earth orbit, you need that capacity in a launch vehicle and you need a deep space crew vehicle with the systems designed for those kind of missions that are totally different than what is needed—they are a step well beyond what is needed for to and from Earth orbit I will point out as well.

Chairman PALAZZO. Thank you. I now recognize Ms. Edwards for five minutes.

Ms. EDWARDS. Thank you, Mr. Chairman.

And thank you very much to our witnesses. I really appreciate your patience today.

I want to start with Dr. Friedman. Dr. Friedman, many of us have had questions about the scientific capability that we gain in terms of asteroid retrieval mission and how that then contributes to going to Mars. And so I wonder if you could very quickly give us a sense of what the science is that is so different than what we would get from Moon—from, you know, a lunar landing and mission if that were the interim step that was chosen?

Dr. FRIEDMAN. Yes, thank you for the question. First of all, it is important to understand that of course the mission—the asteroid retrieval mission wasn't selected for—or its rationale is not for science. If it was, then we have a robotic sample returns and we do missions to asteroids for science purposes. This is part of the human spaceflight program and its primary rationale is a step for humans to take in space.

Having said that, of course, the aspect of what humans could do on an asteroid to delve into the surface to bring back—to conduct experiments related to future resource utilization, to perhaps drill a little bit to do experiments related to asteroid science would contribute greatly not only to the knowledge about asteroids themselves and their relationship to solar system studies but also to what the structure and composition and strength of an asteroid is and the diversity of them so that we can—someday, we might have to deflect one for purposes of planetary protection.

So there will be a lot of human-related science experiments on such an asteroid retrieval mission, but it is important to understand that the real reason for doing it is the human capability of being able to go beyond the Moon, to be able to go on longer flight time missions, to be able to take larger systems with them for longer life support as a first step beyond the Moon and then to more subsequent larger steps after that.

Ms. EDWARDS. Thank you. So I am trying to appreciate then the critical technologies that are necessary with whatever the interim step it is that we choose, whether it is an asteroid retrieval or it is a lunar landing and lunar mission. And so I wonder if each of you very quickly could outline what those critical technologies are so that when we are trying to figure out how do we make the investment in next step to Mars that we are investing in all the right critical technologies whatever the chosen interim destination? And so if we could just kind of go down the line, that would be great.

Dr. FRIEDMAN. Well, I think the fundamental one is related to life sciences and life support for human spaceflight. Once you are outside of the Earth's radiation environment and into deep space, both the length of the system and microgravity and the radiation exposure are key questions. I think that is the dominant one for long duration human spaceflight.

The other big technology that unfortunately is going to have to wait for more robotic missions to Mars is the entry, descent, and landing on Mars. That is huge. That is an unsolved problem. It is not going to be—you can't learn it on the Moon, you can't learn it on an asteroid; you can only learn that on Mars itself. And I think what we are doing in the robotic missions for exploration of Mars is the other key technology. Solar electric propulsion technology is a long duration flight, but that we do know how to do.

Ms. EDWARDS. So could I hear from the other witnesses whether or not it is a lunar mission or an asteroid retrieval?

Dr. SPUDIS. Well, one of the key things that you want to develop to go to Mars, in fact, to do any kind of planetary exploration is the ability to solve some of your logistical problems, and that means learning how to use the materials and energy that space have to offer rather than bringing everything we need with us from the Earth. And I contend that the Moon is an ideal place to do this because it is close enough that we can begin to start doing this robotically with teleoperated machines that could basically pave the way for human arrival later.

Now, survival on a planetary surface—all planetary surfaces are hostile. There is no second Eden. There is no second Earth. They are all required—require us to protect the crew from radiation, from the environment, and to create our own life-support consumables. That can be done on the Moon and that can be done—in fact, a lot of the key technologies we would use there we would use on a trip to Mars eventually anyway.

The other main technological area is learning how to effectively explore planetary surfaces, and that includes using both humans and machines synergistically so that each one builds on the value—on the benefits of the other. That is another experiment that can be done on the Moon because it is a little planet of great complexity. So that is the way I look at it.

Ms. EDWARDS. Thanks. And could we hear very quickly from Dr. Squyres and Mr. Cooke?

Dr. SQUYRES. Yeah, just very briefly I agree with Dr. Friedman that the two most challenging technologies required to send humans successfully to Mars and bring them back are, first of all, deep space, life-support, and habitation; and second, entry, descent, and landing to the Martian surface and assent.

I will point out that to me the connection between particularly the asteroid retrieval mission, which involves proximity operations with a rock that would fit comfortably into this hearing room, I see no obvious connection between that and any of the technologies or capabilities that are required for Martian exploration.

Mr. COOKE. I would agree with most of everything that has been said. I would add that the Moon is unique in that it is a planetary surface that has partial gravity like Mars. It has a dust environment that you have to learn to deal with. You can develop surface operational techniques in a partial G environment in space suits learning those techniques and how to explore and how to get the most out of the missions. So it—and we—in 2006 we had a conference that laid out objectives for the Moon and there are many things that you could do there that would contribute to long-term human exploration.

Ms. EDWARDS. Thank you, Mr. Chairman.

Chairman PALAZZO. I now recognize Chairman Smith for five minutes.

Chairman SMITH. Thank you, Mr. Chairman.

And I, too, want to thank our witnesses today. They have just been excellent in what they have said in their responses to the questions that have already been addressed to them. Several more questions though I would like to ask, and the first one, Mr. Cooke, is addressed to you. This is asking you to speculate a little bit, but I have really not heard anyone answer the question as to why some NASA officials would ignore their own experts—that is those on the Small Bodies Assessment Group—and sort of forge ahead haphazardly with this asteroid retrieval mission. Do you have any idea why they would have chosen to do that?

Mr. COOKE. Well, I don't have any direct information. I am concerned that it was announced without a process that I outlined earlier.

Chairman SMITH. Yeah.

Mr. COOKE. I think that a healthy process gets inputs from your stakeholders and—in terms of objectives and long-term goals and that helps you defined what missions are. I don't see that that has happened here and I don't know exactly—I have no first-hand information—

Chairman SMITH. Okay.

Mr. COOKE. —as to how that occurred.

Chairman SMITH. Other than just a bad judgment call or something like that?

Mr. COOKE. Well, I mean to me it would seem that if we are going to go after an asteroid, it would have—it would be a—there would be science objectives and it has been said publicly that this is not a science-driven mission. And so I don't see the stakeholder objectives having driven a mission that should—you would think of benefit to science.

Chairman SMITH. Thank you, Mr. Cooke.

Dr. Spudis, there are already two asteroid—robotic asteroid retrieval missions by NASA and by Japan who actually, as you know, retrieved an asteroid in 2010 I think. Is there any more to be gained by an astronaut actually being on an asteroid? And we are talking about an asteroid literally the diameter of the table you all are sitting on, 7 to 10 meters. And why can't those robotic missions achieve the same goals as an asteroid would? A while ago Dr. Friedman said, well, an astronaut could drill down into the asteroid, but a robot can do that, too. But is there any value added to having an astronaut land on a 7 to 10 foot diameter asteroid over a couple of robotic——

Dr. SPUDIS. There might be but it is not clear to me at this stage that there is. One thing that keeps getting overlooked in terms of asteroids is that right now we have roughly 45,000 near-Earth asteroids right here on Earth in the terrestrial meteorite collection.

Chairman SMITH. Um-hum.

Dr. SQUYRES. And in fact the largest one is a meteorite named Hoba, which is three meters across and 60 tons. It has been—it was found by a farmer digging in a field in Africa and can't be moved because it is too heavy. So we actually have an NEO right here on the Earth right now for study. It is a nickel metal meteorite.

Fundamentally, meteorites are fairly homogenous. That is one of the interesting things about them. Most of the meteorites are chondrites, which mean they are debris left over from the accretion of the solar system and they have the same chemical composition. They have been heated, they are not heated to varying degrees, and they are—one of the reasons we use them as standards in planetary science is because we can compare planetary compositions to meteorites because they don't vary very much.

Now, one of the key assumptions of a human doing field science either on the Moon or on the Earth or anywhere else is categorizing the diversity in understanding the processes that he is uncovering by sampling, and that is applicable on the Moon, it is applicable on Mars, it is applicable on the Earth; it is not necessarily applicable to a homogenous rock or a homogenous rubble pile.

So the answer to your question is I think we would learn something. No space mission is valueless. But in terms of what we would actually learn in comparison to a robotic sample return, I don't think we would learn that much more.

Chairman SMITH. Okay. Thank you.

And Dr. Squyres, last question, as far as our efforts if we were to embark upon this asteroid retrieval mission is there any reason to believe that our looking for a nonhazardous 7-meter-diameter small asteroid is going to help us in our efforts to try to detect larger and more dangerous asteroids that, if they were to impact Earth, could do us a lot of damage or is there a better more direct way to try to detect those types of asteroids?

Dr. SQUYRES. The kind of search techniques that one would use to find a target for the asteroid retrieval mission will inevitably turn up many, many other objects, some of which will have characteristics that will make them considerably more hazardous to Earth than the target that could actually be deflected and placed—redirected into orbit around the Moon. So I believe that the—one of the truly valuable components of the asteroid retrieval mission is the search for a target because not only will it conceivably come up with a target that you can actually redirect but it is inevitably going to find a whole bunch of other rocks that, on ensemble, maybe much important—much more important both as scientific targets and as objects for future study. But as a threat itself, I think the object you are going to find, as Dr. Friedman has pointed out, is not something that we need to worry about.

Chairman SMITH. Okay. Thank you. Thank you, Mr. Chairman.

Chairman PALAZZO. I now recognize Mr. Posey for five minutes. Sir?

Mr. POSEY. Thank you very much, Mr. Chairman.

You know, so much of what we gain from space every day is unappreciated by the general public. We all know that. And I just think about the tragedy yesterday, without the weather satellites, the early warning that we had, how horrible that could have been if it had been more spontaneous how much more horrible it had been—it could have been.

I think it is unfortunate that we don't really have any space plans right now that inspire the general public. For better or worse, the public that I am familiar with is absolutely totally under-excited about the prospect of going to an asteroid, and I think we need to have a more robust program. I think I agree with three out of four of you to make it a national priority.

And, you know, funding is always the issue and funding is the issue because the NASA budget, as small as it is in comparison to other budgets, is still the biggest pinata. It is the one they go at for totally nonrelated programs because all the Members of the body are not sold on the necessity of it as a matter of return on investment, as a matter of national defense, as a matter of survival for our species ultimately.

And my question to the four of you would be how you think we could better move this space message down the field among our colleagues in the general public? If the general public was more excited about it, Members of Congress would be more excited about it and we wouldn't be really limited to underfunding even the smallest possible missions. So we can start with you, Mr. Friedman, and go on down the line until we run out of time.

Dr. FRIEDMAN. Yes, thank you. That is a key question and it is one that I have worked on my whole career as Executive Director of the Planetary Society until I retired from that position. Public interest is key. It is actually the thing more than science, as I tried to say, more than any other aspect that has gotten me so interested in this asteroid retrieval mission because even in the last Administration with a full and dedicated commitment to building a lunar program and going back to the Moon, the lunar landing, we forget, slipped all the way out to 2028 and that is if the funding had been maintained, which it wasn't going to be maintained. Where would it have been by now in the 2030s?

The joy of the asteroid retrieval mission I think has got me so excited is is we actually begin the process in just a couple of years from now. We are going to be looking for the asteroids this year. We are going to be launching the mission to the asteroid in three or four years from now. We are going to be towing it in an exciting venture that people will be excited about, something never been done in the history of the space program before. We will be engaging the public and human spaceflight, prepping the target in the way we did with Gemini and Mercury before we went to Apollo. And we will be achieving human missions to the destination in a much-sooner timescale rather than having to wait two or three decades. I want to get to Mars quickly. I made that clear. But this is the only way I think that we can engage the public and maybe drive up the money that goes with that.

Dr. SPUDIS. It is an interesting question because the premise sort of assumes that, unless you have an exciting activity, that people won't support something, and yet our society is filled with valuable, critical things that we all agree are needed that people don't get excited about. And so I think really your challenge is to show the public that they are getting value from the money spent. And that is why I believe that building an extensible, reusable system, a space-faring system that allows us to do all the things we want to do at various spots in space is the way to go. And one way to do that is to go back to the Moon and learn to use those resources. That is the way I advocate. There may be other solutions.

But fundamentally, I think the key thing we need to do to become a space-faring people is to develop that system. The things that we get from that, the benefits from that will be self-evident. I mean right now you mentioned the weather satellites. There is communications. We depend on space assets for many aspects of our modern technical civilization, so what we really seek is public support, not necessarily excitement.

Dr. SQUYRES. I think that the best way to maintain public support is with an unwavering focus on Mars as the destination. The night that the Curiosity rover landed on Mars, thousands of people turned out in Times Square in New York City at 2:00 in the morning just so they could watch it on the big screen. It has captured the public imagination. It has captured public interest. And so I think the best way to maintain that interest is to maintain an unwavering focus on Mars as the ultimate destination and show how each milestone along the way is connected to reaching that destination.

Mr. COOKE. I would agree with that. And the Mars program has done an incredible job of making people aware of what is happening and getting them excited about it, and it is a model, I think, for what we do. I think a key aspect of this is having a plan that people recognize. We don't have one right now, a long-term plan on how to get to Mars. I think we need one with defined steps that are exciting, that we know will make a—will have achievements that contribute to the ultimate goal. And if we have a wide range of stakeholders including the science community and including the public and including media, including academia and private industry as a part of the—of defining that set of objectives and goals, then you build in advocacy from those groups that also are part of the plan.

Mr. POSEY. Thank you. Thank you, Mr. Chairman.

Chairman PALAZZO. I now recognize Mr. Rohrabacher for five minutes.

Mr. ROHRABACHER. Holy cow. Thank you very much, Mr. Chairman.

I have been—I would just like to ask a fundamental question here because we have been talking about mission to Mars, okay, mission to Mars and different approaches to mission to Mars and what—I would like to ask the panel whether or not they think a mission to Mars is worth the cost or not. I mean if we do a mission to Mars—and correct me if I am wrong—we will have to defund most of the—I mean if we are going to do it now, start now and go directly into a mission to Mars, we are going to have to defund, you know, asteroid detection and then deflection. I mean we might as well forget that. I mean that is expensive. Debris cleanup which unless we don't—unless we clean up the debris, of course, we may end up having our own use of near space being cut off from the future satellites because debris is knocking our satellites out of the air, no more GPS communication satellites, et cetera. Or how about space astronomy, which we know there is some very important projects moving forward with various telescopes that could give us a really in-depth view of the universe.

You know, reading the—I mean unless we think that the tooth fairy is going to leave all the money under the pillow in order to accomplish a mission to Mars, is it really worthwhile, the vast expense and the canceling of programs like this in order for us to take off and start heading on a Mars mission now? I will just go right down the line. That is fine.

Dr. FRIEDMAN. Well, thank you, Congressman. You and I have been Mars supporters for a long time but I think you are quite right in asking exactly that question. Certainly, I haven't heard any of us advocate canceling programs in order to go to Mars right now. I tried to make clear in my statement that we not only don't have the money to do it but I don't think we have the complete technical knowledge or the scientific understanding. What we are building up with the robotic mission to Mars, what we are building up with taking humans into more complex endeavors in space, but as—and technical steps has to be done. We go to Mars when we can afford it. I think that is one of the things that——

Mr. ROHRABACHER. And we can't afford it now. Next? Thank you for that answer.

Dr. SPUDIS. There—you can sort of imagine two ways that you might go to Mars. And one way you could go to Mars is like we went to the Moon with Apollo. We design a spacecraft, we develop an architecture, we launch everything that we take—we need for the voyage from the surface of the Earth, an enormously difficult and mind-bogglingly expensive thing to do considering how much it costs to launch stuff and you need at least one million pounds in LEO to go to Mars with chemical propulsion. The other way that you might go to Mars is to have it be a logical extension of an expanding space-faring system, so you build it with building blocks. You start with small pieces that basically access the various spots in cislunar and then go to Mars when you have that system in place ready to support a Mars mission.

Mr. ROHRABACHER. But that is not just saying that we are now going to start—this is our project, we are starting going to Mars and that is how we are doing it.

Dr. SPUDIS. No, it is——

Mr. ROHRABACHER. And you said you build it into your existing projects.

Dr. SPUDIS. Yeah, it is one of the destinations that you plan to——

Mr. ROHRABACHER. So I take it your answer to my question is now, we should not start on a way to Mars right now as a project on its own?

Dr. SPUDIS. Yes, sir.

Dr. SQUYRES. Despite the fact that I have spent my entire career devoting my efforts to robotic exploration of the surface of Mars, I am personally a strong supporter of the eventual human exploration of Mars. Two reasons: first, humans are far more capable explorers then robots are. What our magnificent state-of-the-art Opportunity rovers accomplished in 9–1/2 years on Mars, Paul Spudis, who is an experienced geologist, could have done in a good week.

Mr. ROHRABACHER. Yeah, I think we all agree that eventually human beings are going to go to Mars and we are—because we are on this Committee, we love that vision and hopefully it may be in our lifetime maybe, but eventually isn't the question. The question is should we start right now a program at NASA that is engaged in spending significant sums of money that specifically as a Mars—manmade Mars mission?

Dr. SQUYRES. My answer is yes in the following sense——

Mr. ROHRABACHER. Okay.

Dr. SQUYRES. —that the next logical step, I believe, on the road to Mars is to reestablish our capability to operate in orbit around another object, specifically the Moon——

Mr. ROHRABACHER. Um-hum.

Dr. SQUYRES. —and that is the next logical space—next logical place for human spaceflight, and I think we should embark on that as soon as possible.

Mr. ROHRABACHER. Okay. And that was as part of a Mars overall—

Dr. SQUYRES. To eventually get us to Mars, yes.

Mr. ROHRABACHER. I think we can do some of these things without necessarily having the Mars in the background but, as we just heard, building it into a program. What about yourself?

Mr. COOKE. I would submit that we are already on that path in certain ways. It is not necessarily a well-defined path but, for instance, everything that we learned from Mars robotic missions is applicable to our knowledge base that contributes to what we need to know to go to Mars. I would say also that the work that is being done on International Space Station right now in terms of understanding human frailties and how to address those, many of those in fact that human research program is aimed at what you need to know about people and their ability to survive in order to go on long missions like to Mars.

Mr. ROHRABACHER. Right.

Mr. COOKE. So I would say we are already on that path that needs to be more coordinated and to understand the intermediate steps better. And another part——

Mr. ROHRABACHER. And would you then suggested that we should be channeling the money out from this asteroid detection and perhaps a debris cleanup and—or defund the—for example, the astronomy projects we heard about? You would then be supportive of channeling that money into a direct program that is going to Mars?

Mr. COOKE. I would not stop all these programs. It is a matter of priorities and we——

Mr. ROHRABACHER. That is right. It is a matter of priorities.

Mr. COOKE. And we need to establish in light of a well-thought-out, long-duration human spaceflight plan that is coordinated with robotic missions and coordinated with these other things to establish what steps can be taken when. It is not all or nothing in my opinion.

Mr. ROHRABACHER. Mr. Chairman, thank you very much for having this hearing and I believe that the last gentleman was right. We have to establish our priorities, and if we try to prioritize something that today has not come, we are doing a big disservice to the young people who are depending on the technologies that we can put in place right now and utilize if we end up not having the astronomy or the debris cleanup that we need to utilize space simply because we have mission unaccomplishable in mind in terms of Mars. Thank you very much, Mr. Chairman.

Chairman PALAZZO. I now recognize Mr. Schweikert for five minutes.

Mr. SCHWEIKERT. Thank you, Mr. Chairman. And in some ways the extension of where Dana was going, all right, let's deal with sort of the reality of our world up here. I mean we have a, you know, government that is being consumed by mandatory spending, you know, our entitlement state. You know, it is just—it is math. It is not political. It is the reality of where we are at.

So I come to the four of you gentlemen. You are all brilliant. You all have your expertise, but if you listen to each other, you all have very different visions. If I came to you and said help us build a box of decision-making with the resources we actually have, I am not asking you what you think it should be; first, what would you do to analyze saying this is what resources, this is our timeline, how would you build that decision-making model? Start on my left, and it is more do I need to put all of you in a room and the last man standing wins? Do—is it—I, you know, what is the appropriate process here?

Dr. FRIEDMAN. Well, if we use that approach, I am at a big disadvantage so I would rather not—I will try some other one. The mission to the asteroid, which I have been speaking about, doesn't replace missions to the Moon or mission to Mars. It is part of a step of technology development and capability in space. The mission—the only mission it replaces is the one that was going to empty space, lunar orbit.

Mr. SCHWEIKERT. Let me sort of rephrase my box on the question.

Dr. FRIEDMAN. Okay.

Mr. SCHWEIKERT. Do we actually have both, in your opinion, a structure between those of us and Congress, those who are the expertise in space and NASA and the exploration world—I am sorry; we have a lot of echo coming—to say here is what we have resources for, here is what is rational within that, here is where we are going technology on the curve, here is how we lay it out.

Dr. FRIEDMAN. Without taking into account sequestration, which I don't understand, I think you have the existing program right now could take these first steps and accomplish the SLS Orion asteroid retrieval, humans taking a first step beyond the Moon in the existing program.

Mr. SCHWEIKERT. Doctor?

Dr. SPUDIS. In order to figure out how to get where you are going, you have to know where you are going to begin with. And I look at as—I looked on it as your job as part of the national leadership to sort of set the long-term strategic direction. How we get there is a way—is an implementation decision. In the way you—you should oversee that but I don't think Congress should necessarily define it. What you should do is ask for specific technical advice and then weigh the options and then make your decisions on that basis.

I—you know, I wish I could say there is some magic bullet that I can give you guys that would tell you instantly that this is the path we need to follow and there you would be. We all have different views on how to get there. We all want to do that. But my basic observation is that if you craft a program with small incremental steps that all work together, eventually, you can build any kind of capability you want under any kind of budgetary environment because effectively you are building it with small steps. You are not trying to take big chunks out of it.

Dr. SQUYRES. Two messages, sir. The first one is that I believe that all four of us would agree that the logical next step is lunar orbit. It is going there to reestablish the capability to operate in deep space and to do the kinds of tasks that are going to be necessary for any of the pathways that we are talking about. So all of us, I believe, agree on the next step: orbit the Moon. Okay.

Beyond that, my plea to you, my heartfelt plea is please do not dictate—please do not mandate another step for NASA beyond lunar orbit unless there is ample funding to pay for it. As I remarked in my opening comments, that would amount to an unfunded mandate, and that is the bane of government agencies. What that would result in, I believe, would be dilution, dispersion of efforts, wasted effort, and eventually is going to take longer to get to where we want to go.

Mr. COOKE. Once again, I think that we need to have a well-established, long-term plan that is derived by stakeholders, and we all understand what it is so we know what steps we can take and we need to look at the near-term budget run-out and figure out what is the best expenditure of those funds in making our way down that path and come up with a preferred path but understand what constraints you have and try to work within those bounds.

Also as a part of this we need to understand what exit criteria we have for programs. That is something we don't do most often because we have a program, we want to keep funding it. But there is a time when you get to a point of diminishing returns in a program and then you say, well, we want to make these next steps so you free up those funds to go to those next steps. So there is—there can be logical paths.

Mr. SCHWEIKERT. So also the willingness to cancel something once it has either lived its life or——

Mr. COOKE. Right.

Mr. SCHWEIKERT. —not going anywhere.

Mr. COOKE. So that we can invest in what comes next.

Mr. SCHWEIKERT. All right. Thank you, Mr. Chairman. I yield back.

Chairman PALAZZO. All right. Thank you. At this time, we are going to go into a second round of questions if there is no objections. None being heard.

My first question is are—and since we have been talking about an asteroid retrieval mission, we have also been talking about how we are going to get back to Mars and the Moon seems to be, I guess, the majority consensus of—would be a good first step in that direction. My question is are you aware of any other countries that are trying to get to the Moon right now? And if so, what countries could they be and what are their expectations? What is driving their lunar mission? And that is for everyone and we will start with Dr. Friedman.

Dr. FRIEDMAN. Well, Russia has two lunar missions they are planning in this decade but they are both robotic and they, other than that, vaguely talk about humans going to the—having—reinvigorating their manned program with a future lunar destination but no active program going on in that. I believe no country has a human program to the Moon. There is talk about Russia, there is talk about China, but they don't have any human program and they are a long way off from doing that.

Dr. SPUDIS. Well, as a matter of fact, there is a—a lot of the new discoveries about the poles of the Moon have been discovered by a fleet of international lunar orbiters in the past five years. I was involved in the Indian Chandrayaan-1 mission. We flew a payload on that mission to map the poles of the Moon with radar. The Japanese had an enormous satellite that orbited the Moon and mapped it, the Kaguya. China sent two spacecraft to the Moon. Orbiters are getting ready to send a lander this year, I believe. ESA has sent spacecraft, European Space Agency. There is a lot of international interest in the Moon.

In terms of human missions, there was a great deal of interest and support in the European Community for our lunar effort before it was canceled. A lot of them were very upset by that. I have a lot of colleagues in ESA and European countries who really didn't understand why the Moon was just discarded without any thought or any debate. And yet they are still interested in the Moon. They see the value of going there. They still want to go there with people.

The other big player is China and they clearly have a vigorous lunar program. They have a vigorous manned program. Clearly, that is on their strategic horizon. I don't know what their ultimate goals are. I suspect at this stage it is largely to show they can do it like we did it 50 years ago, but if—they can see the value of going back to the Moon just like anyone else here can.

Dr. SQUYRES. I think Dr. Spudis has done an admirable job of summarizing the robotic missions to the Moon taking place lately, basically everybody is doing it. There is enormous interest on the part of all major national space agencies, and I have nothing further to add with respect—I have no particular insights regarding the plans of other space agencies for human exploration of the Moon.

Mr. COOKE. There have been discussions since about 2006 with 13 other space agencies with NASA in developing lunar objectives and participating in that. And in fact, about a year ago, I was on a committee where Russians came in and proposed that the U.S. join with them in leading lunar exploration—human lunar exploration. I think there is very widespread support and interest in lunar exploration and I believe a lot of our international partners are looking for us to be leading them.

Chairman PALAZZO. I definitely agree there are international partners looking to us for space leadership, and hopefully, in the days and years and decades to come, we will be able to provide it.

Now, for example, if one of these countries does achieve human lunar mission, and say perhaps it is China and they create some kind of infrastructure on the Moon, and the United States or international partners have no participation in this, do you see any concerns that, you know, them having infrastructure and the United States and NASA not having any infrastructure could be—is that a warranted question? And we can just go down the line if anybody wants to volunteer.

Dr. FRIEDMAN. The United States and the Soviet Union spent nearly $300 billion of today's kind of money translated to the past on missions to the Moon. As soon as they got there, they quit. As soon as the United States got there, they quit. There has been very little drive either in the science community or technical community to spend anywhere near those kinds of sums of money. I do not believe the Chinese will find any more gold on the Moon than the United States or the Soviet Union did.

Dr. SPUDIS. Well, we didn't know at that time that there was gold on the Moon and the gold is at the poles and it is in the form of water, which is the most useful commodity you can have to create capability and spaceflight. Now, I don't think it is something that—having the Chinese going to the Moon is something we should worry about but it might be something to worry about if we are not there as well, because fundamentally, if you are on the frontier and you are the only one doing something, then it is your worldview, your political economic system, your values that determine the values on the frontier. If we are not there, whose values will be determining that?

Dr. SQUYRES. If we all agree that our long-term focus is Mars and getting humans to Mars in a logical stepwise fashion is the goal of our human spaceflight program, I see no particular concerns one way or the other with the Chinese going to the Moon. I don't think that measurably affects our ability to do what we really want to do, which is send humans to explore Mars.

Mr. COOKE. So one point on this is that great nations have always explored, and if China is going to the Moon and we are not— and we are muddling around somehow, we are not going to be leading. And so I think there is a point in all of that. I think the United States should aspire to be leaders in space exploration.

Chairman PALAZZO. Well, thank you. And since this is going to be our last round of questions, I am going to take a little liberty with time and I encourage my Members to do the same.

This question is for Mr. Cooke and Dr. Friedman. The Keck study proposed to the use of advanced hall thrusters for the mission concept as opposed to other forms of solar-electric propulsion. What advantages would hall thrusters offer that other types of thrusters such as VASIMR do not? Dr. Friedman or Mr. Cooke?

Dr. FRIEDMAN. Well, this is a little bit out of my expertise so I am going to have to relay what others have told me, and that is that the—both the efficiency and the availability, the hall thrusters having been used in space and now being developed and usually scaled up to this kind of a mission, VASIMR is certainly the kind of thing we should look to in the future when we get to the surface of other worlds and certainly on Mars missions. But I think for the fact that we want to do this mission in just three or four years, hall thrusters are here now and they are available, and so they are efficient enough. They can be scaled to the right power level now.

Mr. COOKE. I believe that hall thrusters probably have the most experience in terms of electric propulsion. I actually used to fund VASIMR when I was at Johnson Space Center and it certainly is very interesting technology and uses more readily accessible fuels than the xenon that is required for electric propulsion. The question I have is have we by default somehow made a decision that electric propulsion is exactly the right way to get to Mars? There is also nuclear thermal propulsion, there is nuclear electric, there is—we do need high-efficiency propulsion but I think we are using electric propulsion in this case because it is most readily available and it is in the form of hall thrusters. But I am not sure that the decision—or discussions have been made—or had—or the arguments made to that that is absolutely the right propulsion technique for Mars—eventual Mars—human Mars exploration.

Chairman PALAZZO. I now recognize Ms. Edwards.

Ms. EDWARDS. Thank you, Mr. Chairman. And thank you for allowing us to go on a bit because I think this is really the core of what it is that we have got to come to some agreement about over these next several weeks. I think it has been a shame that NASA as an agency and the industry has not had the kind of concerted direction both from the Congress and from various Administrations that really is appropriate to the task that is in front of the Agency.

I share Dr. Squyres' concerns about, you know, aligning the budget and the workforce to the work that we are charged with doing. I think it has been quite unfortunate that the Agency has been put in a position of having a lot of ideas thrust into its basket and none of the money that is required to perform at the—in the kind of way that we need it to.

And so Dr. Squyres, I know that you talked about the importance of human exploration and how that can serve the task of galvanizing the collective spirit of all of us that then will allow for the match of the money with that spirit and excitement and so I appreciate that. And so I want to explore what is going on with SLS and Orion because, Dr. Squyres, as you indicated in your statement that no human-rated launch system in NASA's history will fly as infrequently as that projected for SLS and Orion and the effect of such a low launch rate, as you stated, would make it difficult to maintain program momentum and to keep flight teams sharp and mission-ready.

And Mr. Cooke, you indicated in your statement that SLS and Orion are essential to any human spaceflight strategy. So I wonder if you can comment about how funding to date, which has been lower than what has been authorized, has impacted your position on this and if SLS and Orion are critical regardless of the interim strategy. Aren't we putting NASA behind the 8 ball by not adequately funding SLS and Orion?

Dr. SQUYRES. I am deeply worried about this as I noted in my written testimony. If you look at the current plans for SLS and Orion, they call for an Orion flight, no crew on board, in 2014 launched not on SLS but on a Delta IV Heavy to go far from the Earth, come back, and reenter and validate that part of the system. Next, we hope in 2017 would be another flight again with no crew on board. And then finally, the first flight with an actual crew on board would be eight years from now in 2021 at the earliest to probably orbit the Moon, which is I think, as I said, a logical next step, and then a flight right after that that is maybe something like every two years or so as we can afford to do it. If you look back at every human-rated flight system that we have ever had over NASA's history, none has flown so infrequently and I am deeply concerned about this.

You can quibble all you want about whether SLS is the right design, whether Orion is the right design, but those decisions have been made. What I now see is a program that is not funded at an adequate level to allow that system to be proven out in—at a logical pace. And that is why I beg of you as a committee not to pile more objectives on NASA beyond what they are already trying to do because they don't even have enough money to do what they are trying to do now.

Ms. EDWARDS. So if we came to a conclusion that Mars is the next ultimate destination and we need a launch vehicle, wouldn't it make sense given that we know that is what we need to make those investments that we have to make to keep us on a pathway but to do it in a way that ensures that, you know, forget the eight-year path, that there are some number of events, of activities that ensured safety and mission teams that were able to provide the kind of support that they need and to be mission-ready? It would seem to me that we would need to really—if that is our goal, that we would really need to frontload what we are doing so that we could stay on a pathway that would result in any kind of success over the next decade.

Dr. SQUYRES. I think there are two elements. I think the first element is, as you say, to more adequately fund SLS and Orion so that they can be developed and proven out on a pace that really supports, I think, a safe pathway towards developing these cislunar orbit capabilities that we have talked about as the next step. And the other is that, in parallel with that, begin to sensibly and aggressively pursue international partnerships that may provide other pieces of the puzzle.

I stress, however, that if we intend to involve international partners in a deep, meaningful way in this adventure to Mars, we need to recognize that those international partners should have a seat at the table when it comes to the negotiating what the steps beyond lunar orbit ought to be.

Ms. EDWARDS. Mr. Cooke?

Mr. COOKE. I think you are definitely on the right path. Once again, those—the capability, for instance, for SLS with its capacity, it is not only just lifting mass but it is also volume of payloads and diameters that you need for the kind of human spaceflight elements that we are going to launch down the road and a deep space crew vehicle is—has capabilities that are incredibly important as well. The flight rate is dependent and is driven totally by funding at this point. They are going through the development, which is a cost, but then you—then the recurring units that you get to when you actually start flying missions, of course, they are expensive. So the flight rate in itself is driven by funding.

And I will go back to a point I made earlier, the fact that they definitely need more funding. I also believe that starting with inflation because the effect of flatlined budget with no inflation increase means that your buying power is decreasing and it is compounding interest. So as you work down the years, your buying power goes—is actually going down. You are able to afford less and you are flying less. And so the inflation aspect of the funding is a first step in that discussion.

Ms. EDWARDS. Thank you, Mr. Chairman.

Chairman PALAZZO. I now recognize Mr. Posey.

Mr. POSEY. I thank you, Mr. Chairman.

In the last two decades we have had two dozen or more programs to nowhere, programs that were started under one Administration or one Congress and canceled or funding stopped by the next or another, and I think one of the biggest fears that we all have is that we will have more of those, that whatever direction we ultimately agree to go in tomorrow that the next day or the next Congress or the next Administration might decide to cease and pivot into another direction, which Constellation, for example, was a waste of $9 billion.

Congressman Culberson has proposed the REAL Space Act that basically would set up a board of directors comprised of astronauts, eminent scientists, and such, and that board would appoint an administrator for a term of ten years. I don't know if it is a rolling ten years, how they will do it, but try and give some sustainability, some continuity to our space assets and their aspirations in our programs.

And I realize, you know, nobody in the near future is going to figure out how to make chicken salad out of chicken manure, but I wonder how you feel Culberson's plan would work in reality, if you think that would be part of the answer that might help us sustain our programs. And we can start with Mr. Friedman.

Dr. FRIEDMAN. Well, I am not sure that that is a magic bullet, but certainly we all want stability in the program, and anything that the Congress can do to add to that, which of course means would they really be giving up their year-by-year funding authority on programs?

I think the key to sustainability really relates also to your first question, which is that public interest. We—if the program is exciting and bringing back results while it is undergoing, not some distant future but something that we can do in the current decade, the next decade and making—setting distance records and speed records and new accomplishment for human spaceflight, learning new things in other worlds, that will—that is the only way we can sustain the space program, and to me, that is going to be the key to have a publicly exciting, interesting program.

Mr. POSEY. Thank you.

Dr. SPUDIS. Yeah, I would certainly agree with that in the sense that regular milestones on short timescales are critical. You need to craft a program that provides paybacks that can be seen under reasonable lengths of time, five years, four years, something like that. If you don't have the program structured that way, you are trying to bite off too big of a chunk. I need a giant 50-ton lunar lander and I have got to have it by this date. You are not going to go anywhere. You are going to consign yourself to future programs to nowhere.

So what I have tried to do is to look at this from a systems point of view. How can I craft a program where I use small pieces? Each one is not particularly expensive in itself but can be operated together as a complex system. And I think that can be done. And one of the values of going to the Moon is that it is close enough to where you can do that. You can actually use robotic systems to create bigger, complex systems out of small pieces so that gives you the ability to start returning regular progress on very short timescales, and I think that is the key to long-term sustainability.

Dr. SQUYRES. I am not personally familiar enough with Mr. Culberson's proposed plan to comment on whether it is the key to maintaining programs——

Mr. POSEY. No, not the key. No program is perfect but just, you know, your initial thoughts.

Dr. SQUYRES. Well, I agree with the previous two speakers that establishing and maintaining stability in this program is critically important. And while the money that gets wasted is a big problem, I think another very big problem has to do with squandering our most precious resource. The most precious thing that NASA has is not SLS, it is not Orion, it is not the Curiosity rover. It is the NASA workforce and the knowledge base that they possess. And what I see when I see NASA changing direction on timescales of a few years is I see demoralization of that workforce and I see erosion of that workforce. And I am constantly discouraged when I see immensely talented young engineers and young scientists who currently work for NASA deciding that the best place for them to pursue their goals in space is someplace else. And if we cannot maintain a continuity of vision and a continuity of purpose within the Agency, we are going to lose that workforce, we are going to lose that capability, and NASA will no longer be able to do what it currently can do.

Mr. POSEY. Well, they did that after Apollo and they are doing it after Shuttle, and I don't think anybody at NASA actually laid a hand on the vehicles but all the people that did are looking for jobs now. They are out of work and they are not going to come back when you call them to come back. It is a tremendous loss of talent and personnel.

Mr. COOKE. I have read that plan that you mentioned and I think it has merit and it should—it merits discussion. I go back to the fact, though, that you need a stable, strategic plan on human spaceflight as well, and then that sort of a structure could then be one you would have confidence perhaps and to manage it. So I think that is important.

And I will use an example of where stability has made a huge difference in a program and it was space station. In the late '80s and early '90s, there—the funding was up and down, very much like what is going through on SLS and MPCV Orion. And we went through a redesign. I was in the middle of all that. I led the engineering under Brian O'Connor and then Bill Shepherd, but we came out of that with an approach and we got stable funding for a number of years. And whereas the program before Space Station Freedom was redesigning and renegotiating contracts every year, we had stable funding that we were able to plan against and actually make progress. And I think without that stability in funding that we got back then—it was $2.1 billion a year I believe—we might not have made it. And the space station is a credit to everyone who ever worked on it because it is an incredible feat. But the stability—that is an example of where stability turned a program around in my view.

Mr. POSEY. And that was sustained by at one time one vote in the House.

Mr. COOKE. Yes, it was. And it was right at that time, it was, yeah.

Mr. POSEY. Thank you.

Chairman PALAZZO. I want to thank the witnesses for their valuable testimony and the Members for their questions. The Members of the Committee may have additional questions for you and we will ask you to respond to those in writing. The record will remain open for two weeks for additional comments and written questions from Members.

The witnesses are excused and this hearing is adjourned.

[Whereupon, at 4:28 p.m., the Subcommittee was adjourned.]

Appendix I

Answers to Post-Hearing Questions

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Louis Friedman
18 June 2013

Rep. Steven Palazzo
Chair, Subcommittee on Space
U.S. House of Representatives Committee on
Science, Space and Technology
Washington DC 20515

Dear Rep. Palazzo,

Thank you again for the opportunity to present to the Space Subcommittee of the House Science, Space and Technology Committee concerning the "Next Steps in Human Exploration to Mars and Beyond." Thank you also for the follow-up questions from you and other members of the Committee. Your interest and concern is sincerely appreciated.

The recent draft authorization bill proposed by the Subcommittee bodes badly for the U.S. space program, particularly human exploration. If it passes, NASA will be left building a rocket to nowhere and crew capsule with only the aging International Space Station to visit. The SLS and Orion will be capable of orbital missions, but as with the past 40 years no destination beyond the Moon. Budget limitations, constantly getting greater, will prevent any plan – not just the asteroid visit, but the far more expensive lunar and Mars landing dreams discussed by space enthusiasts. I urge the members of the subcommittee to ease the prescriptive prohibition of funding for even the next step of asteroid retrieval development when the bill is considered by the full Committee and in Conference by the Senate and House together.

Your request for my responses to your questions is, I hope, a sign of your willingness to consider the issue further. The following are my responses:

<u>To the questions of Rep. Palazzo:</u>

1. NASA has a long history of working with international partners on large-scale programs and missions. What role should the international community play in the next steps to Mars?
a. Can NASA accomplish a mission to Mars without the international community or is it a prerequisite?
b. How was international cooperation coordinated under the Asteroid Retrieval Mission (ARM)?

1. As learned from our experience with the International Space Station, the future of human space exploration should be planned and accomplished internationally. International cooperation will distribute both costs and public interest over a broader base and hence increases the probability of creating a sustainable program which can be afforded and garners political

support. In addition to harnessing greater financial resources, it will also add to the technical assets that can be engaged on the project.

a. NASA *can* accomplish a human mission to Mars without the international community – but it most likely *will not.* I believe international cooperation is a prerequisite for the broad public interest and political support that will be necessary to sustain such an undertaking. That was proven on the International Space Station.
b. The Asteroid Retrieval Mission (ARM) is of course not an approved project and therefore any international cooperation arrangements would have been very premature. However, in the KISS study, we included presentation and discussions with the European Space Agency and their Near-Earth Objects study office had representation in the study. We also presented the ARM to an international meeting of space agencies and industry and held preliminary discussions about potential international interest with representatives from Europe, Japan and Russia. It is of course also to be understood that unlike Moon or Mars landings, robotic asteroid retrieval is a much lower cost mission – it will be the full human asteroid mission that will bring in the larger elements of international cooperation.

2. Generally speaking, which mission is more attractive to the scientific community, the asteroid retrieval mission, or a lunar landing? What has been studied more thoroughly by the scientific community?

2. The planetary science community is of course more familiar with and has studied more the idea of humans landing on the Moon than have they considered about an human asteroid mission. This is a natural result of there having been already 6 human landings and more than 100 other robotic missions to, around and on the Moon. To the larger science community – including physics, chemistry, life sciences, materials science, etc. I would hesitate to say whether another Moon landing would or would not be more attractive than the asteroid retrieval. However, we must keep in mind that the purpose of the asteroid retrieval is not science – it is the development of human space flight, including the advancement of engineering and technology to extend human space flight beyond the Moon.

3. How will a dedicated survey program that focuses on identifying non-hazardous 7-10 meter asteroids affect the existing survey program to identify larger asteroids that could harm the planet?

3. A dedicated survey program looking for *any* size asteroid will inherently find *every* size asteroid. Years ago in testimony to the House Science Committee it was noted that looking for large objects (potentially hazardous) would increase our discovery of small objects. The reverse is even truer, since the telescopes and other instrumentation necessary to find small objects will be more powerful and increase the discovery and characterization rate of all objects. The proposed program for asteroid observation increase is a giant step forward for asteroid discoveries – of potentially hazardous, potentially commercial and potentially scientific interest.

4. In his written testimony, Mr. Cooke mentioned that an additional "robotic mission may be needed in advance of any human mission to characterize the candidate asteroid." Is this true? Does NASA account for this in their Asteroid Retrieval Mission?

4. Mr. Cooke is probably correct in asserting that a precursor visit to the human asteroid target may be necessary. The ARM actually is exactly that – it will serve to completely characterize the target asteroid, and maximize the probability of safety and good planning of astronaut operations there. I doubt that it will be necessary to have a precursor to the precursor, that is to the ARM – since the planning of the robotic mission can be done in a robust and reliable way building on the expected knowledge from Earth-based observations about the target asteroid.

To the Questions from Rep. Edwards:

When I tell my constituents about the great work NASA does, the subject of how NASA affects everyday lives often makes its way into the conversation. In considering your knowledge of what technologies will be needed for human missions to Mars, could you describe how some of those potential technologies and capabilities might find their way into the mainstream? Is there any way to predict the possible economic impact of these potential innovations?

1. Predicting how the results and experience of great scientific and technical ventures will affect individual lives is truly a hard question. We do these things precisely because we don't know how or in what ways benefits come home. Imagine a life without satellites –now used every day by everyone for communications, weather prediction, navigation, land use decisions, etc. Imagine a life without quantum physics which we every day employ in our computers and controls of household appliances and automobiles. Imagine not knowing about the effect of a runaway greenhouse on planetary climate or of the behavior of atmospheric dust storms. We did not predict such practical benefits from the first space probes, from quantum physics theory, or from planetary missions to Venus and Mars. In addition to practical benefits new knowledge alters our perspective about ourselves. Knowing whether the Earth goes around the Sun or Sun goes around the Earth makes no difference to my practical daily life – but it sure alters my view of life and the universe. Similarly, I cannot name a single "product" from the Apollo program that gave me any personal benefit – except that the Apollo program created in me a desire and the means to enter the fields of science and engineering and gain expertise which has helped my country create some of the greatest achievements of human history. I would like to think my experience in space exploration has been a positive contribution to the nation's economic growth. I hope our current younger generation has similar opportunities.

To what extent can potential international partners contribute key enabling technologies to an eventual human mission to Mars? When should potential international partners be asked to participate?

2. Concerning international partners, I have described general benefits of international cooperation in response the questions from Rep. Palazzo. With

respect to citing particular benefits we know that Europe, Russia and Japan have comet and asteroid mission program and have developed science instruments which could help ARM and asteroid exploration. One example is a neutron mass spectrometer used on U.S. missions but supplied by Russia. This has been valuable on Mars and Moon missions. In addition to science sensors, both Europe and Japan are studying potential capture mechanisms for asteroids, and Japan has experience with landing and sampling a near-Earth asteroid. Russia has experience with electric propulsion and in fact supplies solar electric engines to U.S. industry in other satellite programs. Experience by Canada with the robotic arm could also assist in asteroid capture and in the robotic elements of the human mission. ESA is developing a crew support vehicle which should also assist human exploration of the asteroid. In short, there are number of engineering and science opportunities where international cooperation can increase the capabilities of ARM and potentially reduce U.S. costs for human asteroid missions.

To what extent does NASA understand the operations required to support a human mission to a near Earth asteroid? .

3. NASA certainly understands what are and how to do the operations for a human mission to a near-Earth asteroid. However, they do not have currently have the capabilities for such a mission, unless the robotic asteroid retrieval is first achieved. We do not have either the propulsion or crew support vehicle to reach a near-Earth asteroid except for one brought to Earth-Moon space. With the asteroid in lunar orbit, NASA can perform human operations and science there; they have emphatically proved that with their operations at the International Space Station and with the shuttle. A human mission to a near-Earth asteroid is a step beyond low Earth orbit but without the much harder complexities of lunar landing and surface survival and Mars entry and descent. It will require an extension of current capabilities and NASA will have to develop techniques, devices, and new robotic and human operations to carry it out. That is the purpose of this step – to develop new capabilities to take humans further into space for longer periods of time.

Would the technologies and capabilities developed for an asteroid capture and retrieval mission enable a next step to Mars, or would other interim steps be required before undertaking a human mission to Mars?

4. The Asteroid Retrieval Mission is the only way to enable a human mission to an asteroid – at least for the next 15 years and the technologies and capabilities developed on the human mission to the asteroid are a necessary precursor to human flight to Mars. It will be the first step toward interplanetary space beyond the Moon. Specifically, the mission will prove out a significant advancement in SEP technology, demonstrate proximity operations beyond LEO and EVA with a potentially hazardous asteroid, And expose the astronauts to the radiation environment beyond low Earth orbit,

for several (3) weeks – helping to answer one of the principal questions for a human interplanetary flight. The astronaut's operational experience at the asteroid is the same as would be required at the Martian moons – which many think will be a precursor to landing on Mars.

To what extent does the asteroid capture and retrieval mission differ from a human mission to a non-relocated near Earth asteroid? How are the capabilities and operational activities required for sending humans to a near Earth asteroid different or similar to those required for sending humans to a relocated asteroid? Does the relocated asteroid initiative satisfy the rationale given for the President's goal that he stated in 2010?

5. The Asteroid Retrieval Mission is a precursor to relocate an asteroid so that it can be reached by humans within the next ten years. There is no way we could otherwise conduct a human asteroid mission – the relocation is necessary. The human mission to the asteroid relocated to lunar orbit would be a several week mission instead of a 6-9 month mission. A return to Earth would take only days instead of months. Nonetheless it would contain all elements of the longer duration mission to an asteroid further away, not relocated, including exposure to cosmic ray radiation.
    a. To some extent whether the mission to the asteroid relocated in lunar orbit satisfies the President's goal of a human mission to an asteroid by 2025 or not is a matter of semantics. Strictly speaking, it does. However, in my opinion, a human mission to a near-Earth asteroid located in its natural orbit further out in interplanetary space is still a necessary step on the way to Mars. We will undoubtedly want a series of steps with regular milestones as we build up the capability for human to Mars mission – much as we did throughout the Gemini and Apollo program building up to the human lunar landing in 1969.

The inspirational value of a human spaceflight has been a critical means for establishing interest in space and for attracting the next generation to STEM education and careers. The National Academies report, NASA's Strategic Direction and the Need for a National Consensus, stated that *"The committee has seen little evidence that a urrent stated goal for NASA's human spaceflight program-namely, to visit an asteroid by 2025-has been widely accepted as a compelling destination by NASA's own worliforce, by the nation as a whole, or by the international community."* What is **your response to the finding** of the **National Academies?**

6. I agree completely with the National Academies conclusion that an asteroid is not a compelling destination for human space flight. Mars is the only compelling destination. But we cannot achieve Mars in one giant step – we need to build up that capability and achieve interesting and valuable milestones along the way. The asteroid mission is very interesting and very valuable. And the asteroid retrieval makes it possible.

To the question from Rep. Kilner

At the hearing, it was evident that evolving space propulsion will be a key enabler for any human mission to Mars. What are your thoughts on the need to develop space propulsion technologies that will enable the various necessary human exploration missions on the pathway of missions leading us to Mars? To your knowledge, are these technologies being addressed by NASA and are they, in your opinion, adequately prioritized in the agency's current and planned future budgets? What are the key factors that need to be considered in estimating the time to develop, test and field these technologies and in assessing the cost versus benefit of each?

One of the major benefits of the Asteroid Retrieval Mission is electric propulsion development. It scales up by a factor of 4 from current operating deep space systems. Another factor of 4 would enable human missions with electric propulsion leading to Mars. Many in the space community want nuclear power for large power systems, but debate about political considerations and safety issues render this uncertain. Meanwhile solar electric systems are proving more and more capable, and with enough development we still may be to carry out the human to Mars mission. I personally do not think enough is being done with nuclear power sources, but I do think NASA is doing a good job with solar electric development.

Again, Mr. Chairman, thank you and all the members of your subcommittee for the opportunity to discuss the subject with you. I again ask you to reconsider the prohibition for NASA to develop the ARM that is included in the proposed Authorization legislation. I do not believe I am being hyperbolic in stating that without the early milestones for human exploration offered by the asteroid retrieval and subsequent human mission to it, interest and support for the American space program will wither away under the blanket of budget constraints.

Sincerely,

Louis Friedman, Ph.D.
Co-leader, Keck Institute for Space Studies Asteroid Retrieval Study
and Executive Director Emeritus and Co-Founder, The Planetary Society

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Responses by Dr. Paul Spudis

Responses to Questions for the Record

Paul D. Spudis
15 June 2013

Questions from Chairman Palazzo

1. The NASA Authorization Act of 2008 requires NASA to work towards establishing a lunar outpost on the Moon. Is this a necessary step to training for a mission to Mars?

I think that it is. The tasks that we need to master on a human Mars mission may all be addressed and solved in the course of establishing a permanent outpost on the Moon. Moreover, we now know that the material resources of the Moon – specifically, water at the poles – can be harvested and used to support a Mars mission. I look upon a lunar effort in relation to the Mars mission as one of learning to crawl before we try to walk. It is a valuable and necessary learning experience before interplanetary flight is attempted.

2. Generally speaking, which mission is more attractive to the scientific community, the asteroid retrieval mission, or a lunar landing? What has been studied more thoroughly by the scientific community?

It probably depends on which segment of the scientific community you ask, but the value of a lunar outpost has been thoroughly studied and documented at length for the past 40 years, by a wide variety of groups, panels and committees. The value of lunar return has been clearly demonstrated beyond any doubt. In contrast, very little attention has been given to human asteroid missions. Much of what we would like to learn scientifically about asteroids can and is being addressed on a variety of robotic missions. Because of the nature of asteroids (randomized piles of homogeneous rubble), there is much less value to human visits there than the same to the Moon, which is a miniature planet of considerable complexity, requiring human field work to study properly.

3. Given NASA's notionally flat budget for the foreseeable future, the Asteroid Retrieval Mission will necessarily crowd out other priorities. Rather than spending money on this type of mission, should resources be redirected to an SLS second stage and a lunar lander?

An SLS second stage is *required* for any trips beyond low Earth orbit (LEO) and development of that rocket stage is clearly a priority activity. Unless we have an Earth departure stage, no one is going anywhere beyond LEO, either to an asteroid, an L-point, the Moon or Mars. The optimum design of a lunar lander is dependant on the chosen architecture; one emphasizing the use of lunar water to make rocket fuel would dictate a smaller, lighter (and cheaper) lander than an architecture in which the lander is discarded after each use. If the decision is made to build a lunar surface outpost, the architectural decisions made previously under the Vision for Space Exploration should be re-examined and possibly re-scoped to be congruent with the envisioned mission on the Moon.

4. Your written testimony noted the shift to the "flexible path" for human exploration that focused on the development of technology rather than a destination. What were the most important exploration technology achievements of the past three years? How do you think these achievements would have differed if our space program were guided by a specific destination?

My point in bringing up the "flexible path" was to illustrate that it is *not* the best way to achieve genuine spaceflight capability. The experience with technology development within NASA for the past couple of decades is not edifying; much research money has been spent, but few if any of those developments have seen use in actual spaceflight. I believe that we get our best return on technology investment when we are trying to develop systems, equipment or procedures to solve actual problems that arise in specific circumstances (i.e., real flight systems designed to go somewhere). Almost all of the great technical innovations for which NASA can claim credit (e.g., medical sensor instrumentation, flight software, inertial guidance, digital autopilots) were the result of such a genesis.

5. Your written testimony noted the potential perils of a public relations-centered space program. How can we ensure the development of capabilities that will enable missions to Mars on an incremental basis without a national security imperative such as the space race of the 1960s?

Although there may well be national security imperatives that eventually compel us to undertake a human Mars mission, we cannot count on their advent. In such an environment, I suggest that the best way to prepare for missions to planetary destinations is to make the development of an incremental, permanent space faring ability our central goal. This can be done by gradually extending our "reach" first into cislunar space (the volume of space from Earth to the lunar surface). A spaceflight system that can access all of these points can also take us to the planets. A key part of such a strategy is to focus on learning how to use the material and energy resources of the Moon to refuel spacecraft, supply and provision long-term human voyages, and create new space systems and capabilities.

6. NASA requested $20 million in this year's budget to increase observation efforts of near-Earth objects. Less than 1 percent of all the objects that fall in the 7-10 meter range have been identified and catalogued. What is your confidence that we can find an object of the appropriate size, orbit, and rotation necessary for this mission within the next 10 years? What evidence do you have to support your confidence level?

I suspect that such a discovery is likely, but it would be dependent on the level of effort expended. The more small NEOs that you find, the better the odds that you will identify one that we can access easily and that possesses the compositional characteristics that we decide are required. A dedicated space-based telescope to search for NEOs is the most desirable solution, but also the most expensive ($20M would only be a down-payment;

such a mission would cost ~$200-300M). An Earth-based instrument is a close second choice, but a large fraction of small NEOs will never be detected by it. My suspicion is that you will likely find an object that will at least *appear* to be suitable.

7. One of the difficulties of the Asteroid Retrieval Mission is the challenge of categorizing the objects of interest. What is the scientific value of a human encounter with a 7-10 meter asteroid that is not a carbonaceous chondrite?

Presumably, the value of snagging a carbonaceous chondrite is that it is this class of meteorite that contains significant amounts of water (up to 20 wt.%). While true, water in asteroids is present in the form of *chemically bound* water, not free water as in the lunar polar ice. As a result, extraction of such from asteroid materials is more complex in process and requires more energy for extraction. It is unclear whether the ARM as currently envisioned even contemplates any attempt to extract water or other resources. Assuming that some different type of asteroid was retrieved, it could be studied up close and sampled, but as it would most likely consist of known meteorite types, we would not learn much more from this effort than we currently understand from study of meteorites.

8. What lessons could NASA learn from long-duration missions on the moon? Do you see any scientific value in such an endeavor?

The principal value of long-term human presence on the Moon is to learn how to live and work effectively on an alien world. Much of what we would like to do on the Moon is known in principle, but attempts to put theory into practice always develops difficulties and uncovers unknowns, often of surprising value. Living and working on the Moon – extracting the resources we need for sustainable presence there – is invaluable preparation for journeys to the planets. But beyond this, a permanent return to the Moon has immense scientific value in and of itself. The Moon retains a critical and fascinating record of its own history and processes as well as recording the same for the Earth-Moon system, the Sun and the galaxy. This rich and complex story can be accessed and reconstructed in detail by humans and robots working together on the lunar surface.

9. Your written testimony stated that there is a launch opportunity to the Moon every day of the year. How does this compare with launch opportunities for other frequently discussed destinations, such as near Earth asteroids? How does this affect NASA's ability to test technologies in a safe manner?

Accessibility is an important consideration for missions to any space destination. The Moon is easily accessible because it is already in Earth orbit whereas the other planets and asteroids orbit the Sun on their own paths. Thus, we cannot simply depart for an NEO or Mars or Jupiter when we want to, but must wait for a time when the orbits of both the Earth and our destination bring the bodies to a point which we can reach them with the proper impulse and timing. Such an occurrence is infrequent; a launch window to Mars opens only every 24 months. Some opportunities are better than others (e.g., it takes less energy to reach Mars on some occasions than on others). All the planets tend to orbit the Sun in the same plane, but many NEOs have orbital planes inclined to the orbit of the Earth, making launch windows even less frequent and/or requiring more energy to reach them. The net effect of these complications means that missions to such destinations must be planned carefully to depart on time, lest a launch window is missed and additional costs are incurred, awaiting the next opportunity. Moreover, this relative inaccessibility means that in case of emergencies, abort scenarios are more complicated and risky during interplanetary flight than in cislunar flight.

10. How can the Moon's resources be used to create new space faring capabilities? Do we already have the technology needed to make use of those resources once we reach the Moon?

I describe some of the value of the resources of the Moon in my submitted testimony and the supporting documents. In brief, water is the most valuable material to have in space. It can support human life as a consumable and, split into its component oxygen and hydrogen, used for breathing air. Water can jacket space habitats to protect crews from galactic and solar radiation. It is a medium of energy storage, in which by day, electricity generated form solar arrays can crack the water into its component gases and at night, be recombined to generate electricity. But its most important use to create spaceflight capability is its use as propellant – liquid oxygen and hydrogen are the most powerful chemical rocket fuel combination known. Water on the Moon is present in known locations and the technologies we require to extract and use it are well known and have low risk and high degrees of heritage. We can begin to use lunar water from the moment we arrive back there.

11. Your testimony discusses how the Moon's environment is well suited for laboratory study. What types of experiments can be conducted on the Moon that would be impossible or difficult to accomplish elsewhere? How much infrastructure would be required to conduct such experiments?

There are many fields of science and engineering research that require the environmental conditions that are present naturally on the Moon. Any process that utilizes high vacuum (10^{-7} Pa, or about *one-trillionth* the atmospheric density of Earth's surface at sea level) can be performed on the Moon. Communities conducting research in superconductors have expressed interest is using the extreme low temperatures found near the poles to conduct fabrication experiments not currently possible on Earth. For the astronomical community, the far side of the Moon (easily accessible at any pole) is the only known place in the *universe* that is permanently shielded from the radio noise and static of the Earth, both naturally occurring (i.e., the ionosphere) and artificial (i.e., human-caused). The hyper-quiet seismic background on the Moon permits the emplacement of extremely sensitive instruments, including interferometers at optical wavelengths, able to achieve resolutions of micro-arc seconds. Such a telescope could resolve “star spots” (i.e., sunspots on neighboring stellar objects) and the full disks of Earth-sized planets orbiting nearby stars. The possible experiments are limited only by our imaginations. Many of these studies can be undertaken early in lunar return, either as dedicated instruments deployable by human crews or within laboratory facilities that can be emplaced on the Moon early in outpost history.

Questions from Ranking Member Edwards

1. When I tell my constituents about the great work NASA does, the subject of how NASA affects everyday lives often makes its way into the conversation. In considering your knowledge of what technologies will be needed for human missions to Mars, could you describe how some of those potential technologies and capabilities might find their way into the mainstream? Is there any way to predict the possible economic impact of these potential innovations?

Prediction of the economic or societal value of a given technology is difficult, but the historical evidence suggests that it is significant and usually, inevitable. Some of the most valuable technical spin-offs we've received from the space program are in the field of medical science and technology. Keeping people healthy in space has required us to understand better how the human body functions under stress and in unusual environments. Developing new and compact sensors have revolutionized medicine and many other areas of life on Earth. As a society, we take for granted the enormous role that space assets play in our daily lives. Human spaceflight has been critical in many of these developments. I don't believe that there is a simple, straight-forward way to predict possible economic payoffs – many of our most valuable developments were completely unexpected.

2. How should Congress measure progress on near-term and long-term goals in human exploration?

Any space effort should be planned from the outset to provide a number of intermediate milestones and accomplishments to allow Congress and the nation to assess how we are progressing and what areas of the effort require modification or augmentation. Moreover, these dates for achievable milestones should be set at intervals appropriate for governmental terms of office, on the order of every 2-4 years. Much shorter than this and it's doubtful that significant progress can be made; much longer and it is likely that a program can get into trouble before it may be recognized and corrected. Congress requires the agency to submit an operating plan and also report on past progress and this practice should continue. Allowances should be made for potential technical setbacks and difficulties as well as actual funding levels lower than had been originally anticipated.

3. Does the Nation have the industrial capacity and workforce knowledge and skills needed to pursue a sustained and dedicated goal of a human mission to Mars? If not, what is needed to ensure the necessary industrial capacity and workforce skills?

At this point, I think not. We have seen an erosion and deterioration in our high-technology industrial base in the last 20 years and I believe that this is a cause for concern. In part, this is a natural result of the end of the Cold War, a great source of technical innovation, but it also reflects America's current position as the world's sole superpower, making us somewhat complacent about the societal value of technical research and development. In my opinion, the best way to foster high levels of technical achievement is to set, attempt and accomplish difficult goals; human spaceflight beyond low Earth orbit qualifies as such. If the nation desires to lead the world in technical innovation and development, it must conduct such projects to build up these industries, in both material and intellectual terms. I include both infrastructure and human capital in this formulation.

4. To what extent can potential international partners contribute key enabling technologies to an eventual human mission to Mars? When should potential international partners be asked to participate?

We can and should make our journey into space an international collaboration for a variety of reasons. It will not only reduce the total cost burden to ourselves but can also strengthen ties with allies and reduce tensions with potential adversaries. International partners should be made part of the effort at the earliest stage at which we have clearly decided to proceed in a certain direction; this gives them a voice in implementation decisions and makes their commitment to the project more concrete and certain. The international community was deeply involved in and committed to the previous lunar return effort under the Vision for Space Exploration and the partners were mystified by our abandonment of that effort. Such a fiasco should not be repeated in the future.

5. Would a human mission to the Moon require a further interim step (i.e., to a near Earth asteroid) prior to sending humans to Mars, or would knowledge gained from a human expedition to the Moon be sufficient?

In my opinion, lunar return would be sufficient. We are acquiring already the needed knowledge on human physiology and psychology for long-duration spaceflight from current International Space Station missions. We are learning from various robotic missions that the radiation hazard for interplanetary travel is also a solvable problem. What's missing is actual experience in both exploring planetary surfaces (so as to maximize our exploration effectiveness on Mars) and in the use of *in situ* (extraterrestrial) resources, in order to "live off the land" once we get there. Producing fuel and consumables from local materials will greatly reduce risk and cost for future planetary missions and it is essential that we gain some practical experience in this vital skill. Lunar return can allow us to address both of these crucial areas, much more so than an asteroid visit or a journey to some point in free-space, such as an L-point mission.

I thank the committee for inviting my testimony and for their questions and interest.

Responses by Dr. Steven M. Squyres

House Subcommittee on Space
Hearing Entitled
"Next Steps in Human Exploration to Mars and Beyond"

Responses by Steven W. Squyres to
Questions for the Record
June 22, 2013

Questions submitted by Rep. Palazzo:

1. Has NASA developed a roadmap for the future of human exploration which defines key milestones and decision points for an expanded human presence in the solar system?

No.

Would a formal roadmap for future missions be helpful for NASA?

Yes. In my opinion, developing a credible roadmap for human exploration beyond the Earth-Moon system should be one of the Agency's highest priorities.

2. NASA has a long history of working with international partners on large-scale programs and missions. What role should the international community play in the next steps to Mars?

I believe that significant international participation will be necessary to enable human exploration of Mars under any plausible future NASA budget.

a. Can NASA accomplish a mission to Mars without the international community or is it a prerequisite?

The answer depends on the NASA budget. With an adequate budget, NASA could accomplish a human mission to Mars without international partners. With any likely budget, however, I believe that substantial international participation is a prerequisite.

b. How was international cooperation coordinated under the Exploration Systems Architecture Study (ESAS)?

International cooperation played little part in the ESAS study. The study stated that "encouragement of international participation is an acknowledged Level 0 requirement". However, the architecture that was produced by the study involved no significant contribution from any international partners.

c. How was international cooperation coordinated under the Asteroid Retrieval

Mission (ARM)?

To my knowledge there has been little serious discussion of international involvement in ARM to date.

3. Generally speaking, which mission is more attractive to the scientific community, the asteroid retrieval mission, or a lunar landing? What has been studied more thoroughly by the scientific community?

A lunar landing has been better studied by the scientific community. I cannot assess which one is viewed more favorably.

4. Which mission, the Asteroid Retrieval or Lunar mission, represents a better investment for Exploration Technologies?

That is a difficult question. I feel that the long-range goal of exploration technology should be to develop the capabilities necessary to explore the surface of Mars. Neither an asteroid retrieval mission nor a lunar surface mission is clearly necessary or enabling for Mars exploration. I would say that a lunar surface mission is probably somewhat more relevant.

a. What capabilities are more necessary for a Mars mission, improved proximity operations or landing and ascent stages?

By "proximity operations", I presume that this question refers to the kinds of proximity operations that could be demonstrated by near a redirected asteroid. Under that presumption, landing and ascent stages are more important. I should note, however, that because of the martian atmosphere, these stages (particularly for entry, descent, and landing) must be fundamentally different for Mars than for the Moon.

b. Which is more important for a Mars mission, deep space transit or in situ resource utilization?

In my opinion, the answer is deep space transit. In situ resource utilization (ISRU) at Mars could be extremely valuable someday. However, I believe it would be unwise to base any near-term architecture for human exploration of Mars on the assumption of successful ISRU.

c. How should these choices be evaluated in the context of a flat (or slightly increased) budget profile?

My most important point is that it should be left to NASA to propose what the key elements of a roadmap for the human exploration of Mars should be. The goal of that roadmap should be to get human explorers to Mars as quickly and efficiently as possible. My guess is that the most important new developments required to *enable such a roadmap will be (a) advanced propulsion, (b) improved deep-space habitation systems, and (c) a human-rated entry, descent and landing system for Mars. None of these are enabled by either a lunar landing or an asteroid retrieval mission. So I suspect that any sensible get-to-Mars-soonest roadmap will not involve either ARM or a lunar landing.*

5. Given NASA's notionally flat budget for the foreseeable future, the Asteroid Retrieval Mission will necessarily crowd out other priorities. Rather than spending money on this type of mission, should resources be redirected to an SLS second stage and a lunar lander?

I would not favor redirection of ARM funding to a lunar lander. Using ARM funds to improve the performance and flight rate of SLS would be valuable.

6. NASA requested $20 million in this year's budget to increase observation efforts of near Earth objects. Less than 1 percent of all the objects that fall in the 7-10 meter range have been identified and catalogued. What is your confidence that we can find an object of the appropriate size, orbit, and rotation necessary for this mission within the next 10 years? What evidence do you have to support your confidence level?

Current knowledge of the properties and distribution of 7-10 meter objects is not good enough for me to provide a quantitative answer to this question. We won't really know unless we look.

7. One of the difficulties associated with the Asteroid Retrieval Mission is the challenge of categorizing the objects of interest. What is the scientific value of a human encounter with a 7-10 meter asteroid that is not a carbonaceous chondrite?

The scientific value of a human encounter with a 7-10 meter non-carbonaceous asteroid is modest at best, and it is low considering the cost. A good benchmark is the OSIRIS-REx mission, which will visit a 500-meter carbonaceous asteroid, study it in detail, and select and return a sample. Because the OSIRIS-REx target asteroid is carbonaceous and large enough to be compositionally diverse, the scientific value of the sample is likely to substantially exceed that of any sample from a 7-10 meter non-carbonaceous asteroid. The cost of OSIRIS-REx, including launch, will be approximately $1 billion. The cost of redirecting an asteroid and sending humans to visit it will be substantially greater.

Questions submitted by Rep. Edwards:

- In your written statement, you indicate that lunar orbital activities would offer opportunities toward retiring the risks of a potential, future human mission to Mars. Is it your view that surface operations on the Moon or a near Earth asteroid are not necessary for preparing to send humans to Mars?

  Yes.

- Would you see a robust testing and demonstration program in cis-lunar space, carried out using the SLS and Orion, followed by a human mission to orbit Mars as a possible pathway toward achieving the goal of sending humans to land on Mars?

  Yes.

- When I tell my constituents about the great work NASA does, the subject of how NASA affects everyday lives often makes its way into the conversation. In considering your knowledge of what technologies will be needed for human missions to Mars, could you describe how some of those potential technologies and capabilities might find their way into the mainstream? Is there any way to predict the possible economic impact of these potential innovations?

  It is easy to oversell the merits of NASA's technological spinoffs. The situation today is very different from the early 1960s when computer technology was in its infancy. Today consumer demand drives innovation at a dizzying pace, often making NASA a user rather than a developer of key technologies. Many of the remaining innovations necessary to put humans on the surface of Mars are rather Mars-specific, and many of them would have little obvious utility in everyday life. Moreover, the innovations that do find their way into everyday life are often unexpected, and therefore difficult to forecast. So rather than consumers benefitting from a burst of technological spinoffs from a Mars initiative, I think it is more likely that specific vehicles and hardware developed to support Mars missions could find other uses that would benefit the nation. For example, heavy-lift launch vehicles or on-orbit propellant depots (if part of the Mars architecture) could also have important national security uses.

- What are the most important considerations in establishing a sustainable human exploration plan, and how should Congress measure progress on near-term and long-term goals in human exploration?

  The most important considerations, in my opinion, are finding a compelling and achievable long-range goal, and matching program content to budget.

Without the former, it will be difficult to maintain program momentum. Without the latter, the result will be inefficiency and delay. Congress should measure progress by assessing accomplishments vs. milestones in a roadmap that NASA has generated and that has been agreed to by the Congress. It would be a mistake, in my opinion, to measure progress by assessing accomplishments vs. Congressionally-mandated milestones.

- To what extent can potential international partners contribute key enabling technologies to an eventual human mission to Mars? When should potential international partners be asked to participate?

  I believe that international partners can make important, even enabling contributions to a human mission to Mars, just as they have for the International Space Station. Potential partners should be approached regarding participation as soon as NASA has produced a viable roadmap for Mars exploration.

- What information about the Mars environment is needed to ensure the safety of a human mission to the planet?

  The most important information deals with the radiation (both on the martian surface and in transit), and with the potential toxicity of martian surface materials, particularly the ubiquitous fine-grained dust.

  - What are the risks if a robotic sample return mission is not conducted prior to undertaking a human mission to Mars?

    I believe the risks are low compared to other risks that inevitably must be accepted in conducting a human mission to Mars. For more details, see my responses to Rep. Stockman's questions.

  - Are robotic outposts on Mars needed for extended scientific and environmental studies in preparation for human missions?

    Robotic outposts on Mars are highly desirable. In fact, enormously valuable robotic outposts already exist or are planned: Spirit, Opportunity, Phoenix, Curiosity, and InSight are all examples. In my view, these missions are providing information that is adequate for the planning of future human landed missions.

- To what extent are NASA's technology development activities devoted to enabling deep space exploration?

  To a substantial extent. I feel that the current Space Technology program is well aligned with the long-term goals of the Agency.

What is the likely timeline for achieving the necessary technological capabilities to send humans to one or more interim destinations (e.g. Moon, near Earth asteroid), and eventually to Mars, if NASA has to operate under flat or declining budget levels?

I believe that the technological capabilities necessary to get to interim destinations and Mars can be developed fairly quickly. It is important to distinguish, however, between having enough funding to bring technologies to maturity, and having enough funding to actually implement those technologies in flight. We clearly have the technology today to create a launch vehicle with capabilities like the Saturn V – we had it forty years ago. But we do not have the resources to actually build and fly one. With flat or declining budgets and no major infusion of international support, I believe that it will take two decades or more to get to the lunar surface or a near Earth asteroid, and that Mars is out of reach effectively indefinitely.

- To what extent does the asteroid capture and retrieval mission differ from a human mission to a non-relocated near Earth asteroid?

  There are at least three major differences:

  1. *A mission to a near Earth asteroid would have to venture much farther from Earth.*

  2. *A non-relocated asteroid would probably be much larger than a relocated one, so its surface would be likely to offer far greater scientific diversity and opportunities for discovery.*

  3. *There would be no spacecraft affixed to the asteroid that would allow for controlled worksite stabilization of crewmembers during extravehicular activities.*

  - How are the capabilities and operational activities required for sending humans to a near Earth asteroid different or similar to those required for sending humans to a relocated asteroid?

    Referring to the three differences noted above:

    1. *The requirements for propulsion, life support, and radiation protection would be substantially more challenging for a mission to a near Earth asteroid. Vehicles with capabilities well beyond those of Orion and a 70-metric-ton SLS would be needed.*

    2. *At a near Earth asteroid, there would be a much stronger*

motivation to conduct extensive extravehicular activities that are focused on scientific exploration and discovery.

3. *Without an attached spacecraft, new techniques and equipment for crew translation and worksite stabilization during extravehicular activities would be needed.*

Questions submitted by Rep. Stockman:

The long-time top priority of the Decadal Survey has been a Mars sample return mission. To bring to Earth samples of Martian soil, water and atmosphere for detailed study.

- What are some answers necessary for a human landing that a completed Mars sample return may provide?

  I do not feel that any are truly necessary, but there are some that would be valuable. One is whether the ubiquitous fine-grained martian dust would pose health threats if ingested or inhaled. In the absence of such knowledge, I believe that this risk could be addressed by making reasonable worst-case assumptions based on the substantial knowledge that already exists regarding the health effects of fine-grained particulates on Earth. Another is whether or not there is extant life on Mars that poses a threat to human life. I view this as being sufficiently unlikely that it does not constitute a risk to the crew that is significant relative to the other risks they will inevitably face.

- Do you agree a sample return is a key precursor for a human landing?

  No. I think that a sample return mission would be valuable, because of the answers that could be provided to the questions I noted above. But I feel that a human landing could be carried out at an acceptable level of risk without answers to these questions.

- Because the 2018 MAX-C caching rover was cancelled and replaced with a non-specified mission "Curiosity-2" rover, would you agree a key priority for Mars precursor missions should be to assure that sample collection and caching becomes the primary mission of the 2020 rover?

  Yes.

- Are there any potential non-biological toxins on Mars we should learn more about?

  As noted, there could be adverse health effects from ingesting or, particularly, inhaling martian dust. Learning more about this potential hazard could be valuable, but I do not see it as a necessary prerequisite to a human landing.

- Do you expect the 2020 Rover Science Definition Team will follow the Decadal Survey and make sample collection and caching its primary mission?

I have not been part of the Science Definition Team deliberations, so I have no basis for any expectation. I hope that they will follow that recommendation, because it represents the consensus view of the planetary science community as expressed in the Decadal Survey.

Responses by Mr. Douglas Cooke

House Committee on Science, Space, and Technology
Subcommittee on Space
Answers to Questions for the Record Submitted by Ranking Member Donna Edwards
Answers Submitted by Douglas R. Cooke

1. During the question and answer session of the hearing, you noted that "we need to understand what exit criteria we have for programs." Please elaborate on what exit criteria might be considered for human exploration and operations programs? Would exit criteria be applied across all exploration and operations programs or would they need to be specific to individual programs?

Answer: In order to most effectively spend under constrained budgets over multiple program developments, I believe NASA should develop exit strategies for large operational programs. Programs and missions should be planned with specific well thought out objectives. Once it is believed that a mission has satisfactorily achieved these objectives or is reaching a point of diminishing returns, it should be phased out and terminated to make room in the budget for the next high priority program(s). This is true particularly for large high cost programs and missions. This process should be well planned in order to make an efficient transition to the next program. An example is the phasing out of the Russian MIR program so the Russians could focus on the ISS program. The Apollo Program was phased out in favor of the Space Shuttle development. As a current example in Human Space Flight, I believe the ISS program should be addressed in this manner. A long term research, technology demonstration, hardware test program should be in place to achieve long term exploration and other objectives. NASA and Congress could measure progress against this plan and determine when ISS should be retired or turned over to other entities. This would also be true of a future human lunar program. When preparation for Mars human missions is complete at the Moon, and other important scientific objectives are met, the program would be retired or assets given to commercial entities for example. The U.S./NASA has not always performed transitions well, but it is necessary to make progress in long term exploration with multiple related programs and missions operating within constrained budgets.

2. When I tell my constituents about the great work NASA does, the subject of how NASA affects everyday lives often makes its way into the conversation. In considering your knowledge of what technologies will be needed for human missions to Mars, could you describe how some of those potential technologies and capabilities might find their way into the mainstream? Is there any way to predict the possible economic impact of these potential innovations?

Answer: I believe that knowledge and discoveries returned from the missions; many of the technologies, such as advanced life support, energy related technologies, radiation protection, advanced avionics and software; as well as human research and many other achievements will benefit people here on Earth. The economic benefit is always difficult to predict, but the history of these benefits is probably a reasonably good measure of what to expect in the future if we continue to aggressively explore space.

3. What are the most important considerations in establishing a sustainable human exploration plan, and how should Congress measure progress on near-term and long-term goals in human exploration?

Answer: To develop a long term exploration plan, an important early step is to begin to involve all stake holders and partners, both domestic and international in developing near and long term exploration objectives. NASA needs to establish what is needed in technology and capability development for missions to Mars, and then lay out how to satisfy these needs beginning with meaningful near term steps. In written testimony I laid out a way to approach this. In NASA we always talked about having "a plan for the plan." NASA needs a plan and process for developing a long term exploration plan. With this Congress could measure the development of the exploration plan or roadmap, and then could measure progress along the resulting exploration plan, with its important milestones.

4. What are the essential components of a Mars human mission architecture? To what extent can a future architecture be designed with sufficient flexibility to respond to incremental findings from robotic missions?
   a. The President set the goal of sending humans to orbit Mars by the mid-2030s. When do architecture decisions need to be made to meet that timeframe? Does an overall plan with decision milestones exist? At what point in time should we reasonably expect NASA to identify its Mars architecture following a consensus and commitment made to conduct a human mission?

Answer: The essential components of a Mars human architecture begins with a plan including specific steps in how to prepare for Mars missions. These steps include human research, technology developments, and vehicle developments. The steps also include missions to specific intermediate destinations with their own rationale based on detailed, well vetted, objectives for how they contribute to the experience needed for Mars exploration. Each of these intermediate destinations would additionally have their own unique detailed objectives. Vehicle capabilities begin with SLS and Orion. The missions and destinations should be a step by step evolutionary progression in development and testing of capabilities. Ultimately the in-space and Mars vehicles must be designed and developed. Decision points must be included in the plan and flexibility is needed to address unexpected but welcome discoveries, accommodate changing policy and budgets, etc. As missions are conducted to specific destinations discoveries will likely be made that cause us to want to focus on that location. On the other hand, exit strategies are needed to determine when we have reached a point of diminishing returns as described earlier. Robotic missions will provide data to identify specific landing sites for where we want to send people to explore. Decisions need to be made in the near term to develop the long term plan and determine the critical schedule path for development of technologies and capabilities. This plan does not exist, which is why I think it is so important. There are technology roadmaps and developments, but I do not know how they address a long term exploration plan, since it does not yet exist. Some tall pole technologies may not yet be underway. By implementing the process in (3) above the timing should become clear on when these activities need to begin.

5. To what extent are NASA's technology development activities devoted to enabling deep space exploration? What is the likely timeline for achieving the necessary technological capabilities to send humans to one or more interim destinations (e.g. Moon, near Earth asteroid), and eventually to Mars, if NASA has to operate under flat or declining budget levels?

Answer: NASA should be asked to show how technology programs are addressing exploration high priority needs in a timely manner. There are technologies in the Advanced Exploration Systems organization HEOMD, which are likely aligned. I am not current on the technologies being developed in the Space Technology Office. Technologies are adequate or nearly at-hand for near term destinations, including the Moon for short to moderate stay times. More advanced closed loop life support is needed for long missions for long term lunar stays, asteroid missions, and Mars missions. In all cases radiation protection needs to be better understood outside Earth orbit for long missions. Advanced in-space propulsion is needed for longer missions as well. For missions to the Mars surface there is a more extensive list. Declining budgets, including flat budgets with no increases for inflation are crippling over the long term as this leads to ever worsening lost buying power. This is true for all programs, not just exploration programs.

6. To what extent can key enabling technologies or systems for an eventual human mission to Mars be provided through international participation in the mission?

Answer: I think that international collaboration is essential and inevitable in long term space exploration, especially on complex and costly endeavors. The collaboration on ISS has proven to

Exploration planning through the International Space Exploration Coordination Group (ISECG). The international partners are very capable in augmenting U.S. capabilities.

7. To what extent does NASA understand the operations required to support a human mission to a near Earth asteroid?

Answer: I believe NASA understands basic operational capabilities to go to an asteroid, demonstrated in robotic missions. What is not well known is how to interact/attach/ station-keep/ protect for loose dust or rocks, and provide safety to crews under these conditions.

8. What information about the Mars environment is needed to ensure the safety of a human mission to the planet?
    a. What are the risks if a robotic sample return mission is not conducted prior to undertaking a human mission to Mars?
    b. Are robotic outposts on Mars needed for extended scientific and environmental studies in preparation for human missions?

Answer: This question would likely lead to some level of debate. I believe that significant information exists about Mars from the extensive return from excellent Mars missions over the years. On the latest mission a radiation measurement device was flown to the Mars surface. For the first time scientists know the effect of the atmosphere on surface radiation dosage rates. What may be needed is further data on the toxicity of the Mars soil. Another possible concern is whether there might be forms of life/bacteria in water under the surface. However, these can potentially be protected for through designs. There could be a debate over whether a sample return is required. Even if a sample is returned, would you find a sample that completely identifies the hazards for all locations? I never believed we needed a sample return before sending people. It is a matter of risk and design complexity. The more you know, the less uncertainty and complexity you have to design for. I think we are close to knowing enough about Mars now to send people. The more data that is provided by science missions, the better we will know where on Mars we want to send people to explore.

9. To what extent does the asteroid capture and retrieval mission differ from a human mission to a nonrelocated near Earth asteroid?
    a. How are the capabilities and operational activities required for sending humans to a near Earth asteroid different or similar to those required for sending humans to a relocated asteroid?
    b. Does the relocated asteroid initiative satisfy the rationale given for the President's goal that he stated in 2010? If not, why not?

Answer: The human asteroid mission that was initially envisioned would have been a mission to a larger asteroid in its own orbit. I believe that a larger asteroid could be characterized better from asteroid survey assets than a small one. This better characterization would help provide information on the value of exploring the specific asteroid. Therefore the mission would likely be more interesting scientifically than the current asteroid retrieval mission. The capabilities for the human portion of the mission are potentially different. Travelling to an asteroid in its orbit would be closer to the characteristics of a Mars in-space transit mission in mission length and vehicle capabilities. The human portion of the retrieval mission could be a potentially short mission to a LaGrange point or lunar orbit. On the other hand, I believe the retrieval spacecraft is complex and will not contribute in any significant way to further steps in human exploration, except perhaps in flying the electric propulsion technology. Although sized larger than what has been flown on science missions, the solar electric capability is still smaller scale than what is required on a human scale mission. In the end NASA has a proposed mission to an asteroid, but it is significantly different from a development stand point, and probably from a science standpoint than the original asteroid mission announced in 2010.

House Committee on Science, Space, and Technology
Subcommittee on Space
Answers to Questions for the Record Submitted by Chairman Ralph Hall
Answers Submitted by Douglas R. Cooke

The Augustine Commission report found that under the existing funding levels, the Constellation program would face significant delays, and that the Ares I and Orion would likely not reach the International Space Station before the Station's planned termination. Did the Administration lower its budget request for NASA prior to the release of the Augustine Commission report? If so, how did that affect the Augustine Commission's assessment of the Ares schedule?

Answer: The 2009 budget request for the Exploration Systems Mission Directorate was lowered from 2008 projected run-out levels. This reduction effectively eliminated the anticipated early funding wedge for development of the Ares V heavy lift rocket and the ALTAIR lunar lander. It did not affect Ares I or Orion planning at that time. This reduction was prior to the establishment of the Augustine Committee. The Augustine Committee recognized NASA's need for more funding to implement these programs. Although the ISS end date was still on the books as 2016, NASA's previous administrator was planning to propose extension of the ISS to 2020, but the time had not come yet to do it. This was similar to the current situation, where there is serious talk of extending the ISS beyond 2020, but it has not yet been done. Similar to the situation with Orion and Ares I, the "Commercial Crew" implementation is now facing a short series of missions to ISS, if ISS is not extended beyond 2020.

House Committee on Science, Space, and Technology
Subcommittee on Space
Answers to Questions for the Record Submitted by Chairman Steven Palazzo
Answers Submitted by Douglas R. Cooke

1. Has NASA developed a roadmap for the future of human exploration which defines key milestones and decision points for an expanded human presence in the solar system? Would a formal roadmap for future missions be helpful for NASA?

   Answer: NASA has not to my knowledge developed a roadmap for future human exploration, defining key milestones and decision points. NASA has announced one specific mission, the Asteroid Retrieval Mission, and a vague reference to eventual human exploration of Mars. As I advocated in my written testimony such a roadmap is absolutely needed. In my written testimony I outlined a process for developing a roadmap. A roadmap for Human Space Exploration would be helpful not only for NASA, but for its stake holders and the public. I believe a roadmap is needed to inspire the country to be motivated to adequately fund and implement these programs.

2. The NASA Authorization Act of 2008 requires NASA to work towards establishing a lunar outpost on the Moon. Is this a necessary step to training for a mission to Mars?

   Answer: I believe that it is important to explore the Moon for its own sake. There is much more to be learned beyond what we currently know about our nearest neighbor in space, that directly informs us about important aspects of the history and evolution of our home planet Earth. We should be learning from the recent Lunar Reconnaissance Orbiter (LRO), Lunar Crater Observation and Sensing Satellite (LCROSS) and Gravity Recovery and Interior Lab (GRAIL) missions to inform our planning for lunar exploration. These missions have discovered much more than we learned from Apollo, and they have generated more new questions that can only be answered by exploring the Moon. We should establish a presence on the Moon that would prepare us for missions to Mars, while we are exploring and learning about the Moon. We would be preparing for Mars by learning to live and work in a hostile environment that includes temperature extremes, vacuum conditions, low gravity, radiation and dust. We need to develop systems and machines that will operate in these environments with high reliability before committing astronauts to the longer, more distant missions to the Mars surface. We need to develop efficient operational approaches including scientific operations in these environments to make the most of the time there. Although the Mars environment has differences, human operations on the Moon would provide the experience and lessons for evolving the systems and designs for use on Mars. We would learn what to issues to address in designs. Developing systems that extract and utilize in-situ resources can also be developed on the Moon, with its diverse resources. We can learn to rely on these extraction systems for reducing materials launched from Earth, thus reducing mission cost. Past studies have shown these technologies are enabling for missions to Mars. It is as important to learn to rely with confidence in these capabilities as it is to develop the systems. This confidence is needed before engineers will be willing to count on them for mission fuel and habitat consumables of water and air. We can gain that confidence from experience gained at the Moon.

3. Is the International Space Station being used appropriately as a test-bed for future deep space missions? How can NASA improve utilization of the ISS for this purpose?

Answer: The intent at NASA is to utilize the International Space Station (ISS) to prepare for human exploration. There is a Human Research Program that is making progress in learning how to keep humans healthy in the space environment. It includes experiments and research on ISS. What is needed is an ISS integrated plan for all research, systems testing and technology demonstrations that would result in more efficient development of exploration capabilities. Although this plan has been in work for some time, it is not complete and has not begun implementation to my knowledge. This work has not appeared to have had very high priority within the program. I believe this plan should have been in place and ready to implement when the ISS assembly was completed. An ISS integrated test and research plan would be valuable in getting the most out of ISS, and in demonstrating progress and achievements against that plan. An associated issue is that the time available for ISS crew research is a small percentage of the crew time spent on orbit. In my view, this needs to be addressed to make the ISS as productive as is possible. Together the plan and demonstrated progress would help inform how long the ISS operations should be extended.

4. NASA has a long history of working with international partners on large-scale programs and missions. What role should the international community play in the next steps to Mars?
   a. Can NASA accomplish a mission to Mars without the international community or is it a prerequisite?
   b. How was international cooperation coordinated under the Exploration Systems Architecture Study (ESAS)?
   c. How was international cooperation coordinated under the Asteroid Retrieval Mission (ARM)?

Answer: I think that international collaboration is essential and inevitable in long term space exploration, especially on complex and costly endeavors. The collaboration on ISS has proven to be exceptional in developing complementary capabilities, has enabled program stability, and has been a positive in international relationships. There is already excellent collaboration in human exploration planning through the International Space Exploration Coordination Group (ISECG). This group evolved from initial international exploration meetings we started in 2006. The coordination is among 14 space agencies across the world. International development of flight elements and systems will be needed in order to share cost of missions. The collaboration will have to be coordinated carefully to minimize risk of default or delays by any partner and to ensure success of the programs. There are examples of how this type of collaboration has worked in the past. NASA bought from Russia the docking systems for U.S. docking, the initial FGB spacecraft for ISS, and has paid for Soyuz flights. I am sure this helped Russia in lean times.

Early on they had difficulty obtaining the funding to complete the Service Module. On the other hand, we did not have the budget to develop our own complete crew return vehicle early on, and we funded some relatively minor changes to the Soyuz to fit the crew return need. But all this has worked out and they have been a good partner. Italy built the multi-purpose logistics modules (MPLMs) and one of the node structures. The MPLM was a needed element that defrayed costs for NASA. In the early 90s the Canadians had funding difficulties in development of the ISS arm. We helped them with that. They, as well as all of the other partners have done well. The U.S. and its partners have learned to adapt to these situations and help each other in the process. We have had our own difficulties and changes in policy that have created problems for the other partners. In 1993, NASA announced a redesign of Space Station Freedom. Then the U.S. brought the Russian partnership onboard. These were considered major disruptions by the international partners. More recently the administration changed policy from developing a human lunar capability to visiting an asteroid, and then retrieving an asteroid. These are difficult changes for the international partner agencies who take years to persuade their governments to pursue these programs. Their processes are not unlike the normal process in the U.S. It is especially difficult for the partners, when they are out of the decision process that seriously affects their planning and their programs.

a. I think that NASA <u>can</u> accomplish a mission to Mars without international partners, but I think that we should include them. The collaboration can help bring their capabilities to offset costs. Collaboration and commitments help to stabilize the programs in each country, although changing political support in all countries, including the U.S. creates risks. I think collaboration can also be very good for international relationships. It is also very helpful to have them as a part of the mission architecture planning process as we have learned over the past few years in the ISECG process.
b. ESAS did not include international participation. However, since the Moon is a logical next step in human exploration, this future was bought into by the international agencies.
c. I don't believe international partners were consulted for the ARM mission concept. They were not consulted for the 2020 asteroid announcement either. I believe NASA is working with them on this plan now.

5. The International Space Station partnership is a great example of leveraging the international community to accomplish great feats in space exploration, but it also demonstrates how dependence on international partners can leave U.S. exploration vulnerable to foreign actions and decisions. For instance, Russian financial problems and schedule delays impacted its commitments to the ISS program. How should the U.S. seek international participation in a manner that leverages partner investments, but does not put them on the "critical path?"

Answer: This is an important debate to have. I have outlined much of our experience in question 4 above along the lines of the concern expressed in the question. There are risks with these collaborations for all parties, due to evolving space policy in multiple countries, changing funding and technical problems. In addition, there are integration costs for the programmatic and technical negotiations and interactions as well as the associated travel expenses. Decisions will have to be made weighing the benefits of collaboration versus the risk and expense in the case of default or delays. The risk has to be recoverable financially. An important point is that the international partners want to be on the critical path. This is often important for them to sell a program to their governments. Partnerships have to be weighed on a case by case basis considering all these factors. Another important point is that if the U.S. believes the roadmap and program are an important part of its future, than the U. S. should lead the entire effort in order to maintain control of the benefits and risks to the best of our ability. The safest route but potentially the most expensive when viewed from the outset is for the U.S. to develop all elements on the critical path. If we do not own the critical path, then recovering from problems arising from critical hardware developments in these partner agreements can be very costly and can offset any expected savings. Assigning important hardware developments that do not threaten the basic mission critical path is a possible solution.

6. Do you think the United States should lead an international lunar mission?

Answer: Yes, the U.S. should lead an international lunar mission for many reasons. It is consistent with a continued leadership role in space and national prestige. We would control the risks and benefits as described in (5) above. NASA has the unique experience in knowing what is required to lead and manage this kind of massive program. Our partners look to us for leadership in this. I think our public would be disappointed in anything less.

7. Of the two main possibilities discussed at the hearing, which of these missions, the Asteroid Retrieval or Lunar mission, represents a better investment for Exploration Technologies?
   a. What capabilities are more necessary for a Mars mission, improved proximity operations or landing and ascent stages?
   b. Which is more important for a Mars mission, deep space transit or in situ resource utilization?
   c. How should these choices be evaluated in the context of a flat (or slightly increased) budget profile?

Answer: I personally believe that a lunar mission is by far better suited as a precursor for a mission to Mars. The lunar mission accomplishes what is described in question 2 above. I think that as we seriously consider going to Mars, we will decide to go to the Moon first to prepare and will go there for its own sake. The asteroid retrieval mission will employ unique in-space operational capabilities, some of which will be important for the long term. The asteroid mission will require development of a mission-unique retrieval spacecraft capability that will not be of any real benefit to future human exploration that I can envision other than for use of a soler electric capability. It will be expensive and complex. I believe the complexity of the capture will drive costs of the spacecraft significantly. Asteroids are of interest scientifically. In my view a small asteroid or part of an asteroid of the type described as an object for this mission cannot compare with the diversity of composition and information that is possible when exploring the Moon. I am not a scientist, so I would suggest asking about his facet of the discussion from representatives of that community. My view is based on past discussions with scientists.

a. After developing a heavy lift vehicle (SLS) and a deep space capable crew capsule that can enter Earth's atmosphere at high velocities, planetary landing and ascent vehicles are the next key capabilities needed for exploring planetary bodies like the Moon and Mars. Proximity operations for asteroids have already been demonstrated by robotic spacecraft. Science spacecraft have been deployed to Lagrange points.
b. Both in-space transit advanced technology and in-situ resource technology are important for Mars exploration. They are both important in reducing the amount of fuel that must be launched from Earth to perform the mission. Advanced in-space transit capability, whether solar electric, nuclear electric, or nuclear thermal rocket technology can reduce the in-space launched mass by a factor of about 2. It is a huge enabler, probably the biggest enabler. Using fuel produced on Mars from in-situ resources for the crew ascent from the surface to Mars orbit can reduce the amount of launched mass from Earth by about 30 to 40%. I would put the highest priority on in-space propulsion technology, but in-situ resource technology is very important.
c. I would fund both according to the priority in (b), however, I would also scrutinize the rest of the technology budget in terms of relative priorities for exploration.

8. Given NASA's notionally flat budget for the foreseeable future, the Asteroid Retrieval Mission will necessarily crowd out other priorities. Rather than spending money on this type of mission, should resources be redirected to an SLS second stage and a lunar lander?

Answer: I believe the highest priority near term is to develop an upper stage that puts the performance of SLS in the range of 100 to 130 metric tons to LEO, more correctly in the beyond Earth orbit (BEO) throw capacity in the range of 40 to 50 metric tons. The next priority is to develop lander capability, possibly in partnership with international parties depending on U.S. funding availability. The concern is that the asteroid retrieval spacecraft will be funded at the expense of priorities such as SLS and landers.

9. Private sector entities have suggested mining asteroids, and Dr. Friedman's testimony stated that "[a]fter the asteroid is in place even private spacecraft developers could be invited to explore and test new prospecting ideas there and maybe create a new commercial industry for utilization of space resources." Is the Asteroid Retrieval Mission an effort to subsidize the development of technologies for the private sector, much like commercial cargo and crew?
    a. Should NASA subsidize private sector efforts in both low earth orbit and deep space?
    b. If so, is NASA organized in an appropriate manner to facilitate this work, or is a model built on NSF's grant structure more appropriate?

Answer: I don't know if the motivation for this mission is to benefit the private sector in asteroid mining. NASA should be asked this question. I don't believe the current survey capability exists to characterize a small asteroid to know if it is of interest either scientifically or from a resource standpoint. The best that can be done is to determine whether it is stable or not and to determine its orbit for potential rendezvous. Certainly if NASA develops a capability to successfully retrieve asteroids, the design would be available to these entities. The question is whether doing this is more important than an exploration mission with the potential for new discoveries that benefit the entire public. Demonstrating and proving technical capabilities and then making them available to the public is a model that NASA has used in the past. Most times it has been in the form of benefits from capabilities developed closely aligned with use in ongoing NASA missions or technology developments. A lunar example of this might be as follows: in the course of an Exploration mission to set up a small in-situ resource experiment to prove out a resource extraction technique that could be provided to entities interested in lunar mining.

a. I don't think that NASA should subsidize the private sector at the expense of major high priority exploration and science missions. I don't think that NASA should do this on a large scale or subsidize entities to develop critical capabilities central to NASA's mission. Small scale subsidies through grants and other methods for research and developments have been beneficial, when they were envisioned to be of mutual benefit to NASA objectives.
b. NASA currently has the ability to use these methods.

10. Dr. Spudis' written testimony noted the shift to the "flexible path" for human exploration that focused on the development of technology rather than a destination. What were the most important exploration technology achievements of the past three years? How do you think these achievements would have differed if our space program were guided by a specific destination?

Answer: I believe that the majority of NASA technology funding should be focused on mission needs and development schedules. I believe that the mission directorates should develop the performance and schedule requirements for critical technologies that are then carried out in the technology programs. The mission directorates should have their own technology programs that are adequately funded to support their long term plan for missions. I think technology developments have been progressing, but I no longer know what the priorities are or what has been achieved in the last three years.

11. A report issued last December by the National Research Council about NASA's strategic direction stated, "[t]he committee has seen little evidence that a current stated goal for NASA's human spaceflight program—namely, to visit an asteroid by 2025—has been widely accepted as a compelling destination by NASA's own workforce, by the nation as a whole, or by the international community. On the international front there appears to be continued enthusiasm for a mission to the Moon but not for an asteroid mission." Why is this mission any different than those identified by the NRC?

Answer: The human asteroid mission that was initially envisioned would have been a mission to a larger asteroid in its own orbit. A larger asteroid could be characterized better from asteroid survey assets, and I believe would likely be more interesting scientifically than the small asteroid to be retrieved by the current asteroid retrieval mission. I believe that in general, current robotic asteroid missions are providing good scientific return for the cost. I do believe that the international community is logically more interested in exploring the Moon for the reasons mentioned in question 2. There is also more potential for a substantial role for them in lunar missions from hardware development to providing astronauts. Through ISECG, International partners have participated in developing a broad range of lunar exploration, science, resource, outreach, commercial and other human lunar exploration objectives.

12. NASA's Small Bodies Assessment Group also commented on the potential asteroid mission, stating, "[w]hile the participants found it to be very interesting and entertaining, it was not considered to be a serious proposal because of obvious challenges, including the practical difficulty of identifying a target in an appropriate orbit with the necessary physical characteristics within the required lead time using existing or near- to long-term ground-based or space-based survey assets." Do you agree or disagree with their assessment and why?

Answer: I would not question the findings of this group as I assume they are more knowledgeable on this subject than I am. I do think their finding is believable. I understand there are few known viable objects that are potential targets for this asteroid retrieval mission. That is why I understand funding is being requested for augmenting the asteroid survey budget; so they can find more potential targets for this mission.

13. What lessons could NASA learn from long-duration missions on the Moon? Do you see any scientific value in such an endeavor?

Answer: NASA can learn significant lessons from missions to the Moon that will reduce risks in sending astronauts to Mars and other distant destinations. I believe that there is the potential for significant scientific return from the Moon. The LRO mission objectives included high resolution photography and mapping of potential landing sites that were identified by science and exploration experts as the most interesting locations to explore. As stated in the response for question (2):

I believe that it is important to explore the Moon for its own sake. There is much more to be learned beyond what we currently know about our nearest neighbor in space, that directly informs us about important aspects of the history and evolution of our home planet Earth. We should be learning from the recent Lunar Reconnaissance Orbiter (LRO), Lunar Crater Observation and Sensing Satellite (LCROSS) and Gravity Recovery and Interior Lab (GRAIL) missions to inform our planning for lunar exploration. These missions have discovered much more than we learned from Apollo, and they have generated more new questions that can only be answered by exploring the Moon. We should establish a presence on the Moon that would prepare us for missions to Mars, while we are exploring and learning about the Moon. We would be preparing for Mars by learning to live and work in a hostile environment that includes temperature extremes, vacuum conditions, low gravity, radiation and dust. We need to develop systems and machines that will operate in these environments with high reliability before committing astronauts to the longer, more distant missions to the Mars surface. We need to develop efficient operational approaches including scientific operations in these environments to make the most of the time there. Although the Mars environment has differences, human operations on the Moon would provide the experience and lessons for evolving the systems and designs for use on Mars. We would learn what to issues to address in designs. Developing systems that extract and utilize in-situ resources can also be developed on the Moon, with its diverse resources. We can learn to rely on these extraction systems for reducing materials launched from Earth, thus reducing mission cost. Past studies have shown these technologies are enabling for missions to Mars. It is as important to learn to rely with confidence in these capabilities as it is to develop the systems. This confidence is needed before engineers will be willing to count on them for mission fuel and habitat consumables of water and air. We can gain that confidence from experience gained at the Moon.

14. NASA officials assert that the asteroid retrieval mission is the only stepping stone to Mars which the country can afford right now. How could NASA reprioritize its budget to use both schedule flexibility and rolling development projects to meet milestones to Mars?

Answer: While pressing on with developing SLS and Orion, NASA's initial need is to develop a long term exploration plan or roadmap leading to exploration of Mars, according to a process such as the one I outlined in written testimony. Then near term mission options could be compared to see how they best fit that plan. With exciting mission possibilities viewed from a long term plan perspective and supported by stake holders, the most valued possibilities will emerge and have a logical rationale. This could motivate advocacy for more adequate funding downstream.

15. How can the Moon's resources be used to create new space faring capabilities? Do we already have the technology needed to make use of those resources once we reach the Moon?

Answer: Lunar resources are varied. We have much better information now that results are coming back from the LRO mission. Years of technology funding have been investing in ISRU technologies. Capabilities have been tested for extracting these resources, so many of the techniques exist. Initial use would likely be to augment mission consumables to improve the efficiency of the mission. Ultimately they could possibly be extracted by commercial interests. The resources such as Hydrogen and Oxygen can provide fuel for ascent vehicles. Oxygen can be produced to augment breathing air.

16. Your written testimony states that NASA should concentrate on developing the most enabling technologies for a Mars mission.
    a. What criteria should be used to determine which technologies will be the most useful to a Mars mission?
    b. Are there any enabling technologies that NASA is not currently working on?
    c. Are there any specific technologies currently being developed that you think should be put aside?

Answer: The most logical priorities for technology development are those that are needed to protect astronauts from the environments of low gravity, radiation, and dust, along with those needed to reduce mission mass and enable the mission. The SLS vehicle is essential to launch the masses needed for a mission in the lowest number of launches to reduce cost and overall mission risk. Even with the development of key mass-reducing technologies, six or more launches are needed to lift what is needed for a Mars mission. This mass is equivalent to the weight of the existing ISS. Key technologies include shielding and other mitigation techniques for radiation, advanced in-space propulsion, Mars aerobraking technology, closed loop life support systems, advanced lightweight avionics, advanced EVA suits and systems, Mars entry and landing systems, ISRU, surface nuclear power systems, and cryogenic storage and in-space transfer. All of these technologies are high value and enabling. These technology areas have been known for a long time, having been identified in numerous studies over the years. Progress is being made, but some of these get little funding. More detailed lists are available. These technology areas should be compared with current technology development portfolios to see where the shortcomings exist and where lower priority technologies are being pursued. I am not aware of the latest portfolio to provide more specific advice.

17. What additional technologies would be required for a mission to one of Mars' moons that are distinct from those required for a mission to Mars?

Answer: Almost all of the capabilities and technologies needed for Mars Phobos and Deimos missions are encompassed by those needed to land and return from Mars. The Mars in-space human transit vehicle could achieve rendezvous with the moons. In fact missions to the Mars moons would provide an interesting stepping stones on the way to a Mars landing. Work would have to be done on rendezvous and to operate in this very low gravity environment. I believe that most of the technology developments for Mars landed missions are more difficult.

House Committee on Science, Space, and Technology
Subcommittee on Space
Answers to Questions for the Record Submitted by Representative Steve Stockman
Answers Submitted by Douglas R. Cooke

Your testimony covered the privately-funded 'Mars Inspiration' fly-by mission; planned to launch in 2018.

1. From this mission, what would be some of the possible advances in technology and physiological knowledge we may gain, which would be applicable for a Mars landing mission?
2. Do you think 'Mars Inspiration' might increase public pressure on NASA to take sooner the 'giant leaps' of building a lunar research base and then actually landing, not just orbiting Mars?
3. What would be some important ways NASA could cooperate and assist with to help make 'Mars Inspiration' a success?

Answer:

1. If the Inspiration Mars mission moves forward, it will have to address the advancement of heat shield materials and design to cope with the high heating from Mars return entry velocities. It will also develop further closure of life support systems to reduce consumable mass and volume during the mission. Radiation protection for the crew for approximately 500 days will have to be addressed. These are major areas that will be useful for future human exploration missions to Mars and other destinations. Other aspects of the design in communications and operations will contribute the experience for follow on missions. Physiological, psychological and medical experience will also be valuable experience for follow on missions to Mars.
2. A major objective of the Inspiration Mars program as I understand it is to demonstrate that missions to the Mars vicinity are possible in the near term, and to inspire the public to support further human exploration missions that are increasingly complex leading to human exploration of the Mars surface.
3. Inspiration Mars is already working with NASA to find areas where NASA expertise, existing capabilities, and capabilities in development can benefit the mission, as well as to understand how capabilities developed by inspiration Mars, such as those in (1) above can benefit long term NASA exploration needs. These are being worked through traditional Space Act Agreements.

Appendix II

ADDITIONAL MATERIAL FOR THE RECORD

REPORT SUBMITTED BY DR. PAUL SPUDIS

AIAA SPACE 2011 Conference & Exposition
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AIAA 2011-7185

Using the resources of the Moon to create a permanent, cislunar space faring system

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We have previously described an architecture that extends human reach beyond low Earth orbit by creating a permanent space transportation system with reusable and refuelable vehicles. Such a system is made possible by establishing an outpost on the Moon that harvests water and produces rocket propellant from the ice deposits of the permanently dark areas near the poles. Our plan is affordable, flexible and not tied to any specific launch vehicle or family of vehicles. Robotic assets are teleoperated from Earth to prospect, demonstrate and produce water from local resources. These robots are launched separately over several years, allowing the program to be implemented under constrained and uncertain funding conditions. In addition, the stepwise, incremental approach encourages and facilitates international and commercial participation. Humans arrive only after we have begun water production. Once there, the human mission begins to explore the potential for possible, practical, and affordable use of regolith for material production for outpost sustainment and growth. Consistent with the overarching goal to see if we can learn how to live off-planet, another objective of human activity on the Moon will be the experimentation of biological systems and their interaction and performance in the lunar environment. Our arbitrarily defined end stage is a fully functional, human-tended lunar outpost producing 150 metric tonnes of water per year – enough to export water from the Moon to orbiting propellant depots and create a permanent, extensible reusable transportation system that allows routine access for people and machines to all points of cislunar space. This cost-effective architecture advances technology and builds a sustainable space transportation infrastructure. By eliminating the need to launch everything from the surface of the Earth, we fundamentally change the paradigm of spaceflight. This lunar outpost serves as the vanguard for studying the practical employment of techniques, processes, and systems that allow humanity to effectively extend its reach off-planet.

Nomenclature

CEV	Crew Exploration Vehicle
CL	Cargo Lander
CTS	Cislunar Transfer Stage
CWS	Cislunar Way Station (fuel depot)
DoD	Department of Defense
DoE	Department of Energy
EELV	Evolved Expendable Launch Vehicle
EH	Excavation/Hauler
ESAS	Exploration Systems Architecture Study
GEO	Geosynchronous Orbit
GPS	Geographic Positioning System
HL	Human Lander
HLV	Heavy Lift Vehicle

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ISRU	In Situ Resource Utilization
LCROSS	Lunar Crater Observation and Sensing Satellite
LEO	Low Earth Orbit
LLO	Low Lunar Orbit
LM	Lunar Module
LRO	Lunar Reconnaissance Orbiter
Mini-SAR	Miniature Synthetic Aperture Radar (Chandrayaan-1)
M^3	Moon Mineralogy Mapper (Chandrayaan-1)
MEO	Medium Earth Orbit
MT	Metric ton (1000 kg = 2200 lbs.)
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Agency
PSLV	Polar Satellite Launch Vehicle (India)
RFC	Rechargeable Fuel Cell
RFT	Rover Fuel Tanker
RHL	Robotic Heavy Lander
RML	Robotic Medium Lander
RTG	Radioisotopic Thermal Generator
RWTL	Robotic Water Tank Lander
SPP	Solar Power Plant
SSM	Shuttle Side-Mount (launch vehicle)
VSE	Vision for Space Exploration or "the Vision"
WEFS	Water Electrolysis and Fuel Storage
WIE	Water Ice Explorer
WPS	Water Processing and Storage
WT	Water Tanker

I. Introduction

A key part of the 2004 Vision for Space Exploration (VSE) was learning how to use off-planet material and energy resources to create new space faring capability[1,2]. The Moon was selected as the initial destination for the human spaceflight program because it contains the raw materials needed to do this. The Moon's proximity and accessibility allows us to conduct a significant amount of this work in relative safety with robotic machines teleoperated remotely from Earth and from cislunar space prior to human arrival.

The objective of the Vision was not a series of Apollo-style expeditions or a human Mars mission but rather the extension of human reach to all of the Solar System, for the myriad of purposes imagined over many years. The high cost of launch to orbit is one barrier to widespread activity in space. Despite numerous and continued attempts to lower launch costs over the last 30 years, a cost plateau has been reached at around $5000/kg (based on the price of the two cheapest existing launch services, India's PSLV and SpaceX's Falcon 9.) Launch cost is a "Catch-22" problem: costs are high because volume (traffic to LEO) is low and volume is low because costs are high. In the future we may expect to see some improvement in launch cost numbers but a drop by factors of 2 or 3 (rather than by orders of magnitude) is most likely.

One approach to break this impasse is through the use of In Situ Resource Utilization (ISRU) to create new space faring capability by learning how to use what we find in space to sustain and extend our presence there. In contrast to the problem of launch cost, this approach has only recently been seriously considered. The architects of the VSE specifically included a return to the Moon as the first destination beyond low Earth orbit because of its resource characteristics and its proximity. Our objective in returning to the Moon is to learn how to live and work productively on another world. The Moon possesses the material and energy resources necessary to learn new skills to create new space faring capabilities. Its proximity to the Earth permits easy and routine access to its surface for just such an endeavor that, if successful, will serve as the catalyst and the true historical starting point for human expansion off-planet.

These goals are very ambitious and quite unlike those of any previous space program so there is no *a priori* guarantee of success. Lunar return under the VSE is an engineering research and development project; it is not known how difficult the extraction and use of off-planet resources might be. But because the amount of leverage provided through the use of space resources is so great, this effort is a task worth attempting. If the ultimate rationale for human spaceflight is to create new reservoirs of culture off-planet, it follows that learning to adapt and use the resources of space becomes essential and a critical skill necessary for the future survival of the human race.

Thus, our challenge is to craft an architecture that attempts the never-been-done with funding at less-than-usual levels. We believe this is possible through the development of an incremental, cumulative architecture that uses robotic assets for early and continual accomplishment. We go back to the Moon in small, discrete steps, interlocking with and building upon each other. We scale our return to the Moon to match the resources available. In lean years, we make less (but still positive) progress, while more money allows an accelerated pace of effort. The key to success is to make the incremental steps small enough such that progress is made even in the most financially constrained times. We go when we can, as best we can. But we go.

II. The Mission on the Moon

The mission statement of lunar return is provided by the VSE founding documents: We go to the Moon to learn how to live and work productively on another world. We do this by using the material and energy resources of the lunar surface to create a sustained human presence there. Specifically, we will harvest the abundant water ice present at the lunar poles with the objective of making consumables for human residence on the lunar surface, and propellant, initially for access to and from the Moon, increasing the production with time for eventual export to support activities in cislunar space. This architecture focuses initially on water availability and conversion into propellant because propellant is the holy grail of rocket mechanics; propellant mass is by far the dominant term in the rocket equation and is the most significant factor in cost for human missions. The availability of lunar consumables and propellant allows us to routinely access all the levels of cislunar space where our economic, national security and scientific satellites reside.

This mission objective defines the architecture of lunar return. We stay in one place to build up capabilities and infrastructure in order to stay longer and create more. Thus, we build an outpost; we do not conduct sorties[3]. We go to the poles of the Moon for three reasons: 1) near-permanent sunlight near the poles permits almost constant generation of electrical power from photovoltaics, obviating the need for a nuclear reactor to survive the 14-day lunar night; 2) these quasi-permanent lit zones are thermally benign compared to equatorial regions (Apollo sites), being illuminated at grazing solar incidence angles and thus greatly reducing the passive thermal loading from the hot lunar surface; 3) the permanently dark areas near the poles contain significant quantities of volatile substances, including hundreds of millions of metric tonnes of water ice.

We return to the Moon gradually and in stages, making use of existing assets both on Earth and in space. We emplace small robotic assets on the lunar surface first. These robots will establish a communication/navigation satellite system around the Moon, prospect for promising volatile deposits, conduct demonstration experiments to document the physical state and extraction potential of water, and conduct the initial preparation of the outpost site. In the second phase, larger, more capable robotic machines (also operated from Earth but with more autonomy) will begin production of water in quantity, which is then converted into its component hydrogen and oxygen and made into cryogenic liquids for rocket propellant. The third phase involves emplacing the elements and infrastructure of the lunar outpost, including a habitat, roads and landing pads, solar power arrays and distribution grid, thermal control systems, and communications systems. In the fourth phase, humans arrive on the Moon, where they live in a pre-emplaced outpost and begin using previously landed robotic machines to increase production and extend operations. This work proceeds as resources and technical development permit; schedule is the free variable. Our objective is to produce surplus water that is exported to cislunar space (e.g., Earth-Moon L-1) for processing into propellant and other products. Because this phase coincides with human lunar return, we also begin to use lunar resources to supply materials such as metals, glasses, and ceramics for use at the outpost. Finally, in the fifth phase, we study the biological interaction and practicality of supporting plant growth in the lunar environment as well as develop a transition plan to commercial or international interests in an effort to allow the foothold on the Moon to enter a new phase of growth toward extending the human reach off-planet.

Will this architecture be practical and cost effective compared to launching products from Earth? Only time will tell, but it is possible that this foray into the unknown for the explicit purpose of extending human reach could be similar to other life-changing technological events in human history. Thus far, we have concentrated on the production of water and cryogenic propellant derived from it. However, that is only the beginning of our use of lunar resources. Once humans are on the Moon, we will exploit what is there, including structural fabrication using local resources, experimenting with large structures for plant cultivation, ceramics manufacture and use, metal extraction and processing experiments, and prospecting for other usable resources in the local environment. A significant goal of lunar return is also to learn whether it is feasible to export lunar products to Earth orbit or beyond in addition to answering the question of local resource usefulness at an outpost on a planetary body. By laying out our objectives and specific aims beforehand, we create an architecture that is actually more flexible and sustainable than one that is designed to the still poorly understood requirements of a human Mars mission and staged completely from the surface of the Earth in an "Apollo" mode of operation. We have the knowledge, technology and assets to begin this lunar resource work now.

III. Destination Moon

The Moon is the closest planetary object to Earth and it contains the necessary material and energy resources to create new space faring capability. The proximity of the Moon to Earth is a key attribute: because round-trip light-time between Earth and Moon is only 3 seconds, we can control robotic machines on the lunar surface from Earth to accomplish a variety of tasks. This relation is crucial; it permits early and significant accomplishment on the Moon prior to human arrival. We use the proximity of the Moon to set up a functioning, productive lunar surface installation before the first human crew arrives. With constant availability of a launch window and relatively low Δv requirements, our Moon is the most accessible extraterrestrial body. This accessibility adds significant flexibility to our operational plans, as we can send or retrieve assets to and from the Moon at any time.

In the last two decades, an increasing variety of new sensors have explored the Moon from orbit and significantly changed our perception of its history, processes and composition. Our earlier understanding about the Moon as a volatile-poor object with a harsh and unforgiving surface environment came from studies of the Apollo samples and data. These samples are bone-dry; hydrogen found in returned lunar soil samples is present at a few parts per million concentration levels. Although we had tantalizing suggestions that water might be present near the permanently dark areas near the poles[4], previous data were inconclusive. In addition, we lacked high quality images and topographic maps of the poles to fully understand their lighting and thermal conditions.

New data from a variety of missions have documented the nature and occurrence of water on the Moon[5-7] and the unique lighting[8] and thermal environment[9] near the poles. Measurement of the surface temperatures[9] near the poles show large areas with temperatures lower than 100 K; some permanently dark areas are as cold as 25 K. These "cold traps" serve to collect and sequester water molecules and ice deposits may build up here over the billion year time scales of polar evolution. In addition to cold traps, the new mapping data show areas of near-permanent sun illumination[8] close the poles. Some areas are illuminated more than 90% of the lunar year (Fig. 1). Because darkness is primarily caused by local topography, eclipse periods occur at irregular intervals and have durations ranging from a few hours to a few tens of hours. For this study, we assume solar illumination for 80% of the lunar day, a conservative estimate that is valid for identified places near both poles. Periods of darkness are easily accommodated through temporary transition to power from batteries or rechargeable fuel cells. In addition to being suitable localities for solar arrays, these lit regions are also thermally more benign (surface temperatures on the order of $-50° \pm 10°$ C) than the equatorial regions, permitting extended operations for almost the entire 708-hour lunar day.

Water is present in the polar areas in several different modes of occurrence. Thin layers of water molecules are widespread over the high latitudes; the Moon Mineralogy Mapper (M^3) documented the presence of water[5] poleward of about 65° latitude, with amounts increasing with increasing latitude. Additionally, the impact of the LCROSS spacecraft in October 2009 kicked up a plume of dust, water vapor and ice particles[7]; water is present in this locality at concentrations between 5 and 10 weight percent. Finally, the Mini-SAR radar mapper[6] on Chandrayaan-1 found dozens of craters at both poles that appear to contain nearly pure (90-100%) deposits of water iee; estimates for the north pole suggest that up to 600 million cubic meters of water ice may occur within these craters (Fig. 1). The new data indicate the presence of pervasive and significant water ice at the poles of the Moon. For the purposes of this study, we assume a concentration of 10 wt.% water within our resource mining prospects. This is a very conservative estimate; our productivity and output will be commensurately higher with greater water concentrations. The polar regions contain resources of materials and energy that permit us to use the Moon as a logisties base for space faring within and beyond the Earth-Moon system.

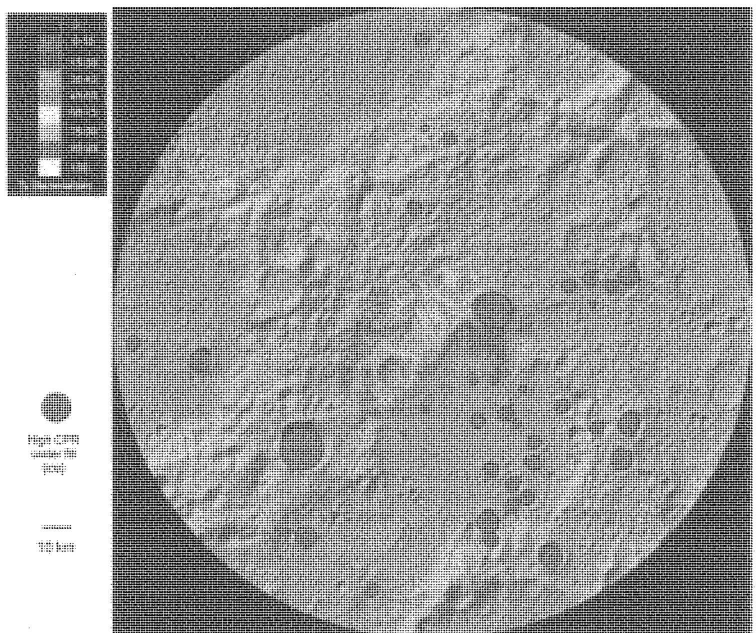

Figure 1. Resources map of the north pole of the Moon. Lighting duration near the pole is shown for northern summer; craters showing anomalous radar behavior consistent with ice are indicated in green.

At present, we do not know the optimum location for the lunar outpost based on the availability of water and illumination but existing data show several highly promising areas near the poles (Fig. 1). To find these optimum locations, we conduct surface reconnaissance at both poles early in our program.

IV. Launch Vehicles

At least three different studies examined the cost problems of the ESAS architecture and offered alternatives that cost less, take less development time, and are adequate for lunar surface return. One approach uses the commercially available Delta IV and Atlas V Evolved Expendable Launch Vehicles (EELV) and orbital propellant depots to perform lunar return[10]. This approach has the advantage of using existing launch vehicles but development of propellant depots is required to permit journeys beyond LEO. Two other approaches use existing Shuttle hardware to create new launch vehicles capable of launching lunar spacecraft in two or three pieces, which are then assembled in low Earth orbit for trips outward. Two concepts – DIRECT[11] and Shuttle side-mount (SSM)[12] – take advantage of the existing space industrial base, including tooling and assembly facilities, as well as the existing processing and launch infrastructure at Kennedy Space Center, to create new vehicles that can deliver tens of metric tonnes to LEO. The advantage of this approach is that we launch what is needed to go to the Moon complete and no depots are required; the disadvantage is that there is some new vehicle development needed.

We assume the use of multiple launch vehicles, using the best available LV assets to meet given payload and mission requirements, including EELV to launch early lunar surface robotic elements. These vehicles are coupled with use of propellant depots in both LEO and LLO as described below in the Architecture section, to make maximum advantage of the launch assets by significantly increasing lunar landed mass capability. A Delta IV Heavy and large Atlas V (551) can place 1-2 MT on the surface of the Moon. This payload delivers significant capability to the lunar surface. We begin by conducting detailed robotic site exploration and characterization of the poles. We know enough to pick promising landing sites, however, strategic knowledge about the physical state, distribution, conditions and quantities of lunar volatiles must be gathered from a lander and rover mission.

The development of a heavy-lift vehicle adds capability and flexibility to our architecture but is not a requirement for early missions, although we recognize that other strategic considerations (such as preservation of HLV infrastructure) may require the near-term development of such a vehicle. A Shuttle-derived vehicle has the least impact on existing facilities and the least amount of new development and thus, lower total cost. A single Shuttle side-mount (SSM) can launch about 70 MT to LEO and place 8-9 MT (including lander) on the lunar surface. Two SSM launches can fly an entire human lunar mission; this is a valuable capability for a lunar return program. Once we have established a foothold on the Moon and have the capability to at least partly supply ourselves from lunar materials, the need for a very heavy lift vehicle lessens. In fact, the best time for the creation of propellant depots is after we are able to supply them with lunar propellant. Such an approach makes human planetary missions easier; the dead weight of propellant (at least 80% of the total mass of the spacecraft for a human Mars mission) need not come from the deep gravity well of Earth.

Much of the current debate about launch vehicles stems from the mission or objective of human flights beyond LEO. We believe that the fundamental objective of such flight is to extend human reach and presence from its current limitation in LEO to all levels of space beyond. To that end, we are agnostic on the need for any specific launch vehicle solution; our goal is to make complete dependence on such vehicles unnecessary as rapidly as possible through the use of off-planet resources. If a heavy lift vehicle is available early in the program, we will use it. If one is not, we will use other launch vehicles. Because we must scope the total effort within an assumed budget profile that would be available to NASA for any launch vehicle development as well as all mission hardware development, we developed an architecture that accomplishes the goal while fitting under the budget. We assume that a medium heavy lift launch vehicle (~70 MT) will be available during the later phases of our program (when humans are needed on the Moon.) Our particular architecture uses such a vehicle and reflects the cost of its development and operations, but other solutions are possible within the assumed budget wedge used by the Augustine Committee[13] (2009). We couple this medium heavy lift capability with use of a LEO propellant depot to leverage a much larger payload on the surface (12mT of payload on the lunar surface – not including the lander) as opposed to a much larger launch vehicle (~150 MT), the approach proposed for Constellation. We assume that commercial launch vehicles should be able to supply the depot with water, which the depot will convert into propellant.

V. Architecture Summary

We have described our architectural approach and elements in some detail previously[14]. Here we summarize the basic features of the architecture, its phasing in time and its programmatic implications. In short, we envision landing robotic spacecraft on the Moon to characterize its resources in detail, demonstrate that water can be extracted, processed and stored, and begin to set up a resource processing system that is largely automated and supervised under human control from Earth. These assets are gradually built and expanded, leading to the robotic emplacement of the lunar outpost elements: habitats, power systems, thermal control systems, navigation and communication, along with surface infrastructure such as roads and landing pads made from fusing the lunar soil by microwave. In effect, we emplace the lunar outpost robotically so that when people arrive, they move into a turn-key facility. Human presence is needed to maintain and repair the processing machines, expand and extend surface operations and conduct local exploration. We envision a remotely operated, robotic mining station; we send people to cannibalize common parts, fix problems, conduct periodic maintenance, upgrade soft goods, seals, valve packing, inspect equipment for wear, and perform certain logistical and developmental functions that humans do best.

A key attribute of our architecture is flexibility – because we build surface infrastructure in increments with small pieces (Table 1), we emplace and operate surface facilities as opportunity and capability permit. International and commercial partners can participate at whatever level they desire, since we use small, incremental pieces. This allows a broader, more integrated participation in lunar return than was possible under previous agency plans. Smaller units (rovers and experiments) can be grouped together and launched on one large HLV or they can be launched separately on smaller EELVs. Such flexibility allows us to create a foothold on the Moon irrespective of budgetary fluctuations.

In our architecture, commonality occurs at the component level, with common cryo engines, valves, avionics boxes, landing subsystems, filters, and connectors to allow maximum use of the assets that are landed on the surface. This is significant because the lifetime of the landed elements in the hard environment of the lunar surface (dust, large temperature swings, radiation, extreme temperatures), without lower level maintenance, would be so low that it would make this strategy unsustainable.

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Orbital	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
Landers	[illegible]	[illegible]		[illegible]	[illegible]	
	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
	Human	[illegible]	[illegible]		[illegible]	[illegible]
	Cargo	[illegible]	[illegible]		[illegible]	[illegible]
Rovers	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]			[illegible]	[illegible]
	[illegible]	[illegible]			[illegible]	[illegible]
	[illegible]	[illegible]			[illegible]	[illegible]
Facilities	[illegible]	[illegible]			[illegible]	[illegible]
	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
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Table 1. Elements of the lunar return architecture

A. Phase I: Resource Prospecting

To begin our return to the Moon, we first launch a series of robotic spacecraft to: 1) emplace critical communications and navigational assets; 2) prospect the polar regions to identify suitable sites for resource mining and processing; and 3) demo the steps necessary to find, extract, process and store water and its derivative products (Fig. 2). The poles of the Moon have intermittent visibility with the Earth. This property creates problems for an architecture that depends on constant, data-intensive communications between Earth and Moon. Moreover, precise knowledge of location on the Moon is difficult and transit to and from specific points requires high-quality maps and navigational aids. To resolve both these needs with one set of assets, we envision a small constellation of satellites that serve as a communications relay system, providing near-constant contact between Earth and the various spacecraft around and on the Moon, as well as a lunar GPS system which provides detailed positional information both on the lunar surface and in cislunar space. This system can be implemented with a constellation of small (~250 kg) satellites in polar orbits (apolune ~2000 km) around the Moon. Such a system must be able to provide bandwidth (several tens to hundreds of Mbps) and positional accuracy (within 100 m, 3σ) necessary to support transit and navigation around the lunar poles.

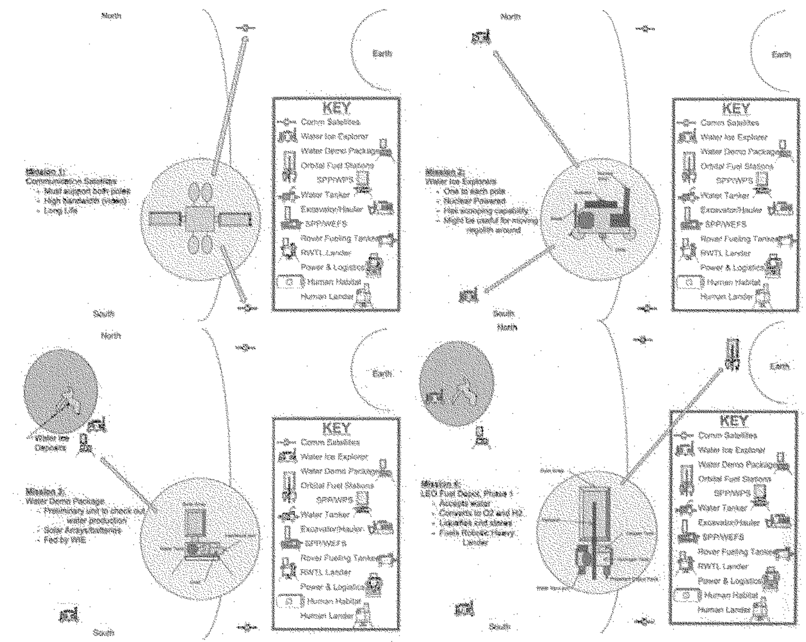

Figure 2. Phase 1 of the lunar return architecture. Orbital assets include the lunar comm/nav system and Earth departure depot. Surface elements include prospecting rovers (one at each pole) and water extraction demo unit.

Two rovers will be sent to each lunar pole to explore the polar light and dark areas and characterize the physical and chemical nature of the ice deposits. We must understand how polar ice varies in concentration both horizontally and vertically, the geotechnical properties of polar soils and access to and location of mining prospects. The rovers will begin the long-term task of prospecting for lunar ice deposits so that we may site the outpost near high grade deposits. In addition to polar ice, we must also understand the locations and variability of sunlit areas, as well as the dust, surface-charging and plasma environment. The rovers are about 500 kg and carry instrumentation to measure the physical and chemical nature of the polar ice[15] (e.g., GCMS, neutron spectrometer, XRF/XRD). In addition, they will excavate (via scoop, mole, and/or drill) and store small (kg) amounts of ice/soil feedstock for transport to resource demonstration experiments mounted on the fixed lander in the permanent sunlight. Power is best provided by some type of radioisotopic thermal generator (RTG) but rechargeable batteries or a Regenerative Fuel Cell (RFC) are possible non-nuclear alternatives for long-lived power.

A mission during this phase will launch the Phase 1 LEO fuel depot, which will be placed in a 400 km orbit (to allow for efficient fueling for spacecraft going to the Moon or to another future Fuel Station at L1 for Earth-Moon escape velocities and from altitude/debris avoidance considerations.) It will launch with some orbit station-keeping fuel with margin to allow a smooth transition to commercial water transfer and subsequent electrolysis and liquefaction. The depot will receive water initially from Earth and later from the Moon via space tugs, convert this water to GH_2 and GO_2, then liquefy and store it. The Phase 1 Station will fuel the Robotic Heavy Lander with roughly 8,000 kg of propellant. This propellant fueling results in a growth of landed payload mass by more than a factor of two. The depot must be flexible enough to control its attitude with varying inertias of docked vehicles. Our intent is to supply the depot by commercial launch of water to the Station, which can begin immediately after orbit emplacement and checkout. If no commercial providers emerge, a separate NASA mission can send water to the fuel depot.

B. Phase II: Resource Mining, Processing and Production

The next phase moves us from resource exploration and supporting assets to actual water production (Figs. 3, 4). We incrementally add excavators, dump haulers, soil processors and storage tanks to get, haul and store the water. Power stations generate electricity at the permanently illuminated (> 80%) peaks; equipment periodically connects to these stations to recharge their batteries. Our goals are to learn how to remotely operate these machines and begin to produce and store water for eventual use when people arrive. The processed water is easily stored in the permanent shadow areas. During this phase we also land our first electrolysis units to begin practicing the cracking of water, making the cryogens, and storage of liquid fuels. Because we would be learning an operational cadence as we go, it might take several months or a year to get into a smooth rhythm which results in maximized amounts of propellant produced per unit time. Large unknowns related to transit time between source and use site, thermal profiles, power profiles, lighting, sensor performance, metal fatigue, lubrication performance, and feedstock density remain to be discovered.

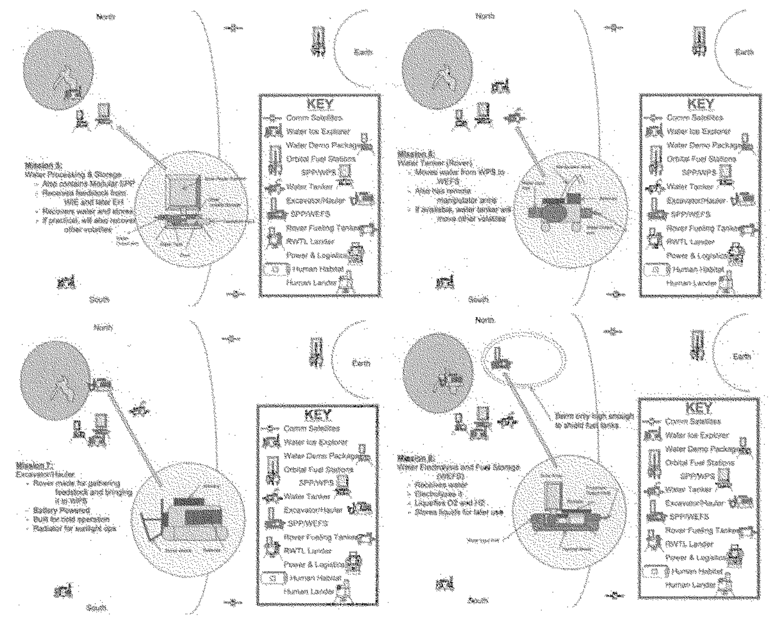

Figure 3. Phase 2 of the lunar return architecture. In Phase 2, we emplace and begin to use the water harvesting and processing units. Each landing adds capability to the processing stream with the aims of continually increasing production levels.

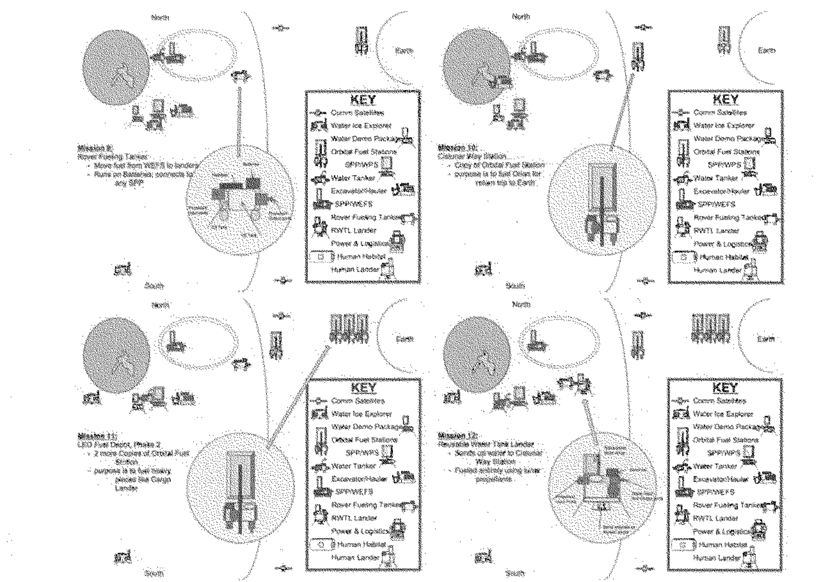

Figure 4. Phase 2 of the lunar return architecture (continued). Each landing continues to add capability to the processing stream with the aims of continually increasing production levels. In the latter part of this phase, we add a second propellant depot in LEO and one in low lunar orbit.

The equipment used in this phase is described in detail elsewhere[14]. The excavation rovers, processors, and power units are all on the order of 1200-1500 kg mass. Power stations are rolled solar arrays gimbaled about the vertical axis to track the sun; each generates about 25 kW. Multiple power stations can be arranged in serial or parallel to provide the power needs of the various robotic equipment. We intend to investigate the making of roads and work floors through the microwave sintering of regolith; many areas near the outpost site, particularly around the power stations, will get much repeat rover traffic and keeping raised dust to a minimum is necessary to maximize equipment lifetime and for proper thermal control.

C. Phase III: Outpost Infrastructure Emplacement and Assembly

The next phase brings to the Moon the pieces of the human lunar outpost (Fig. 5) and begins to prepare the outpost site, emplaces critical infrastructure for power generation and thermal control, and prepares the lunar surface transportation hub, which will receive and service the reusable robotic and human landers that make up our cislunar transportation system. We will also add to existing robotic assets, including the upgrading of surface mining and processing equipment, replacement of damaged items, and extension of processing capability. Our goal in this phase of development is to increase the mass output of water product in order to support human arrival.

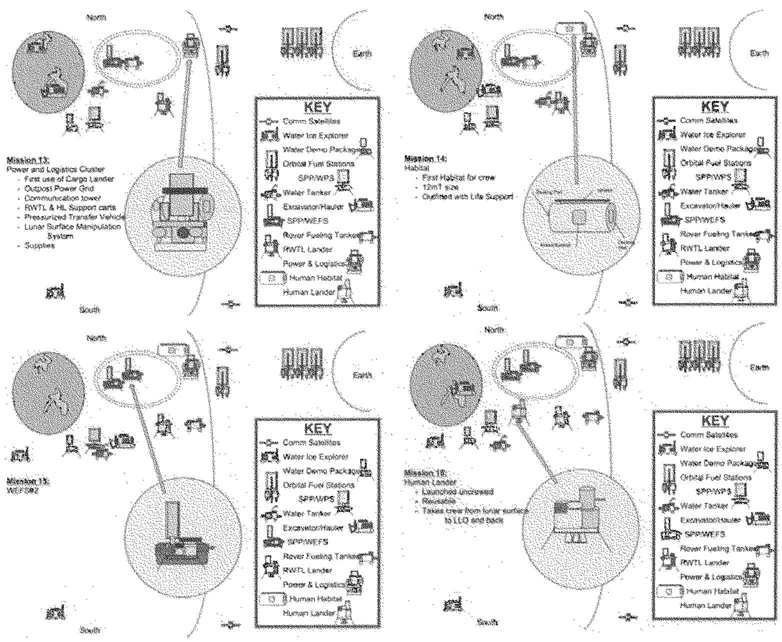

Figure 5. Phase III involves landing and installing the pieces of the lunar outpost. Robotic rovers and manipulators build the outpost and create supporting infrastructure, such as landing pads, roads, and blast berms. The human habitat is operational prior to the arrival of crew.

Propellant is needed on the lunar surface to re-fuel robotic and human landers that come to and return from the Moon. Returning cargo landers can carry payloads as water or as propellant; both options may be necessary, as propellant could be needed in the vicinity of the Moon to re-fuel transfer stages, but water delivered to low Earth orbit can be cracked and frozen there just as efficiently as on the lunar surface. We recognize that cryogens have a boil-off problem, particularly for the highly volatile LH_2. We also note that part of this architecture includes the energy required for liquefaction, which essentially removes a large amount of heat from the fluid, and in doing so should also address the challenge of keeping the hydrogen cold enough to preclude boil-off. However, it is a challenge that is recognized and should be addressed via selected technology development early in this campaign.

The first Heavy Cargo mission will bring all of the logistics and power necessary to support human habitation for the initial stay on the lunar surface. In this architecture, it was not assumed that there would be enough surplus energy from the modular power plants to support human needs, and therefore part of this cargo would include additional power plants with appropriate connectivity to power the habitat, arriving later. This initial cargo complement would probably not include enough battery power to weather an eclipse, but it is expected that this capability would arrive on the third cargo mission. Also part of this complement would be any supplementary equipment needed to attach to the habitat or otherwise make it usable (leveling equipment, high priority spares, filters, thermal shields, various pieces of support equipment, lifting equipment, mobile pallets, EVA Suit components, logistics supplies), including a method to transfer the crew to the habitat in the form of a tunnel/airlock so that the human lander could be streamlined as much as possible. We propose a small mobile human rover (4.5 MT) to interface between the lander and the habitat to allow shirt sleeve ingress, as well as local mobility to access all deployed equipment.

The second Heavy Cargo mission will bring the habitat to the Moon. While it is envisioned that ultimately the human habitable areas at the outpost will be significantly larger than a single 12 MT module, initial needs are to have sufficient habitable volume to support 2-4 crew for a short period of time, with the crew size tradable with duration. Included in either this mission or the previous one would be the radiators and heat rejection equipment, as well as a fully-operational Environmental Control and Life Support System.

D. Phase IV: Human Lunar Return

During this phase, we prepare the outpost site, emplace the elements, and connect the pieces to create a "turn-key" facility, ready to use by arriving human crew (Fig. 5). These pieces include the power and thermal control systems, habitats, workshops, landing pads, roads, and other facilities. The initial outpost can support a crew of four for visits of several weeks each at least twice per year. The arriving crew will interact with, repair, service and operate the previously emplaced robotic assets in ensure maximum efficiency. At least part of the crew will have time to conduct local surface exploration and other science-related tasks. By the time of arrival of the first human crews, we plan for the production of 150 MT of water per year, enough to completely supply the lunar transportation system with propellant.

The lander for human missions is closer to a LM-class system (~30 MT) rather than Constellation's *Altair*-scale lander (~50 MT). Its primary mission is to transport crew to and from the lunar surface. It does not contain significant life-support systems, as the crew will live in pre-emplaced surface habitats while on the Moon; unlike the Altair lander, this lander is merely a mechanism for transport. This lunar taxi becomes a permanent part of the cislunar transportation system. It is re-useable and re-fuelable with lunar produced propellant and can be stored on the lunar surface or at the cislunar transport node. Because of the similarity in size and functionality for the HL and RWTL, it is important to develop common components so that the parts count for lunar surface maintenance can be minimized. Specifically, we again envision both landers using a common reusable cryo engine developed in part or totally by the RHL development, with both vehicles using a multiple engine complement for reliability and redundancy as well as cost. Single engines are designed to be serviced or changed out on the Moon, thus maximizing the lifetime of the vehicles in which they reside.

We also use a cargo variant of the human lander. It is launched on a HLV and can deliver 12 MT of payload to the lunar surface, with fueling at the LEO Fuel Station. Once on the surface, it will be used for scrap parts (another reason for a common parts list). The lander has a dry mass of 8300 kg, a propellant mass of 22000 kg and a payload capacity of 12000 kg. It is launched from the LEO station using a Cislunar Transfer Stage (CTS), which requires about 60,000 kg of cryo propellant to take the lander to the Moon. The CTS is another candidate for reusability, although we assume that it is non-reusable, at least initially. Once lunar propellant production is up and running, we can reuse this element by rendezvousing in LLO with the Cislunar Way Station. Future studies can examine the possibility of later reuse of the cargo lander to ship goods back to the Earth, or to LEO, or even to L1 as a staging area, depending upon the specific needs at the time. Note that this architecture does not presume full success with extracting lunar resources except for refueling for human Earth return. As this concept matures, and our understanding of the logistics, cost, and sustainability of this approach solidifies, lunar refueling can expand significantly (as much as the demand will allow) including incorporation of the cargo landers.

E. Phase V and beyond: Human Habitation of the Moon

Once the outpost has been established (Fig. 6), initial human occupancy will consist of periodic visits designed to explore the local site and to maintain and assure the proper operation of the mining and production equipment. These visits will be interspersed with the landing of additional robotic assets as our intention is to continually increase the production of water with the aim of exporting water to cislunar space. Our architecture stops after 30 missions and at a production level of 150 MT of water per year, the threshold for the production and export of surplus product.

Initially, the first objectives for the crew will be to assure the propellant and water production chain, including periodic maintenance and optimization of the operations concepts and timelines. With subsequent cargo deliveries, the crew will examine production techniques, procedures, technologies, and tools that allow a full revision of and expansion of the next step in utilization. Although many studies have been conducted on this activity, many unknowns need to be addressed, starting with basic technologies and technology applications in the lunar environment. In addition, techniques, tools, and extensive physical and metallurgical analysis of the properties of the final products need to be examined to obtain the best products for as yet undefined applications. Our objective in these ISRU efforts lead to the development of a pressurized surface habitat in which 90% of the mass of the structure uses local materials. This phase is vitally important to extending human reach in space, and so will be a long-term plan, although it is important to realize that habitat upkeep and propellant supply chain management has higher priority. This broad ISRU material investigation lends itself well to international participation and commercial development, since there is no single strategy or technology or method that works for every application and can be divided into discrete investigations. Toward that end, on one of the cargo missions a full unpressurized habitat as material laboratory for these investigations will be delivered. Next in line for crew time would be data on biological interaction and plant growth in lunar gravity. These investigations will examine the vitality, reaction, and long term logistical needs for developing a plant farm and its value to sustainable human habitation of the Moon.

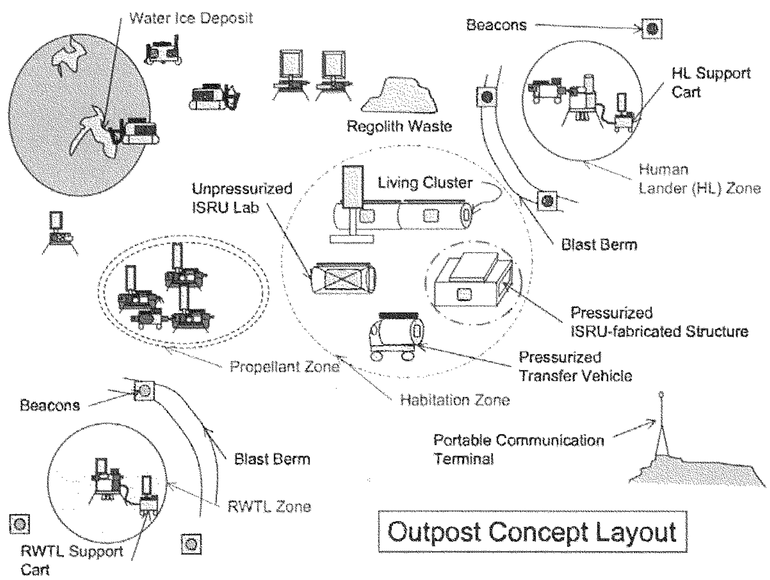

Figure 6 Final configuration of the working outpost, ready for human arrival.

At that stage, we anticipate that the resource outpost will be in a position to recoup our investment in it. Several possible models for the privatization of the water processing may be viable. We anticipate that the federal government will be an early and repeat customer for lunar water, not only for future NASA missions beyond the Earth-Moon system but also other agencies, such as the Department of Defense. Additionally, international customers could emerge and eventually, commercial buyers as well. Whether the production facilities are commercialized before or after these markets emerge cannot be easily foreseen at the this stage and in fact, is unimportant. The critical point is that we will be in a position to industrialize the Moon and cislunar space, a key step in making space part of our economic sphere. Furthermore, we will openly share the technology developments as well as the experiment undesirable outcomes and pitfalls so that others can leverage what we have learned. This will enable the commercial sector to take over many of the lunar activities and services. Transition to commercial activity may be early or late in outpost development. We recognize that part of NASA's ultimate purpose is to expand and enhance the nation's commercial and industrial base and we have attempted to encourage such industrial activity where possible.

VI. MISSION SEQUENCE

The systems and surface elements described above collectively comprise our lunar outpost. An advantage of keeping the individual pieces small is that we have considerable flexibility when we combine them into mission packages. For example, a group of small spacecraft (e.g., the comm/nav system and lander/exploration rover) could be combined into one launch. If cost or schedule precludes such an approach, these spacecraft can be launched separately on smaller launch vehicles. Moreover, few of the outpost elements require other pieces to be emplaced simultaneously; most can be launched and operated independently and begin operations immediately. We have crafted the sequence scenario below so as to get the outpost into production mode as soon as possible (Fig. 7). Depending on budgetary or programmatic considerations, alternative implementations are possible.

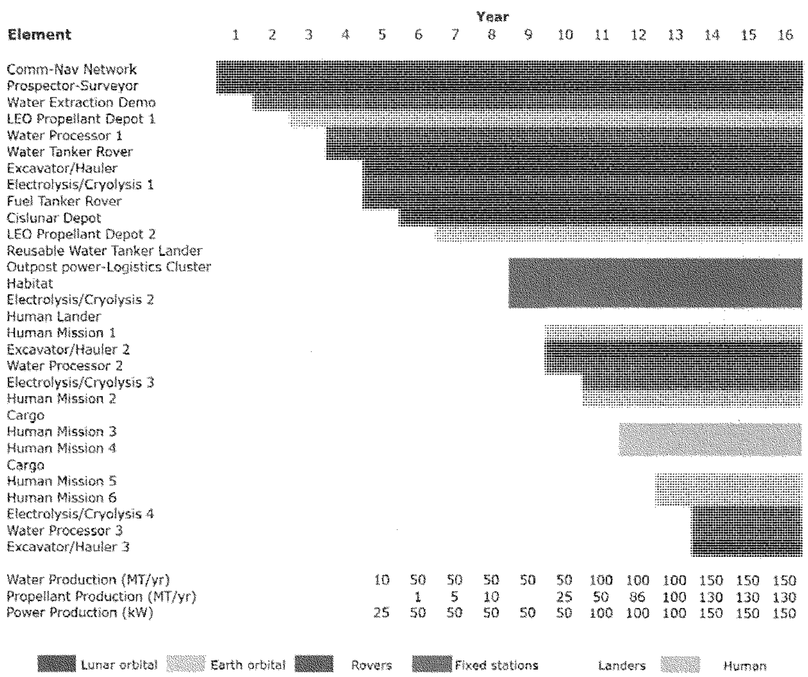

Figure 7. Sequence of missions and architectural elements. Each piece is designed to work by itself and in conjunction with other elements so that cumulative capability increases with time.

Our estimate of capabilities within a 16-year initial window shows roughly 5 human missions, 4 Heavy Cargo Missions (two of which are 12 MT wedge mass and cost allocations at this point), and a lunar surface resource production of roughly 100 MT per year of cryogenic propellant. As there are unallocated resources during this 16-year period, more capability could be added if desired and assessed as to its efficacy. We plan to continue study of possible options and augmentations of this architecture to fully understand its possibilities.

VII. Cost and Schedule

Costs are summarized in Table 2 and details are given in the appendix. We estimate that a fully functioning lunar outpost – capable of producing ~150 tonnes of water per year and roughly 100 tonnes of propellant – can be established for an aggregate cost of approximately $88 billion (Real Year dollars), including peak funding of $6.65

billion starting in Year 11. This total cost includes development of a Shuttle-derived 70 MT launch vehicle, two versions of a CEV (LEO and translunar), reusable lander, cislunar propellant depots and all robotic surface assets, as well as all of the operational costs of mission support for this architecture. The outpost is deployed and operations are fully implemented within 10-15 years of program start, but as the use of robotic assets early in the program makes the schedule flexible, we can either accelerate or slow the progress of the program, as fiscal circumstances require. Human arrival comes relatively late in the process, after we have established a productive resource processing facility but within a few years of the arrival of robotic surface assets. Still, this architecture provides for 5 human missions within the 16-year time window that we studied and many more after that at rates of 1 or 2 per year.

Mission	Description	Launch Vehicle	Lander #	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Total
1	Lunar Communications Satellites	Atlas 401		25	100	175	100													400
2	Characterize Water Deposits	Atlas 551	RML 01, 02	150	350	550	350	200												1600
3	Water Extraction Demo	Atlas 401	RML 03		50	350	250	100												750
4	LEO Fuel Station Phase 1	Atlas 551		100	600	700	550	400	250											2600
5	Water Processor #1	Atlas 551	RHL 001	200	450	600	650	500	420	300										3120
6	Water Tanker	Atlas 401	RML 04				50	150	230	135										565
7	Ore Excavator/Hauler #1	Atlas 551	RHL 002			100	150	350	550	440	200									1790
8	Water Electrolysis #1	Atlas 551	RHL 003				100	250	450	350	150									1300
9	Rover Fueling Tanker	Atlas 401	RML 05					50	150	220	145									565
10	LLO Way Station	Atlas 551					50	100	250	400	205	145								1150
11	LEO Fuel Station Phase 2	Atlas 551							150	430	500	300	170							1550
12	Reusable Water Tank Lander	Heavy Lift	RWTL #1					50	300	475	600	510	350	315						2600
13	Human Power and Logistics Cluster	Heavy Lift	CL 01						100	400	600	700	650	550	450					3450
14	Water Electrolysis #2	Atlas 551	RHL 004								100	145	150	205	125					725
15	Human Habitat #1	Heavy Lift	CL 02								50	350	630	870	900	800				3600
16	Human Lander (reusable)	Heavy Lift	HL 01							100	400	500	800	850	900	950				4500
17	First Human Mission (cost for P/I	Heavy Lift										25	100	100	100	175				500
18	Ore Excavator/Hauler #2	Atlas 551	RHL 005								50	100	100	100	175	200				725
19	Water Processor #2	Atlas 551	RHL 006							50	100	100	100	150	100	75				675
20	Water Electrolysis #3	Atlas 551	RHL 007											100	100	325	200			725
21	Human Habitat #2	Heavy Lift	CL 03											60	150	375	375			960
22	Human Mission 2	Heavy Lift												50	150	200	100			500
23	Human Mission 3	Heavy Lift													50	150	200	100		500
24	Human Mission 4	Heavy Lift													50	150	200	100		500
25	Unpressurized ISRU Lab	Heavy Lift	CL 04												50	200	600	600	450	1900
26	Human Mission 5	Heavy Lift														50	150	200	100	500
27	Human Mission 6	Heavy Lift															50	150	200	400
28	Human Mission 7	Heavy Lift															50	150	200	400
29	Water Electrolysis #4	Atlas 551	RHL 008														100	150	250	500
30	Water Processor #3	Atlas 551	RHL 009													100	100	200	200	600
31	Ore Excavator/Hauler #3	Atlas 551	RHL 010															50	200	250
																				0
																				0
																				0
																				0
	Heavy Lift Launch Vehicle (includes Ground Systems at KSC)			100	400	1000	1200	1300	1100	1000	1000	1000	1000	1350	1350	1350	1350	1350	1350	17200
	Block 1 CEV			300	600	1200	1200	1000	500											4800
	Block 2 CEV (including TLI Stage)									200	300	425	550	550	500	500	500	500	500	4525
	Cislunar Transfer Stage							100	200	300	300	400	400	300	400	400	400	400	400	4000
	Cargo Lander										100	400	700	700	600	150	150	150	100	3050
	Technology Wedge																			
	Undefined Mission Wedge																			
	JSC Ops Cost for 2 Human Flts/yr			40	40	40	40	40	120	160	240	240	280	320	400	400	400	400	400	3560
	Architecture Integration			10	10	10	10	10	30	40	60	60	70	80	100	100	100	100	100	890
	Totals per year			3400	3650	4950	4700	4600	4800	5000	5100	5400	6050	6650	6650	6650	6650	6650	6650	87150

Table 2. Cost of the lunar return architecture in Real-Year (RY) dollars. Total cost includes development and building of a medium (70 MT) heavy lift launch vehicle (Shuttle-derived), two versions of the human CEV (Block II is lunar-capable) and a reusable refuelable lunar lander. All estimates include a margin of 25-30% for cost growth.

This projected cost and schedule profile falls under the projected budget run-outs supplied by NASA to the Augustine Committee[13]. In contrast to the conclusions of that committee, we believe that productive and useful human lunar return is possible under this budgetary envelope. Our program creates a reusable, extensible space faring system that uses the material and energy resources of the Moon. The Flexible Path scenarios developed by the committee[13] continue the existing use-and-discard paradigm of spaceflight in which everything is launched from the bottom of the deep gravity well of Earth, leaving us with few permanent capabilities in space.

VIII. What will this give us?

Establishing a permanent foothold on the Moon opens the space frontier to many parties for many different purposes. By creating a reusable, extensible cislunar space faring system, we build a "transcontinental railroad" in space, connecting two worlds (Earth and Moon), as well as enabling access to all points in between. We will have a system that can access the entire Moon, but more importantly, we will have the capability to routinely access all of our space assets within cislunar space[16]: communications, GPS, weather, remote sensing and strategic monitoring satellites. These satellites will then be in reach to be serviced, maintained and replaced as they age.

We have concentrated on the water production attributes of a lunar outpost because the highest leveraging capabilities that are most easily exploited are associated with the availability of propellant. However, there are other possibilities to explore, including the paradigm-shifting culture to eventually design all structural elements needed for lunar activities using lunar resources. These activities will spur new commercial space interest, innovation and investment. This further reduces the Earth logistics train and helps extend human reach deeper into space, along a trajectory that is incremental, methodical, sustainable and within projected budget expectations.

Instead of the current design-build-launch-discard paradigm of space operations, we can build extensible, distributed space systems, with capabilities much greater than currently possible. Both the Shuttle and ISS experience demonstrated the value of human construction and servicing of orbital systems. What we have lacked is the ability to access the various systems that orbit the Earth at altitudes much greater than LEO – MEO, GEO and other locations in cislunar space.

A transportation system that can access cislunar space, can also take us to the planets. The assembly and fueling of interplanetary missions is possible using the resources of the Moon. Water produced at the lunar poles can fuel human missions beyond the Earth-Moon system, as well as provide radiation shielding for the crew, thereby greatly reducing the amount of mass needed to be launched from the Earth's surface. To give some idea of the leverage this provides, it has been estimated that a chemically propelled Mars mission requires roughly one million pounds (about 500 metric tonnes) in Earth orbit[17]. Of this mass, more than 80% is propellant. Launching such propellant from Earth requires more than five Ares V-class launches, at a cost of almost $2 billion each. This does not establish true exploration capability. A Mars mission staged from the facilities of a cislunar transport system can use the propellant of the Moon to reduce the needed mass launched from Earth by a factor of five.

This return to the Moon is affordable and can be accomplished on reasonable time scales. Instead of single missions to exotic destinations, where all hardware is discarded as the mission progresses, we instead focus on the creation of reusable and extensible space systems, flight assets that are permanent and useable for future exploration beyond LEO. In short, we get value for our money. Instead of a fiscal black hole, this extensible space program becomes a generator of innovation and national wealth. It is challenging enough to drive technological innovation yet within reach on a reasonable timescale.

Propellant and water exported from the Moon will initially be used solely by NASA, both to support lunar surface operations and to access and service satellites in Earth orbit[16] and to re-fuel planetary missions, including human missions to Mars. Over time, other federal agencies such as the Defense Department (intelligence satellites) or NOAA (weather satellites) may need lunar propellant for the maintenance of their space assets. Additionally, international partners or other countries may require propellant for access to their own satellites and space platforms. Finally, lunar propellant would be offered to commercial markets to supply, maintain and extend the wide variety of commercial applications satellites in cislunar space as well as enabling other emerging space ventures.

The modular, incremental nature of this architecture enables international and commercial participation to be easily and seamlessly integrated into our lunar return scenario. Because the outpost is built around the addition of capabilities through the use of small, robotically teleoperated assets, other parties can bring their own pieces to the table as time, availability and capability permit. International partners can contemplate their own human launch capability to the Moon without use of a Heavy Lift vehicle. This feature becomes politically attractive by simply providing lunar fuel for a return trip for the international partners. This flexibility makes international participation and commercialization in our architecture much more viable than was possible under the previous ESAS architecture.

We have described only the initial steps of lunar return based on resource utilization. Water is both the easiest and most useful substance by far that we can extract from the Moon and use to establish a cislunar space faring transportation infrastructure. Once established, we imagine many different possibilities for the lunar outpost. It may evolve into a commercial facility, which manufactures water and propellant and other commodities for sale in cislunar space. It could remain a government laboratory, exploring the trade space of resource utilization by experimenting with new processes and products. Alternatively, it could become a scientific research station, supporting detailed surface investigations to understand the planetary and solar history recorded on the Moon. We may decide to internationalize the outpost, creating a common use facility for science, exploration, research and commercial activity. By emphasizing resource extraction and use early, we create new opportunities for flexible growth and evolution beyond our initial operational capability.

IX. Conclusion

We desire to extend human reach in space beyond its current limit of low Earth orbit. The Moon has the material and energy resources needed to create a true space faring system. Recent data show the lunar surface richer in resource potential than we had thought; both abundant water and near-permanent sunlight is available at selected areas near the poles. We go to the Moon to learn how to extract and use those resources to create a space transportation system that can routinely access all of cislunar space with both machines and people. Such a goal makes our national space program relevant to national security and economic interests as well as to scientific ones. This lunar outpost serves as the vanguard for studying the practical employment of techniques, processes, and systems that will allow humanity to effectively extend its reach off-planet.

This return to the Moon is affordable under existing and projected budgetary constraints. Creation of sustainable space access opens the Solar System to future generations. Having access to the Moon and the ability to use its resources is more important than how we go or how soon we get there. This architecture can relax schedule to fit any monetary or programmatic shortfall, as well as accelerate schedule if funding increases. But regardless of program pace, our goals and tactics remain the same; open the space frontier for a wide variety of purposes by harvesting the material and energy resources of the Moon. The decisions we make now will determine if our long-delayed journey into the cosmos can begin and be sustained over time.

Appendix

A. Cost assumptions and Ground rules

1. The cost of crew to ISS is not budgeted in this portfolio, consistent with the funding profile provided to the Augustine Commission for a lunar architecture.
2. This architecture relies upon a Design To Cost philosophy at NASA such that performance and to a certain extent risk is secondary to cost; NASA is undergoing that paradigm shift evaluation now. This architecture has robust performance margins such that performance can be sacrificed if cost growth is too high. All cost in Real-Year dollars.
3. The Heavy Lift Development cost thru first flight (including KSC DDTE) but not including cost of any future flight is $9.4B for a 75mT LV. Profile shows dip in the middle to get KSC pad modifications performed early. This is consistent with the current planning for the SLS Program.
4. Heavy Lift Operations cost is $1.2B per year (from HLLV Ops cost in Implementation Plan) plus $150M/yr for upgrades, assuming 2 flights and flight sets, and includes all KSC and MSFC costs to launch 2 flights per year (any mix of crew and cargo).
5. Lunar resource processing will be procured from private endeavors when and if they can first demonstrate viability on the lunar surface. In the interim, this architecture assumes that NASA will develop resource producing capabilities and use them throughout the 16-yr duration of this architecture. Viable demonstrations by commercial entities will reduce the cost of the total architecture, but are not assumed here.
6. The fuel producing infrastructure on the Moon (EH, WPS and WEFS) has a 10 yr life with on-site maintenance.
7. The acquisition approach for the various landers is assumed to be one contractor for the robotic landers (RML and RHL), and one contractor for the larger landers (RWTL, HL, and CL). Because of similar designs, parts, components, tooling, and test systems, certain cost savings can be realized. These have not been shown and constitute hidden cost margin for the DDTE of three of the 5 landers.
8. The acquisition approach for the various power systems is assumed to be a single contractor. All power systems on the robotic landers to support lunar water extraction and electrolysis are a single, modular design with only one DDTE cycle.
9. All transport from LEO to LLO (except for the robotic landers) will use the CTS. The variable mass of payloads will be accommodated using propellant offload.
10. JSC Ops Cost (prior to first human mission) includes development of EVA suits and all JSC activity supporting Flight and Mission Ops (from FY02 cost of $450M including everything for Shuttle). There is probably margin in this allocation, but we have not studied this number in detail.
11. This architecture assumes two CEVs per year cost $500M total.
12. The Rovers (WT, RFT) have a 15 yr life with on-site maintenance.
13. The Solar Power Plants have a 20 yr life.
14. JSC Ops cost (after the first human mission) for Ops for two crewed missions per year assumes worst-case 6-month stays and costs $400M/yr (see cost of Shuttle program, above in #10).
15. The RHL DDT&E will include a new cryogenic engine that will also be used for RWTL, HL, and CL.

16. All Atlas 551 launches except LEO Fuel Station include \$50M for water to the LEO Fuel Station, assuming a launch cost of ~\$5000/kg.
17. Cislunar Transfer Stage Ops cost is \$400M/yr for two missions, either crew, cargo, or mix, including hardware, integration, and flight support.
18. The cost of the first flight of the Water Processor System includes the DDT&E cost for the Solar Power Plant and the Robotic Heavy Lander.
19. The Atlas 551 cost is assumed to be \$200M; Atlas 401 is assumed at \$150M (reference cost data from ULA web site)
20. Year 13 has three heavy-lift launches. Assume that the LV hardware for the first launch is paid for with prior year dollars (only one launch in previous year) and stored for a while.
21. The LLO Way Station should be as close to the LEO Fuel Depot design as possible, with a goal to be exact, leading to one DDTE development for modular assets in LEO and LLO. The LEO asset is three identical, modular units. The acquisition approach for these assets is a single contractor.
22. The HL is derived with the same basic structure and systems as the CL, developed at the same time.
23. The Outpost Power Grid is the same basic design as the Power Plants, but with the ability to transport them.
24. Management, Integration, and SE&I are 10% of the cost of all the pieces unless specified. When there is only a single piece launched, the cost of those three pieces is embedded into that element cost.
25. All Elements include between 25 and 30% cost margin as part of their cost allocation. Cost growth is addressed by a reduction in performance down to a floor, and then schedule slippage for the architecture.
26. All integration activity for integrating more than one element into a launch is performed by NASA.

B. Costing of individual missions

Mission 1:

Launch Cost:	\$150M (Atlas 401)
Launch Payload:	
Comm Satellites	Several
Upper Stage Solid	one
Final payload:	Multiple communication satellites in LLO
Final Payload Mass:	1000kg
Payload cost:	\$250M (including upper stage solid)
PM, SE&I, etc	\$0 (Included in payload cost)
Total Mission Cost:	**\$400M**

Mission 2:

Launch Cost:	\$200M (Atlas 551)
Launch Payload:	
RML First Unit	\$500M
RML Second Unit	\$125M
WIE First Unit	\$400M
WIE Second Unit	\$100M
Final payload:	2 WIE's, one to each pole
Final Payload Mass:	1000kg
Payload cost:	\$1125M
PM, SE&I, etc	\$175M
Special Req'ts	\$50M (Nuclear)
	\$50M (Upper Stage solids)
Total Mission Cost:	**\$1600M**

Mission 3:

Launch Cost:	\$150M (Atlas 401)
Launch Payload:	
RML Third Unit	\$125M
Water Demo Pkg	\$400M
Final payload:	Water Demo Package
Final Payload Mass:	500kg
Payload cost:	\$525M

PM, SE&I, etc	$50M
Special Req'ts	$25M solid
Total Mission Cost:	**$750M**

Mission 4:

Launch Cost:	$200M (Atlas 551)
Launch Payload:	
LEO Fuel Station	$2400M
Final payload:	LEO Fuel Station part 1
Final Payload Mass:	8000kg
Payload cost:	$2400M
PM, SE&I, etc	$0 (included in payload cost)
Special Req'ts	None
Total Mission Cost:	**$2600M**

Mission 5:

Launch Cost:	$200M (Atlas 551)
Launch Payload:	
RHL First Unit	$2000M
WP&SP First Unit	$500M
PP First Unit	$200M
Final payload:	WP&SP unit plus PP on the surface
Final Payload Mass:	2300kg
Payload cost:	$2700M (including upper stage solid)
PM, SE&I, etc	$370M ($100M more than 10%)
Special Req'ts	$50M (10,000kg of water for fuel)
Total Mission Cost:	**$3120M**

Mission 6:

Launch Cost:	$150M (Atlas 401)
Launch Payload:	
RML Forth Unit	$125M
Water Tanker	$250M
Final payload:	Water Tanker (rover) on the surface
Payload cost:	$375M (including upper stage solid)
PM, SE&I, etc	$40M
Special Req'ts	None
Total Mission Cost:	**$565M**

Mission 7:

Launch Cost:	$200M (Atlas 551)
Launch Payload:	
RHL Second Unit	$400M (2x the nth copy cost for the 2^{nd} unit)
EH First Unit	$1000M
Final payload:	Excavator/Hauler on the surface
Final Payload Mass:	2300kg (may be more than 1 piece)
Payload cost:	$1400M
PM, SE&I, etc	$140M
Special Req'ts	$50M (10,000kg of water for fuel)
Total Mission Cost:	**$1790M**

Mission 8:

Launch Cost:	$200M (Atlas 551)
Launch Payload:	
RHL Third Unit	$200M
WEFSP First Unit	$700M

PP Second Unit	$50M
Final payload:	WEFSP and PP on surface
Final Payload Mass:	2300kg
Payload cost:	$950M
PM, SE&I, etc	$100M
Special Req'ts	$50M (10,000kg of water for fuel)
Total Mission Cost:	**$1300M**

Mission 9:

Launch Cost:	$150M (Atlas 401)
Launch Payload:	
RML Fifth Unit	$125M
RFT First Unit	$200M
Final payload:	Rover Fueling Tanker on surface
Final Payload Mass:	500kg
Payload cost:	$375M
PM, SE&I, etc	$40M
Special Req'ts	None
Total Mission Cost:	**$565M**

Mission 10:

Launch Cost:	$200M (Atlas 551)
Launch Payload:	
LLO Way Station	$800M (mostly a copy of LEO Fuel Station)
Final payload:	LLO Way Station in LLO (10,000kg fuel)
Final Payload Mass:	8000kg
Payload cost:	$800M
PM, SE&I, etc	$100M (Included in payload, plus complicated ops)
Special Req'ts	$50M (10,000kg of water for fuel)
Total Mission Cost:	**$1150M**

Mission 11:

Launch Cost:	$200M (Atlas 551)
Launch Payload:	
LEO Fuel 2nd copy	$600M
LEO Fuel 3rd copy	$600M
Final payload:	LEO Fuel Station Phase 2 in LEO (75,000kg fuel)
Final Payload Mass:	16000kg
Payload cost:	$1200M
PM, SE&I, etc	$100M (some included in payload cost)
Special Req'ts	$50M (10,000kg of water for fuel)
Total Mission Cost:	**$1550M**

Mission 12:

Launch Cost:	$0 (Heavy Lift cost entered elsewhere)
Launch Payload:	
RWTLFirst Unit	$2100M
CTS First Unit	$0 ($1.8B DDTE entered elsewhere)
RWTL Support Cart	$150M
Final payload:	Reusable Water Tank Lander on surface
Final Payload Mass:	5020 kg
Payload cost:	$2250M
PM, SE&I, etc	$200M
Special Req'ts	$150M (30,000kg of water for fuel)
Total Mission Cost:	**$2600M**

Mission 13:

Launch Cost:	$0 (Heavy Lift cost entered elsewhere)
Launch Payload:	
HPLC:	
Personnel Transfer Vehicle	$2000M
Outpost Power Grid	$200M
Portable Comm Terminal	$100M
LSRS Heavy	$100M
HL Support Cart	$150M
Logistics supplies	$100M
Cargo Lander 1st unit	$0 ($2500M DDTE entered elsewhere)
CTS 2nd Unit	$0 ($200M Unit cost entered elsewhere)
Final payload:	Human Power & Logistics Cluster on surface
Final Payload Mass:	10,000kg
Payload cost:	$2750M
PM, SE&I, etc	$400M ($125M Extra for complex integration)
Special Req'ts	$300M (60,000kg of water for fuel)
Total Mission Cost:	**$3450M**

Mission 14:

Launch Cost:	$200M (Atlas 551)
Launch Payload:	
RHL Fourth Unit	$200M
WEFSP 2nd Unit	$175M
PP Third Unit	$50M
Final payload:	WEFSP #2 and PP on surface
Final Payload Mass:	2300kg
Payload cost:	$625M
PM, SE&I, etc	$50M (Repeat, so cost below 10%)
Special Req'ts	$50M (10,000kg of water for fuel)
Total Mission Cost:	**$725M**

Mission 15:

Launch Cost:	$0 (Heavy Lift cost entered elsewhere)
Launch Payload:	
Habitat First Unit	$3000M
Cargo Lander 2nd unit	$0 ($300M Unit cost entered elsewhere)
CTS 3rd Unit	$0 ($200M Unit cost entered elsewhere)
Final payload:	Habitat #1 on surface
Final Payload Mass:	10,000 kg
Payload cost:	$3000M
PM, SE&I, etc	$300M
Special Req'ts	$300M (60,000kg of water for fuel)
Total Mission Cost:	**$3600M**

Mission 16:

Launch Cost:	$0 (Heavy Lift cost entered elsewhere)
Launch Payload:	
HL First Unit	$2100M
CTS 4th Unit	$0 ($200M Unit Cost entered elsewhere)
Final payload:	Human Lander (reusable) on surface
Final Payload Mass:	10,000kg
Payload cost:	$4000M
PM, SE&I, etc	$200M (easier than 10% because of RWTL synergy)
Special Req'ts	$300M (60,000kg of water for fuel)
Total Mission Cost:	**$4500M**

Mission 17:

Launch Cost:	$0 (Heavy Lift cost entered elsewhere)
Launch Payload:	
Block 2 CEV 1st Unit	$0 ($6925M DDTE for Block 1& 2 covered elsewhere)
CTS 5th Unit	$0 ($200M Unit Cost entered elsewhere)
Misc Payload	$50M
Final payload:	First Human Mission to Outpost
Final Payload Mass:	1000kg
Payload cost:	$350M
PM, SE&I, etc	$0 (included in payload cost; Ops cost covered elsewhere)
Special Req'ts	$150M (30,000kg of water for fuel)
Total Mission Cost:	**$500M**

Mission 18:

Launch Cost:	$200M (Atlas 551)
Launch Payload:	
RHL Fifth Unit	$200M (unit cost)
EH Second Unit	$225M (unit cost)
Final payload:	Excavator/Hauler #2 on the surface
Final Payload Mass:	2300kg (may be more than 1 piece)
Payload cost:	$625M
PM, SE&I, etc	$50M (duplicate of Mission 7, so <10%)
Special Req'ts	$50M (10,000kg of water for fuel)
Total Mission Cost:	**$725M**

Mission 19:

Launch Cost:	$200M (Atlas 551)
Launch Payload:	
RHL Sixth Unit	$200M
WP&SP 2nd Unit	$125M
PP 4th Unit	$50M
Final payload:	WP&SP #2 plus PP on the surface
Final Payload Mass:	2300kg
Payload cost:	$575M (including upper stage solid)
PM, SE&I, etc	$50M (duplicate of Mission 7, so <10%)
Special Req'ts	$50M (10,000kg of water for fuel)
Total Mission Cost:	**$675M**

Mission 20:

Launch Cost:	$200M (Atlas 551)
Launch Payload:	
RHL Seventh Unit	$200M
WEFSP 3rd Unit	$175M
PP 5th Unit	$50M
Final payload:	#3 and PP on surface
Final Payload Mass:	2300kg
Payload cost:	$625M
PM, SE&I, etc	$50M (Repeat, so cost below 10%)
Special Req'ts	$50M (10,000kg of water for fuel)
Total Mission Cost:	**$725M**

Mission 21:

Launch Cost:	$0 (Heavy Lift cost entered elsewhere)
Launch Payload:	

Habitat Second Unit	$600M
Cargo Lander 3rd unit	$0 ($300M Unit cost entered elsewhere)
CTS 6th Unit	$0 ($200M Unit cost entered elsewhere)
Final payload:	Habitat #2 on surface
Final Payload Mass:	10,000kg
Payload cost:	$600M
PM, SE&I, etc	$60M
Special Req'ts	$300M (60,000kg of water for fuel)
Total Mission Cost:	**$960M**

Mission 22:

Launch Cost:	$0 (Heavy Lift cost entered elsewhere)
Launch Payload:	
Block 2 CEV 2nd Unit	$0 ($ covered elsewhere)
CTS 7th Unit	$0 ($200M Unit Cost entered elsewhere)
Misc Payload	$50M
Final payload:	Second Human Mission to Outpost
Final Payload Mass:	1000kg
Payload cost:	$350M
PM, SE&I, etc	$0 (included in payload cost; Ops cost covered elsewhere)
Special Req'ts	$150M (30,000kg of water for fuel)
Total Mission Cost:	**$500M**

Mission 23:

Launch Cost:	$0 (Heavy Lift cost entered elsewhere)
Launch Payload:	
Block 2 CEV 3rd Unit	$0 ($6925M DDTE for Block 1& 2 covered elsewhere)
CTS 8th Unit	$0 ($200M Unit Cost entered elsewhere)
Misc Payload	$50M
Final payload:	Third Human Mission to Outpost
Final Payload Mass:	1000kg
Payload cost:	$350M
PM, SE&I, etc	$0 (included in payload cost; Ops cost covered elsewhere)
Special Req'ts	$150M (30,000kg of water for fuel)
Total Mission Cost:	**$500M**

Mission 24:

Launch Cost:	$0 (Heavy Lift cost entered elsewhere)
Launch Payload:	
Block 2 CEV 4th Unit	$0 ($6925M DDTE for Block 1& 2 covered elsewhere)
CTS 9th Unit	$0 ($200M Unit Cost entered elsewhere)
Misc Payload	$50M
Final payload:	Fourth Human Mission to Outpost
Final Payload Mass:	1000kg
Payload cost:	$350M
PM, SE&I, etc	$0 (included in payload cost; Ops cost covered elsewhere)
Special Req'ts	$150M (30,000kg of water for fuel)
Total Mission Cost:	**$500M**

Mission 25:

Launch Cost:	$0 (Heavy Lift cost entered elsewhere)
Launch Payload:	
Unpress ISRU Lab	$1500M
Cargo Lander 4th unit	$0 ($300M Unit cost entered elsewhere)
CTS 10th Unit	$0 ($200M Unit cost entered elsewhere)
Final payload:	Unpressurized ISRU Lab on surface

Final Payload Mass:	10,000kg
Payload cost:	$1500M
PM, SE&I, etc	$100M
Special Req'ts	$300M (60,000kg of water for fuel)
Total Mission Cost:	**$1900M**

Mission 26:

Launch Cost:	$0 (Heavy Lift cost entered elsewhere)	
Launch Payload:		
Block 2 CEV 2nd Unit		$0 ($ covered elsewhere)
CTS 7th Unit		$0 ($200M Unit Cost entered elsewhere)
Misc Payload		$50M
Final payload:	Fifth Human Mission to Outpost	
Final Payload Mass:	1000kg	
Payload cost:	$350M	
PM, SE&I, etc	$0 (included in payload cost; Ops cost covered elsewhere)	
Special Req'ts	$150M (30,000kg of water for fuel)	
Total Mission Cost:	**$500M**	

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References

[1]Executive Office of the President, White House, Washington DC, A renewed Spirit of Discovery, Washington DC, http://www.spaceref.com/news/viewpr.html?pid=13404 [cited 14 January 2004]

[2]Marburger J., Speech by OSTP Director John Marburger to the 44th Robert H. Goddard Memorial Symposium, Office Science and Technology, Washington DC, http://www.spaceref.com/news/viewsr.html?pid=19999 [cited 20 March 2006]

[3]Clarke A.C., *The Exploration of Space*. New York: Harper, 1951, 198 pp.

[4]Spudis P.D., Ice on the Moon. *The Space Review*, http://www.thespacereview.com/article/740/1 [cited 6 November 2006]

[5]Pieters C.M. *et al.*, Character and Spatial Distribution of OH/H_2O on the Surface of the Moon Seen by M3 on Chandrayaan-1. *Science* **326**, 2009, 568-572.

[6]Spudis, P. D. *et al.*, Initial results for the north pole of the Moon from Mini-SAR, Chandrayaan-1 mission, *Geophys. Res. Lett.* **37**, L06204, 2010, doi:10.1029/2009GL042259

[7]Wooden D. *et al.*, LCROSS: Volatiles and Exosphere Associated with a Permanently Shadowed Region in Cabeus NLSI Lunar Forum 2010, http://lunarscience2010.arc.nasa.gov/node/199

[8]Bussey D.B.J., J.A. McGovern, P.D. Spudis, C.D. Neish, H. Noda, Y. Ishihara, S.-A. Sørensen, Illumination conditions of the south pole of the Moon derived using Kaguya topography. *Icarus* **208**, 2, 2010, 558-564

[9]Paige D.A. et al., Diviner Lunar Radiometer Observations of Cold Traps in the Moon's South Polar Region. Science **330**, 2010, 479-482.

[10]Zegler F., B. F. Kutter, J. Barr, A Commercially Based Lunar Architecture. AIAA 2009-6567, 2009.

[11]Metscham S.L. et al., Achieving the Vision for Space Exploration on Time and Within Budget. Space 2007, AIAA 2007-6231, 2008.

[12]Space Shuttle Program Office, Shuttle-derived Heavy-lift Launch Vehicle Assessment. NSTS 60583, NASA Johnson Space Center, June 2010.

[13]Augustine Committee, *Seeking a Human Spaceflight Program Worthy of a Great Nation*. NASA Washington DC, 2009, http://www.nasa.gov/pdf/397898main_HSF_Cmte_FinalReport_High.pdf

[14]Spudis P.D. and Lavoie T., Mission and Implementation of an Affordable Lunar Return. *Space Manufacturing* **14**, Space Studies Inst., Princeton NJ, 2011, in press.

[15]RLEP-2 Study team, Robotic Lunar Exploration Program Mission 2 Study, NASA Exploration Systems Mission Directorate, April 2006.

[16]Spudis P. D., The New Space Race, Space Ref, http://www.spaceref.com/news/viewnews.html?id=1376 [cited 9 February 2010]

[17]Hoffman S.J. and Kaplan D.I., *Human exploration of Mars: The reference mission of the NASA Mars Exploration Study Team*. NASA **SP-6107**, 1997, NASA-JSC, Houston TX, 147 pp.

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Chapter 12, *Toward a Theory of Spacepower*, C.D. Lutes and P.L. Hays, eds., Institute For National Strategic Studies, National Defense University Press, Washington DC, p. 241-251, 2011.

The Moon: Port of Entry to Cislunar Space

Paul D. Spudis

If God wanted man to become a space-faring species,
He would have given man a Moon. — Krafft Ehricke[1]

One can imagine many possible missions and destinations for America's civil space program. Voyages to the planets, large scientific instruments at orbital libration points, and continued use of the International Space Station (ISS) are all possible missions of both machines and people from many countries in the coming decades. With the imminent completion of the ISS and retirement of the space shuttle, a national discussion has emerged as to both the purpose and rationale for human spaceflight.

The Vision for Space Exploration (VSE) outlined by President George W. Bush in 2004[2] and endorsed by Congress in 2005[3] and 2008[4] (under different parties) called for human missions beyond low Earth orbit (LEO), including a return to the Moon. The inclusion of the Moon has drawn comment from the space community, many of whom think that since the Apollo program ended over three decades ago, it was included as a way to regain valuable experience. In fact, the Moon is the critical element of the VSE. It is where we will learn how to use what we find in space to create new spacefaring capability.

Why the Moon?

The Moon has a major advantage over other potential destinations beyond LEO as it is both close and easily accessible. Only a 3-day trip from Earth, the Moon is close enough for existing space systems to reach. Additionally, it is only a 3-light-second round trip between Earth and Moon, which allows robotic missions on the lunar surface to be controlled remotely from the Earth in near real time. The Moon's low gravity permits landing and operations with a minimal expenditure of energy.

The Moon is a scientific laboratory of unique character. Its location near Earth ensures that it records the geological history of this part of the solar system. Such history includes the impact of solid objects and the solar wind and their possible changes with time. It holds a historical record of cosmic radiation, including nearby supernovae. The Moon's timeless surface preserves a record of ancient events, and whatever is preserved on the lunar surface must have also affected the Earth. This record is long gone from our dynamic terrestrial surface but remains preserved on the static, ancient lunar surface.

The Moon has the material and energy resources needed to support human presence and to begin building a long-lasting transportation infrastructure. Its surface is covered by a very fine-grained soil that is useful as radiation shielding and building material.[5] Oxygen extracted from lunar materials can support life and be used for rocket propellant. Light elements, such as hydrogen, helium, and nitrogen, are present in the lunar soil in low concentrations, but in enough quantity to permit their extraction and use. More importantly, we now find that significant amounts of hydrogen are present in soils at high latitudes and that the polar areas may contain water ice in permanently dark areas. Because the spin axis of the Moon is nearly perpendicular to its orbit around the Sun, some areas at the poles are in near-permanent sunlight. This is a unique asset: areas in constant sunlight for power generation are proximate to shadowed terrain enriched in the light elements, such as hydrogen. Another asset unique to the Moon is its far side, the only place in our solar system permanently shielded from Earth's radio noise. Here we can scan the sky to observe the universe in entirely new areas of thc spectrum.

The Moon is the first, but not the last, destination in the VSE. It is not only an important destination in its own right, but also an enabling asset. The objective of this program is to go to the Moon to learn how to use off-planet resources to create new capability and to make future space flight easier and cheaper.[6] Rocket propellant made on the Moon permits routine access to cislunar space by both people and machines, and is vital to the servicing and protection of national strategic assets and for the repair and refurbishing of commercial satellites. The United States cannot afford to forfeit its lead in the access of cislunar space. There are serious national security and economic ramifications if our leaders fail to recognize thc importance of the Moon to our future in space and herc on Earth.

Spaceflight: The Current Template

Fifty years of space travel have been possible because we accepted the iron rules of spaceflight that are dictated by the rocket equation.[7] In brief, this requires a significant expenditure of energy to get something out of the deep gravity well in which the Earth resides. As it is very expensive to escape this gravity field, thc things we launch into space are made as small and low in mass as possible. As long as this mode of operation prevails, we are mass- and power-limited in space and therefore, capability-limited. These limitations greatly restrict what we can do in space.

The prevailing rules of spaceflight have led to the development of a template of operations for satellites and other space assets. For a given mission, a specialized, usually custom, spacecraft is designed. The spacecraft is built to exceedingly fine standards, with numerous environmental tests and retests. It is launched on an expendable vehicle into a specially designed orbit and in most cases is unreachable by other spacecraft. If all goes well, it is operated for as long as possible and ultimately abandoned. The entire process is then repeated. Sometimes, by incorporating the results from previous missions, the design is improved.

Because each satellite is eventually thrown away, space operations are expensive and difficult. If it were possible, these assets would benefit greatly from servicing, maintenance, and expansion. A system that routinely accesses orbiting satellites with servicing robots and people would fundamentally change our approach to spaceflight. The difficulty in developing this capability is that the machines and propellant we would need to do this must also be lifted up from the deep gravity well, again at great cost and difficulty. The greatest mass of this system is rocket propellant.

If we develop a source of rocket propellant in space (so that we do not have to lift it up from Earth's surface), a new type of operational template might be possible. Instead of one-off designs and throwaway assets, we would think about long-term, extensible, and maintainable modular systems. The availability of a source of rocket propellant in LEO would completely change the way engineers design spacecraft and the way companies and the government think about investing in space assets. It would serve to dramatically reduce the cost of infrastructure in space to both government and the private sector, thus spurring economic investment (and profit).

Cislunar Space: Where All Our Assets Reside

The various altitudes and levels of orbit around the Earth[8] create very different environments and capabilities and hence are utilized by many different types of satellites designed to take advantage of the opportunities they offer. The closest zone is LEO, a space lying roughly within 2,000 kilometers (km) from the Earth, with most satellites operating around 200 to 300 km. It is within this zone most human and robotic space activity occurs. All satellites must at least pass through this zone before arriving at their final destinations.

LEO has many advantages for a variety of missions, including being where orbits are closest and easiest to get to. It is largely below the Van Allen radiation belts, so spacecraft and instruments are protected from hard radiation. Robotic satellites carry out a variety of scientific missions including orbital remote sensing of Earth and its atmosphere. Extended human missions are undertaken in LEO, both on temporary orbital spacecraft such as the shuttle and permanent facilities such as the ISS. Orbital periods are low (on the order of 90 minutes) and repeat passes occur at least twice a day over the same area from inclined orbits (and on every pass from an equatorial orbit).

Medium Earth orbits (MEO) range from 2,000 km up to about 35,000 km altitude. Orbital periods become much longer, which is useful for space applications that require long visibility times, such as global positioning systems (GPS). Typically, such applications are achieved using constellations of multiple satellites, such that two or more assets can work in tandem to achieve the desired result. MEO comprises the Van Allen radiation belts and thus is a difficult environment in which to maintain satellite life.

Highly elliptical orbits (HEO) are very elongated (thousands of kilometers at apogee, the high point of such an orbit) and have very long orbital periods. Because of their very long dwell times at apogee, these orbits are used in some national security missions, as they can "hover" over specific areas for long periods of time. Satellite radio also uses this zone of cislunar space.

Geosynchronous orbits occur around 35,000 km altitude; their periods coincide with the rotation period of the Earth, and thus the satellites appear twice a day over the same spot on the Earth's surface. A perfectly equatorial orbit at 35,786 km is a geostationary orbit (GEO), in which a satellite appears to be stationary in the sky. These orbits are widely used by all nations for a variety of communications purposes and for global weather observation and monitoring. GEO is one of the most valuable places in Earth orbit.

Beyond GEO are the Earth-Moon libration points (also called Lagrange points)[9]; L1 through L3 are in line with the Earth-Moon baseline, while L4 and L5 trail and lead the Moon in its orbit around the Earth. Except for the occasional scientific mission, such as a solar wind monitor, the L-points are not used by spacefaring nations at present. These points are of great value for transportation nodes and logistics depots. Because they are gravitational equipotential points (or weak stability boundaries),[10] all points in cislunar space can be reached from the L-points with minimal changes in velocity. After the L-points, the Moon is the next dominant feature in cislunar space. Both lunar orbit and the lunar surface are possible destinations; both are easily accessed using minimal additional energy from GEO or the Lagrange points.

All zones of cislunar space have practical and theoretical uses.[11] All are accessible with existing systems, but only once. To continually revisit a given space asset, we must build a duplicate of the system that originally got us there. For example, if a communications satellite in GEO stops working, the only alternative is to design, build, and launch a completely new satellite. There is no way to send either servicing crews or machines to repair or upgrade the balky equipment. In short, if the fundamental premise of being a spacefaring nation is the ability to routinely conduct missions anywhere in space for a variety of purposes, we are actually quite far from that capability.

The Value of the Moon

Rock and soil samples returned by the Apollo missions taught us the fundamental chemical makeup of the Moon. It is a very dry, chemically reduced object, rich in refractory elements but poor in volatile elements. Its composition is rather ordinary, made up of common rock-forming minerals such as plagioclase (an aluminum-calcium silicate), pyroxene (a magnesium-iron silicate), and ilmenite (an iron-titanium oxide). The Moon is approximately 45 percent oxygen by weight,[12] but this oxygen is tightly bound to metals in the surface rocks. Light elements, including hydrogen and carbon, are present in small amounts—in a typical soil, hydrogen makes up between 50 and 90 parts per million by weight, with similar quantities of carbon and nitrogen. Soils richer in titanium appear to be also richer in hydrogen, thus allowing us to infer the extent of hydrogen abundance from the titanium concentration mapped from orbit.

Lunar materials offer many possible uses. Because radiation is a serious problem for human spaceflight beyond LEO, the simple expedient of covering surface habitats with soil can protect future inhabitants from both galactic cosmic rays and even solar flares. Lunar soil (regolith) can be sintered by microwave into very strong building materials, including bricks and anhydrous glasses that have strengths many times that of steel.[13] When we return to the Moon, we will have no shortage of useful building materials.

Because of its abundance on the Moon, oxygen is likely to be an important early product. The production of oxygen from lunar materials simply involves breaking the very tight chemical bonds between oxygen and various metals in minerals.[14] Many different techniques to accomplish this task have been developed; all are based on common industrial processes easily adapted to use on the Moon. Besides human life support, the most important use of oxygen in its liquid form is rocket fuel oxidizer. Coupled with the extraction of solar wind hydrogen from the soil, this processing can make rocket fuel the most important commodity of a new lunar economy.[15]

The Moon has no atmosphere or global magnetic field, so solar wind (the tenuous stream of gases emitted by the Sun, mostly hydrogen) is directly implanted onto surface dust grains. Although solar wind hydrogen is present in very small quantities over most of the Moon, it too can be extracted from the soil. Soil heated to about 700°C releases more than 90 percent of its adsorbed solar gases.[16] Such heat can be obtained from collecting and concentrating solar energy using focusing mirrors. Collected by robotic processing rovers, solar wind hydrogen can be harvested from virtually any location on the Moon. The recent discovery that hydrated minerals are abundant at higher latitudes suggests that water is being created constantly at the lunar surface.[17] Some of this water migrates to the poles where it may be concentrated in abundance, thereby making its potential collection and use much easier.

The Department of Defense–National Aeronautics and Space Administration (NASA) Clementine mission in 1994 made global maps of the mineral and elemental content of the Moon. It mapped the shape and topography of its surface with a laser altimeter and gave us our first good look at the intriguing and unique polar regions.[18] Clementine did not carry instruments specifically designed to look for water but an ingenious improvisation used the spacecraft communications antenna to beam radio waves into the polar regions; the resulting radio echoes, which were observed using antennas on Earth, indicate that material with reflection characteristics similar to ice is found in the permanently dark areas near the south pole.[19] This discovery was supported subsequently by the discovery of large amounts of hydrogen near both poles[20] by a neutron spectrometer flown on NASA's Lunar Prospector spacecraft[21] in 1998.

Water is added to the Moon over geological time by the impact of comets and water-bearing asteroids. Because the Moon's axis of rotation is nearly perpendicular to the plane of the ecliptic (the plane in which Earth and Moon orbit the Sun), the Sun is always near the horizon at the poles. If you are in a hole, you never see the Sun, and if you are on a peak, you always see it—the Sun goes around, not up and down. Depressions near the poles never receive sunlight; these dark areas are very cold—only a few degrees above absolute zero.[22] Any water that gets into these polar cold traps cannot get out, and over time, significant quantities can accumulate. Our current best estimate is that over 10 billion cubic meters of water exist at the poles,[23] an amount roughly equal to the volume of Utah's Great Salt Lake. Although hydrogen and oxygen can be extracted directly from the soil as described above, such processing is difficult and energy-intensive. Polar water has the advantage of being in an already concentrated form, greatly simplifying scenarios for lunar return and habitation. Broken down into hydrogen and oxygen, water is a vital substance both for human life support and rocket propellant.

The poles of the Moon are useful from yet another vital resource perspective: the areas of permanent darkness are proximate to areas of near-permanent sunlight. We have identified several areas near both the north and south poles that offer near-constant illumination by the Sun.[24] Moreover, such areas are in darkness for short periods, interrupting longer periods of illumination. An outpost or establishment in these areas will have the advantage of being in sunlight for the generation of electrical power (via solar cells) and in a benign thermal environment (because the sun is always at grazing incidence, the surface temperature remains a near-constant -50° ± 10°C);[25] such a location never experiences the temperature extremes found on the equator (from 100° to –150°C) and thus, thermal control is much easier, making the poles of the Moon inviting "oases" in near-Earth space.

Besides its material and energy resources, the Moon is an operational laboratory where we can experiment with and learn how to conduct planetary surface exploration, utilization, and habitation. The Moon is a world, alien yet familiar, that allows us to learn the skills needed to make other worlds part of humanity's universe. Those skills can be summarized by the words "arrive, survive, and thrive." We need to develop a system that allows access to the lunar surface on a routine basis. Thus, we require long-lived reusable subsystems and equipment that can take advantage of products made from lunar resources. To survive on the Moon, we must protect humans and equipment from the harsh surface environment and make consumables. Water production protects habitats and supports people with drinking water and breathable oxygen. But for permanent human presence on the Moon, we must not only survive, but also thrive. This means that we must make "a profit": some product that we make on the Moon must exceed the value of the investment in building surface infrastructure. In the near term, such a product is likely to be lunar water, the currency of cislunar space. Water exported from the Moon can be used to make rocket propellant to fuel a transportation infrastructure and thereby lower the costs of spaceflight.

Lunar Return: Incremental Steps

Although we possess enough information now to plan a lunar return, we should conduct new robotic missions to reduce programmatic risk and to generate program milestones. The Lunar Reconnaissance Orbiter (LRO)[26] is now mapping the Moon in detail—collecting information on the physical nature of the surface, especially the exotic and poorly understood environment of the polar regions. LRO is mapping the polar deposits of the Moon using imaging radar to "see" into the dark regions. Such mapping will establish the details of water ice locations as well as its thickness, purity, and physical state. The next step is to land small robotic probes to conduct chemical analyses of the polar deposits. Although we expect water ice to dominate the deposit, comets are made of many different substances, including methane, ammonia, and organic molecules, all preserved in the polar regions and all potentially useful resources. We need to inventory these substances and determine their chemical and isotopic properties as well as their physical nature and local environment. Just as robotic missions such as Ranger and Surveyor[27] paved the way for Apollo, a new set of robotic precursors will make subsequent human missions safer and more productive.

As soon as robotic orbiters and landers have documented the nature of the deposits, focused exploration and research should be undertaken to develop the machinery needed to harvest and process the resources of the Moon. We must understand the physical nature of the polar deposits and how we might extract water from its (currently unknown) native state. This could mean excavating and moving dirt and/or developing schemes that remove the water in place. A variety of mining and extraction processes can be experimented with using robotic missions, thus paving the way to industrial-scale activities and commercialization of the production of hydrogen and oxygen from lunar materials.

Forty years ago, America built the mighty Saturn V to launch men and machines to the Moon in one fell swoop. This technical approach was so successful that it has dominated the thinking on lunar return for decades. One feature of nearly all architectures of the past 20 years is the initial requirement to build or rebuild the heavy lift launch capability of the Saturn V or its equivalent. However, parts of the Saturn V were literally handmade,[28] making it a very expensive spacecraft. Development of any new launch vehicle is an enormously expensive proposition. What is needed is an architecture that permits lunar return with the least amount of new vehicle development possible (and hence, the lowest possible cost.) Such a plan will allow concentration of effort and energy on the most important aspects of the mission: learning how to use the Moon's resources to support space flight beyond low Earth orbit.[29]

To deliver the pieces of the lunar spacecraft to Earth orbit—lander, habitat, and transfer stage—the architecture should use existing launch assets, including shuttle-derived components augmented by existing expendable boosters. Assembled into a package in space, these items are then transferred to the Moon-Earth L1. The L1 point orbits the Earth with the Moon such that it appears "motionless" in space to both bodies. Because there is no requirement for quick transit, cargo and unmanned mission elements can take advantage of innovative technologies such as solar electric propulsion and the weak stability boundaries between Earth, Sun, and Moon to make long, spiraling trips out to L1, thus requiring less propellant mass launched from Earth.[30] These unmanned cargo spacecraft can take several months to get to their destinations. The habitat module can be landed on the Moon by remote control and activated to await the arrival of its occupants from Earth. Previously landed robotic rovers and robots become part of the surface infrastructure and can be used telerobotically to prepare and emplace outpost elements.

The human crew is launched separately in the crew exploration vehicle and uses a chemical stage and a quick transfer trajectory to reach the L1 depot in a few days. There, the crew can transfer to the lunar lander, descend to the surface, and occupy the pre-emplaced habitat. Because the outpost elements are already on the Moon, the lunar lander does not have to be the 50-metric-ton behemoth called for by the Exploration

Systems Architecture Study,[31] but rather a much smaller, reusable version—its only job is to transfer the crew from L1 to the lunar surfacc.

The preferred site for a lunar outpost is at one of the almost permanently sunlit areas near a pole of the Moon. The south pole is attractive from the perspective of both science and operations, but final selection should await complete surveys of the poles, so as to locate the outpost as close as possible to the highest grade resources. The strategy on the Moon is to learn how to mine its resources and build up surface infrastructure to permit ever-increasing scales of operation. Each mission brings new components to the surface, and the size and capability of the outpost grows over time.

Resource utilization on the Moon will expand with time. Initially, demonstration production levels of a few kilograms of product (water, oxygen) will document the difficulty of mining and processing. After we determine the optimum techniques, our initial production goals are to make consumables (water for drinking, air, and shielding, in that order); this requires production levels of hundreds of kilograms. Once this is well established, we can begin to make rocket propellant. Initial propellant production at the metric ton level can support extended exploration around the lunar outpost and perhaps ballistic flights to other locations on the Moon. A major breakpoint will come with the production of tcns to hundreds of tons of propellant; at such a level, we can export our surplus propellant to depots in cislunar space, making it available for commercial sale to many different users. It is the ultimate realization of this act that creates a cislunar economy and demonstrates a positive return on investment.[32]

In addition to its technical advantages, this architecture offers important programmatic benefits. It does not require the development of a new heavy lift launcher. Costs in space launch are almost completely dominated by the costs of people and infrastructure. Creating a new launch system requires new infrastructure, new people, and new training. Such costs make up significant fractions of the total program. By using existing systems,[33] we concentrate our resources on new equipment and technology, all focused toward the goal of finding, characterizing, processing, and using lunar resources as soon as possible. The use of the L1 point as a staging depot allows us to depart at any time for both the Earth and Moon; the energy required to go nearly anywhere beyond this point is very low. The use of existing, low-thrust propulsion technology (that is, solar-electric) for cargo elements permits us to use time as an asset, not an enemy. We will acquire new technical innovation as a byproduct of the objective, not as a critical requirement of the architecture.

A New Template for Spacefaring

By mining the Moon for water, we establish a robust transportation infrastructure capable of delivering people and machines throughout cislunar space. Make no mistake: learning to use the resources of the Moon or any other planetary object will be a challenging technical task. We must learn to use machines in remote, hostile environments while working under difficult conditions to extract ore bodies of small concentration. The unique polar environment, with its zones of near-permanent illumination and permanent darkness, provides its own challenges. But for humanity to live and work in space, we must learn to use the material and energy resources available off-planet. We are fortunate that the Moon offers us a nearby "safe" laboratory where we can take our first steps toward using space resources. Initial blunders in operational approach or feedstock processing are better practiced at a location 3 days from the Earth than one many months away.

A return to the Moon to learn how to use its resources is scalable in both level of effort and the types of commodities to be produced. We begin by using the resources that are easiest to extract. Thus, the logical first product is water derived from the polar deposits. Water can be produced there regardless of the nature of the polar volatiles; ice of cometary origin is easily collected and purified. If the polar materials are composed instead of molecular hydrogen, this substance can be combined with oxygen extracted through a variety of processes from rocks and soil to make water. Water is easily stored and will be used as a life-sustaining substance or retained in a separated, cryogenic state for use as rocket propellant.

The world relies on a variety of satellites in cislunar space—weather satellites, GPS, communications systems, and a wide variety of reconnaissance platforms. Commercial spacecraft makes up a multi-billion-dollar market, providing telephone, Internet, radio, and video services. America has invested billions in space hardware. Yet at the moment, we have no infrastructure to service, repair, refurbish, or protect any of these spacecraft. They are vulnerable to severe damage or permanent loss by accident or intentional action. If we lose a satellite, it must be replaced. From redesign though fabrication and launch, such replacement takes years and involves extraordinary investment in the design and fabrication to make them as reliable as possible.

We cannot access these spacecraft because it is not feasible to maintain a human-tended servicing capability in Earth orbit; at thousands of dollars per pound, the costs of launching orbital transfer vehicles and propellant are excessive. Creating the ability to refuel in orbit by using propellant made from lunar materials will revolutionize the way nations view and use space. Satellites will be repaired rather than abandoned. Assets can be protected rather than written off. Very large satellite complexes can be built and serviced over long periods, creating new capabilities and expanding bandwidth (a critical commodity of modern society) for a wide variety of purposes. And along the way, there will be new opportunities and discoveries. We will become a true spacefaring species.

A return to the Moon with the purpose of learning to extract and use its resources creates a new paradigm for space operations. Space becomes a realm in our economic sphere, not an exotic environment for arcane studies. Such a mission ties the American space program to its original roots, making us more secure and more prosperous. It also enables new and broader opportunities for science and exploration. A transportation infrastructure that can routinely access various points of cislunar space can take humanity to the planets. We will learn to use what we find in space to create new spacefaring capabilities. A cislunar transportation system, fueled by lunar propellant, will be the transcontinental railroad of the new millennium.[34]

Chapter 12 Notes

[1] Krafft A. Ehricke, "Lunar Industrialization and Settlement—Birth of a Polyglobal Civilization," *Lunar Bases and Space Activities of the 21st Century* (1985), 827–855.

[2] George W. Bush, "A Renewed Spirit of Discovery," press release, Executive Office of the President, Washington, DC, 2004, available at <www.spaceref.com/news/viewpr.html?pid=13404>.

[3] NASA Authorization Act of 2005, S.1281 ENR, available at <www.govtrack.us/congress/bill.xpd?bill=s109-1281.>

[4] NASA Authorization Act of 2008, H.R.6063 ENR, available at <http://thomas.loc.gov/cgi-bin/query/D?c110:6:./temp/~c110UMnxII::>.

[5] P.D. Spudis, *The Once and Future Moon* (Washington, DC: Smithsonian Institution Press, 1996).

[6] J. Marburger speech to the 44th Robert H. Goddard Memorial Symposium, March 15, 2006, available at <www.spaceref.com/news/viewsr.html?pid=19999>.

[7] "Tsiolkovsky Rocket Equation," available at <http://en.wikipedia.org/wiki/Rocket_equation>.

[8] "List of orbits," available at <http://en.wikipedia.org/wiki/List_of_orbits>.

[9] "Lagrangian point," available at <http://en.wikipedia.org/wiki/Lagrangian_point>.

[10] W.W. Mendell, "A Gateway for Human Exploration of Space? The Weak Stability Boundary," *Space Policy* 17 (2001), 13–17.

[11] T. Cremins and P.D. Spudis, "The Strategic Context of the Moon: Echoes of the Past, Symphony of the Future," *Astropolitics* 5 (2007), 87–104.

[12] G. Heiken, D. Vaniman, and B. French, eds., *The Lunar Sourcebook: A User's Guide to the Moon* (Cambridge: Cambridge University Press, 1991).

[13] L.A. Taylor, E. Hill, and Y. Liu, "Unique lunar soil properties for ISRU microwave processing," in *Space Resources Roundtable 2005* (Houston: Lunar and Planetary Institute, 2005), 2075, available at <www.lpi.usra.edu/meetings/leag2005/pdf/2075.pdf>.

[14] D.M. Burt, "Mining the Moon," *American Scientist* (November-December 1980), 574–579.

[15] P.D. Spudis, "Augustine Commission and Space Exploration: Objectives before Architectures, Strategies before Tactics," Spaceref.com, available at <www.spaceref.com/news/viewnews.html?id=1349>.

[16] L.A. Haskin, "Water and Cheese from the Lunar Desert: Abundances and Accessibility of H, C, and N on the Moon," Second Conference on Lunar Bases and Space Activities of the 21st Century, 1992, available at <http://tinyurl.com/y88d6mm>.

[17] C. Pieters et al., "Character and Spatial Distribution of OH/H2O on the Surface of the Moon Seen by M3 on Chandrayaan-1," *Science* 23 (October 2009).

[18] S. Nozette et al., "The Clementine Mission to the Moon: Scientific Overview," *Science* 266 (1994), 1835–1839.

[19] S. Nozette et al., "The Clementine Bistatic Radar Experiment," *Science* 274 (1996), 1495–1498.

[20] W.C. Feldman et al., "Polar Hydrogen Deposits on the Moon," *Journal of Geophysical Research* 105 (2000), E2, 4175–4195.

[21] A. Binder, "Lunar Prospector: Overview," *Science* 281 (1998), 1475–1476.

[22] A.R. Vasavada, D.A. Paige, and S.E. Wood, "Near-surface Temperatures on Mercury and the Moon and the Stability of Polar Ice Deposits," *Icarus* 141 (1999), 179–193.

[23] P.D. Spudis, "Ice on the Moon," TheSpaceReview.com, 2006, available at www.thespacereview.com/article/740/1.

[24] D.B.J. Bussey, P.D. Spudis, and M.S. Robinson, "Illumination Conditions at the Lunar South Pole," *Geophysical Research Letters* 26, no. 9 (1999), 1187.

[25] Heiken, Vaniman, and French.

[26] "Lunar Reconnaissance Orbiter," available at <http://lunar.gsfc.nasa.gov/>.

[27] D.M. Harland, *Paving the Way for Apollo 11* (Berlin: Praxis, 2009).

[28] M. Gray, *Angle of Attack: Harrison Storms and the Race to the Moon* (New York: Norton, 1992).

[29] Spudis, "Augustine Commission."

[30] V.R. Bond et al., "Cislunar Libration Point as a Transportation Node for Lunar Exploration," AAS/AIAA Spaceflight Mechanics Meeting, 1991, AAS–91–103.

[31] National Aeronautics and Space Administration, "Exploration Systems Architecture Study," 2005, available at <www.nasa.gov/exploration/news/ESAS_report.html>.

[32] D. Wingo, P.D. Spudis, and G. Woodcock, "Going Beyond the Status Quo in Space," SpaceRef.com, 2009, available at <www.spaceref.com/news/viewnews.html?id=1334>.

[33] F. Zeglar, B.F. Kutter, and J. Barr, "A Commercially Based Lunar Architecture," AIAA Space 2009 Conference and Exposition, AIAA 2009–6567, available at <http://tinyurl.com/l9efn5>.

[34] Spudis, "Augustine Commission."

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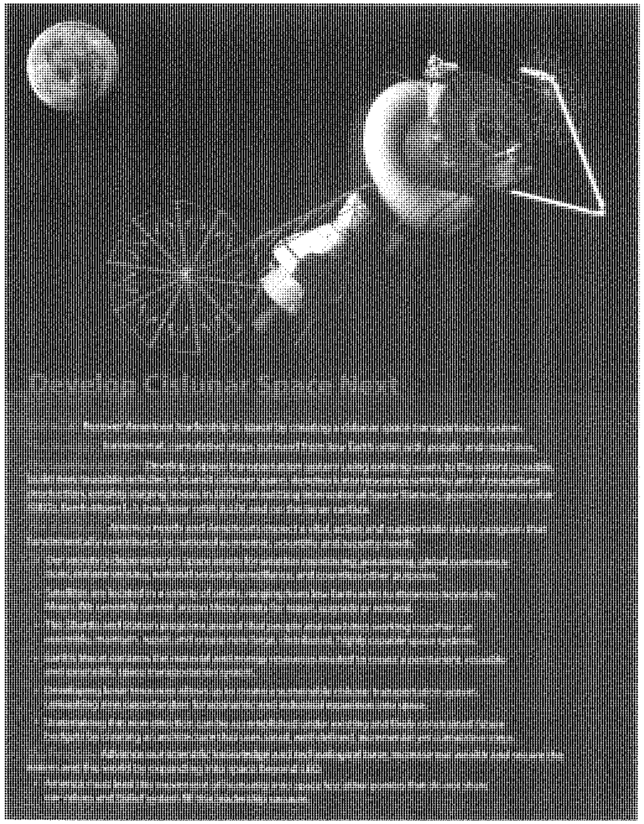
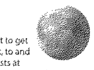


A Compelling Case for Developing Cislunar Space Next and Soon



Realizing Economic, National Security, and Scientific Advantage for the United States and our International Partners, sooner rather than later.

Our national space program is in crisis

The United States Space Program is going nowhere fast. No Space Shuttle, no American access to space, a cancelled Constellation program, massive layoffs of a skilled technical workforce, an International Space Station at risk of a possible catastrophe, recent Russian launch failures (currently the only possible way to get to and from the ISS), dependence on unproven and receding commercial transport and an expensive NASA Heavy Lift Launch Vehicle with no defined purpose and first crewed flight a decade away, if ever.

What's the way out of this bad situation?

Sustainability

In an era of limited resources, our challenge is to create a worthwhile space program with an expenditure rate that falls at or below a supportable level of approximately 0.4% of the Federal budget. Given this reality (regardless of assertions about projected deep space destinations) it is highly likely that cislunar (or Earth-Moon) space will be the sphere of human space operations for the foreseeable future. The questions should be: What are we doing in space and why are we doing it? Attempting a series of space exploration "firsts" (flags-and-footprints forever) implies one set of activities and missions. Incrementally developing a permanent space transportation infrastructure, one that creates an expanding sphere of human operations, suggests a different approach.

The real debate

The real debate is not about launch vehicles or spacecraft or even destinations; it is about the long-term purpose of our space program. One approach requires mega-rockets to distant targets for touch-and-go missions, the "Apollo" template. Another approach is an incremental, go-somewhere-to-stay-and-then-expand-onwards mind set – call it the "Shuttle" approach. The one that you adopt and follow depends on what purpose you believe human spaceflight serves.

Mars?

Because Mars may harbor former or existing life, NASA has presumed that it is our "ultimate destination" in space. In effect, the human spaceflight effort is rationalized as "The Quest for Life" (which means maybe finding a fossil or bacterium, not ET). Thus, debate about what to build, where to go and how to do it is always formulated towards massively expensive missions to Mars.

This unspoken assumption has been at the root of most space objective studies for the past 20 years. Mars was the end point of President George H.W. Bush's Space Exploration Initiative, President George W. Bush's Vision for Space Exploration, of former Lockheed-Martin President Norm Augustine's two reports, and a myriad of space groups and societies. From the 1990s to the present, a multi-billion dollar robotic campaign has sent mission after mission to Mars, each discovering that the red planet once had liquid water. The mania for Mars and preoccupation with searching for life there has limited our perceptions of the space program and distorted our reality of what is possible or attainable on reasonable time scales with available resources – the simple fact is that Mars is unreachable in both technical and fiscal terms now and will remain so for the foreseeable future.

Real Goals and Objectives

In the long term, the goal for human spaceflight is to create the capability to go where we choose, for as long as we need, and do what we want. For the sake of argument, if one accepts such a goal, which model makes more sense as a step to implement it: the Apollo template (flags and footprints) or the Shuttle template (an expanding, incremental extension into space)?

We need a navy to "sail on the ocean of space."

If our goal is to "sail on the ocean of space," we need a fleet. Navies don't operate with just one class of ship because one class isn't capable of doing all the various and necessary jobs. Not all ships will look or operate the same because they have different purposes and destinations. Needed are transports, way stations, supply depots, the International Space Station, and ports. In space terms: spacecraft to get people and equipment to and from Low Earth Orbit, to and from points beyond LEO, to way stations and outposts at Geosynchronous Earth Orbit, to stable Libration Points that are located at the equilibrium of the Moon and Earth gravity, to low lunar orbit, and to the lunar surface. To fuel and provision our space fleet, we require supply and propellant depots in LEO, L-1 and on the lunar surface. Ports of call are all the places we may go. Initially, those ports are satellites in various orbits, which require service, maintenance and replacement with larger, more capable systems. Later, our harbor will be the surface of the Moon, to harvest its resources, thereby creating more capability and provisions from space. Reliable and frequent access to any place in Solar System, not singular trips to a couple of destinations, should be our ultimate goal.

By designing and building mission-specific vehicles and elements (the "Apollo" template) forfeits going everywhere and doing everything. In contrast, adopting the "Shuttle" model does not preclude going to Mars; it enables missions to Mars in an affordable manner that sustains repeated trips, using the infrastructure and propellant resources provided by a space faring navy. Building a series of one-off spacecraft – huge launch vehicles to dash to Mars for expensive, unsustainable extravaganzas – will keep us locked into our current predicament.

The Space program needs rethinking

It is the mind set of the space program that needs re-thinking – not the next destination, not the next launch vehicle, and not the next spacecraft. How can we change the discussion? First, we need to understand and articulate the true choices so that people can see and evaluate the different approaches and requirements. Second, we need to develop sample architectures that fit the requirements for "sustainability." Finally, we need to get such plans in front of the national leadership. There is no guarantee that they will accept it or even listen to the arguments. But right now, they have no alternatives to consider because they are not hearing the case for any.

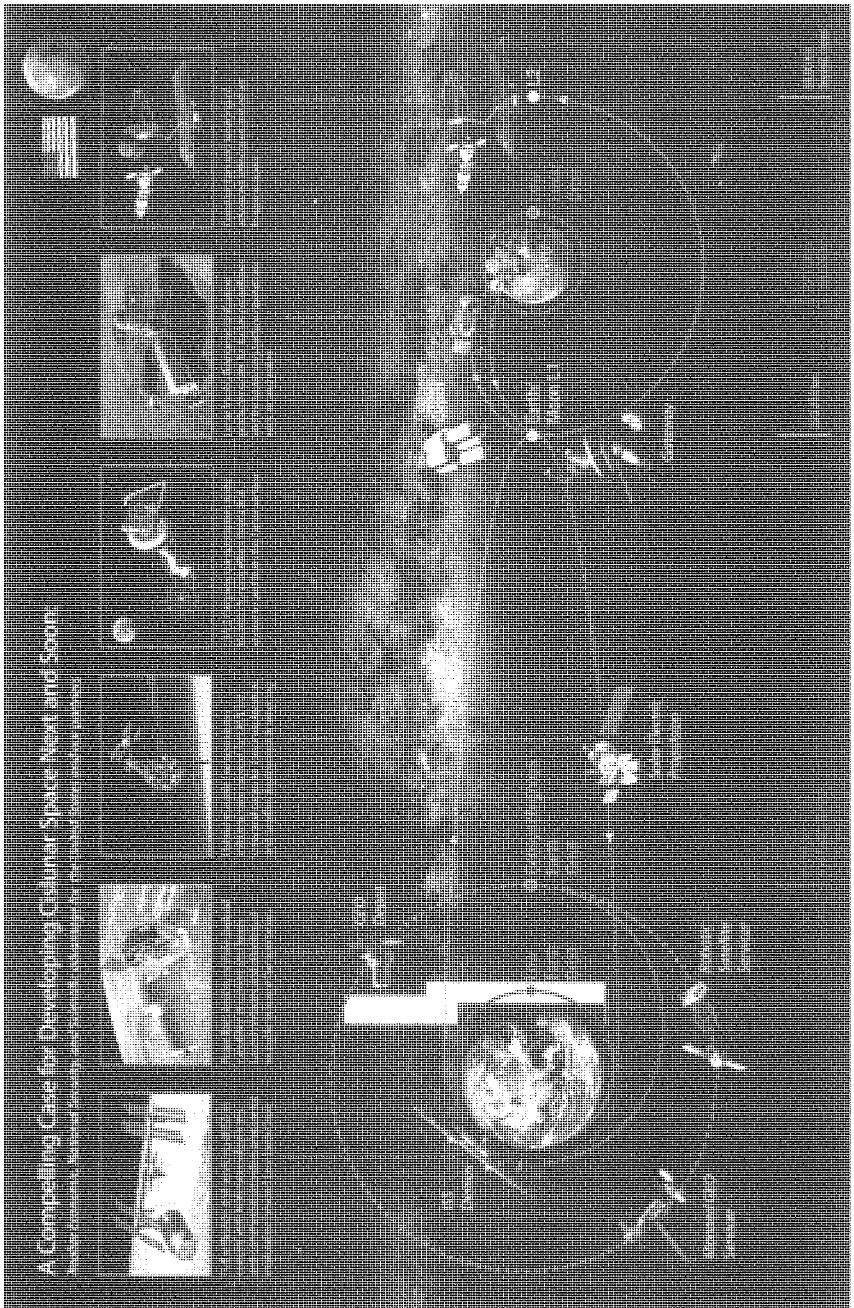
A cost-effective, sustainable human spaceflight program must be continuous, incremental and cumulative. Our space program must continually expand our reach, creating new capabilities over time. Moreover, it should contribute to compelling national economic, scientific and security interests. Building a lasting and reusable space transportation system does that, whereas a series of limited "PR stunt" missions will not. The original intended vision of the Shuttle system was to incrementally move into the Solar System – first a Shuttle to-and-from LEO, then a Space Station as a jumping off platform and then go beyond LEO into cislunar space. The Shuttle-derived heavy-lift cargo variant was always envisioned to go beyond LEO and on to the Moon. Decommissioning the Shuttle Program, the only proven operational heavy lift human launch capability without a replacement to get U.S. astronauts to space is a terrible mistake.

The right answer

The right answer is to adopt the principle that we are going somewhere with the purpose of gradually, yet continuously expanding human reach. Initially, our domain is cislunar space. We should develop an architecture using smaller assets, launching more frequently, working together to build up new and expanded capabilities throughout cislunar space. America can fly spacecraft, create new commercial markets, access and protect the International Space Station and expand beyond LEO. By developing cislunar space next, our values and the societal paradigm of free markets, rule of law and democratic pluralism will prevail on the new frontier of space.

To stand down the development of cislunar space for a decade or more is detrimental to our national interests. Ceding this territory to others endangers our nation and the world and puts the future economic development of the Solar System in hazard.

For more information: www.cislunarnext.org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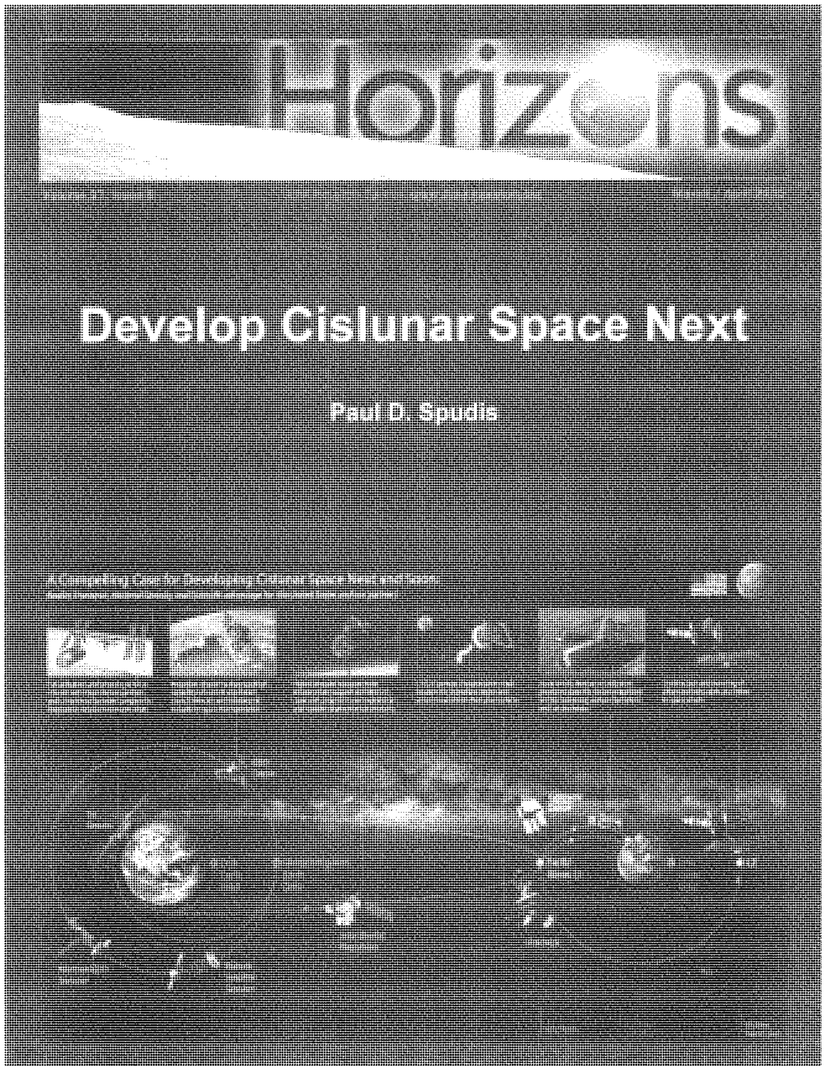

Develop Cislunar Space Next

Cover Story

PAUL D. SPUDIS

The retirement of the Space Shuttle, our national space transportation system, accentuates the absence of national leadership in the American civil space program. Since the Vision for Space Exploration was discarded by the current administration in 2010, confusion and uncertainty reign as the agency is mired in building a launch vehicle they do not want in order to implement human missions of undefined rationale and scope beyond low Earth orbit to destinations whose outstanding characteristic is that they have not yet been visited. Meanwhile, our aerospace industrial infrastructure and human workforce dissipates into nothingness as the vacuum of leadership intensifies. We depend on foreign assets for access to and from the International Space Station, a transportation system whose reliability is in question on the basis of several recent mishaps. With no clear long-term strategic objectives and squabbling over the roles government and commercial sectors, confusion rules supreme.

In an era of limited resources, our challenge is to create a worthwhile space program with a rate of expenditure that falls at or below a supportable level; recent history suggests that approximately 0.5% per year or less of the discretionary federal budget is the level that is politically sustainable. Given this stringent fiscal reality (regardless of assertions about either the desire or intent for deep space destinations), it is highly likely that destinations in cislunar (Earth-Moon) space will be the sphere of human space operations for the foreseeable future. What are we doing in space and why are we doing it? Attempting a series of space exploration "firsts" (flags-and-footprints forever) implies one set of activities and missions. Incrementally developing a permanent space transportation infrastructure, one that creates an expanding sphere of human operations, suggests a different approach.

The Real Debate

The real debate should not be about launch vehicles or spacecraft or even destinations, but about the long-term purpose of our civil space program. Different rationales have been proposed, including: scientific knowledge, technology development, creating enthusiasm for science and math education, societal inspiration and many others less tangible. Fundamentally, all of these rationales (not all of them mutually exclusive) may have merit to a greater or lesser extent, but in times of national fiscal uncertainty, only those projects providing clear practical value and understandable societal benefit have any reasonable expectation of long-term political and fiscal support.

Long-term aspirations, such a human missions to Mars or space settlement, get gener-

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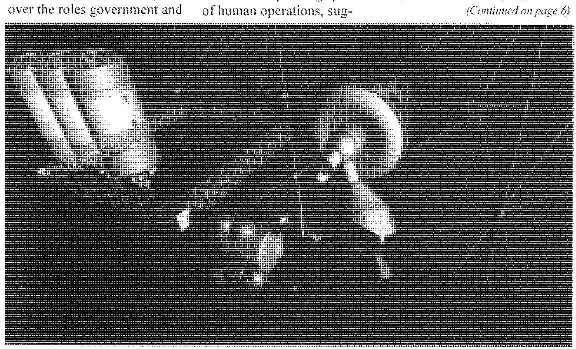

Left: Depot and staging node in cislunar space. Propellant is initially supplied from Earth, but goal is to supply LOX and LH_2 propellant from the poles of the Moon. Image credit: John Frassanito & Associates, reproduced with permission and thanks.

Cover Story

(Continued from page 5)
ous and eager news coverage but they are too distant in both time and technical readiness (on the scale of a decade or a presidential term of office) to serve as rationales for the civil space program. Because Mars may harbor former or existing life, NASA has presumed it to be our "ultimate destination" in space. In effect, the human spaceflight effort is rationalized as "The Quest for Life" (which means maybe finding a fossil or bacterium, not ET). The debate about what to build, where to go and how to do it is always formulated towards massively expensive missions to Mars. This unspoken assumption has been at the root of most studies for space program objectives for the past 20 years.

Mars was the end point of President George H.W. Bush's Space Exploration Initiative, President George W. Bush's Vision for Space Exploration, of former Lockheed Martin President Norm Augustine's two reports, and a myriad of space groups and societies. From the 1990s to the present, a multi-billion dollar robotic campaign has sent mission after mission to Mars, with each "discovering" for the first time that the red planet once had liquid water. The mania for Mars and our preoccupation with searching for life has limited our perceptions of the purpose for a space program – distorting our reality of what is possible or attainable on reasonable time scales with available resources. The simple fact is that Mars is presently unreachable in both technical and fiscal terms and will remain so for the foreseeable future.

A better approach to space exploration would: use existing assets to the maximum extent possible, rely on in-hand technology, and extend our reach incrementally. Ultimately we seek the ability to go everywhere and do everything. That objective is currently unattainable because we do not posses the infrastructure needed to routinely travel throughout the medium of interplanetary space. Given this restriction, it makes sense to develop a space system in a slow, incremental manner whereby each new step works in tandem with previously emplaced pieces, creating an integrated system extending beyond LEO. It can be built up as slowly or as quickly as is needed or permitted by exigent circumstances – in lean budget years, we go slower, but can pick up the pace if more funding becomes available.

Real Goals and Objectives

At the end of the 1960s, when the Apollo mission objective of man-Moon-decade was satisfied, the nation attempted to return to a logical, incremental sequence of increased spaceflight capability. Laid out by Wernher von Braun over 60 years ago, this sequence first envisions routine access to and from LEO, followed by a space station to serve as a platform for missions beyond, a Moon tug to travel to and from the Moon and other localities in cislunar space, and finally, interplanetary missions, including human missions to Mars and

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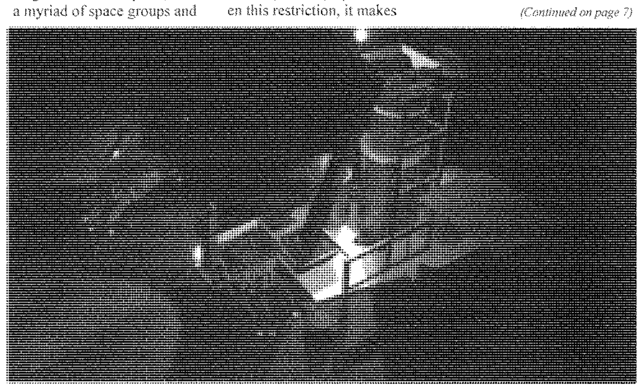

Right: Robotic ore haulers bring ice-rich soil to processing machines for water extraction and subsequent propellant production. Image credit: John Frassanito & Associates, reproduced with permission and thanks.

(Continued from page 6)
beyond.

The Space Shuttle and International Space Station programs were attempts to implement the first steps of this template. For a variety of technical, programmatic and political reasons, these programs developed along non-optimum lines, only partly serving as a working space system. But the basic concept of incremental extension of human reach into space is still valid. As we have a working Space Station, the logical next step is to increase human reach to the Moon, with routine access to the lunar surface and all places in cislunar.

In implementing such an objective, we must reconsider and revise the existing paradigm of spaceflight, which holds that we design custom-built spacecraft, launch them on expendable vehicles, operate them for a time, and then abandon them as space debris. This interminable "Groundhog Day" process continues with each new mission starting from scratch, requiring new development, testing and fabrication. A new template would develop and launch flight elements designed for continuous service and re-use. We would assemble and maintain large distributed space systems and service them with robotic and human assets throughout cislunar space. With such a system in place, the size and capability of Earth orbital satellite assets are literally unlimited. That such an operational principle is possible is demonstrated by such past missions as the Hubble Space Telescope servicing and the building of the International Space Station.

This is a very different kind of space program than the one we are currently attempting to implement. Instead of individual missions in custom-designed spacecraft to distant destinations (for science or to plant the flag) we instead develop a robust, reusable space faring system that can be adapted to a wide variety of potential missions – to build, to service and maintain, to explore, or to live. We satisfy all objectives and impulses to explore space by designing and building a reusable, extensible system for space travel. Just as the American West was opened for development and settlement by the building of the transcontinental railroad, the construction of a cislunar space transportation system will open up and spawn the utility of a vast space frontier.

We Need a Navy to "Sail on the Ocean of Space"

If our goal is to "sail on the ocean of space," we need a fleet. Navies don't operate with just one class of ship because one class isn't capable of doing all the various and necessary jobs. Not all ships will look or operate the same because they will have different purposes and destinations. Needed are transports, way stations, supply depots, Space Station, and ports. In space terms we need the means to get people and equipment to different orbits: Low Earth Orbit (LEO), to and from points beyond LEO, to way stations and outposts at Geosynchronous Earth Orbit (GEO), to stable Libration

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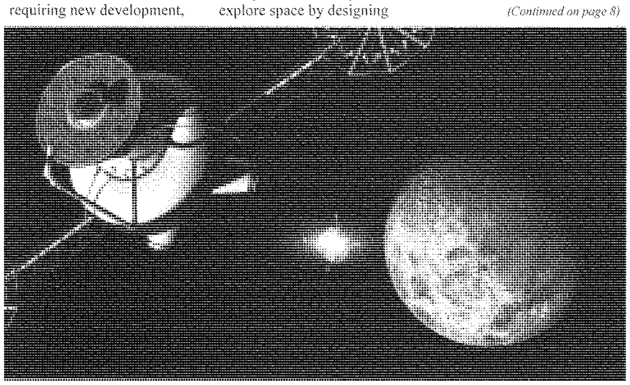

Left: Spacecraft departs Earth-Moon L1 node for lunar surface mission. Image credit: John Frassanito & Associates, reproduced with permission and thanks.

Cover Story

(Continued from page 7)
Points that are located at the equilibrium of the Moon and Earth gravity, to low lunar orbit, and to the lunar surface. In order to fuel and provision this space fleet, staging nodes and supply and propellant depots are required in various places in cislunar space, including such possible locations as LEO, the Earth-Moon L1 and L2 libration points, low lunar orbit and on the lunar surface. Ports of call are all the places we may go. Initially, those ports are satellites in various orbits that require service, maintenance and replacement with larger, more capable systems. Later, our harbor will be the surface of the Moon, to harvest its resources, thereby creating more capability as well as developing the ability to provision ourselves and the expanding transportation network by utilizing what is found in space. Reliable and frequent access to any place in the solar system, not singular trips to a couple of destinations, should be our ultimate goal.

In the past few years, a series of international missions to the Moon has demonstrated that the lunar surface contains significant deposits of water ice near both of its poles and at certain pole locations offers near-permanent sunlight. The Moon is close enough to Earth so as to permit nearly instantaneous remote control of robotic machines from operators on Earth. These facts allow us to set up remotely controlled, robotic resource-processing outposts on the Moon and begin the production water, the most useful substance in space. Water can support human life, serve as a medium for energy storage, and is the most powerful chemical rocket propellant known. Thus, the Moon serves a critical role in the development of cislunar space – it is our first "offshore supply base" for our emergent space navy.

Custom designing and building mission-specific vehicles and elements forfeits the option of going everywhere and doing everything. By adopting an incremental, cumulative space faring model, we *enable* missions to Mars and many other destinations. This affordable model will sustain repeated trips by using the infrastructure and propellant resources provided by a space -faring navy. Building a series of one-off spacecraft – huge launch vehicles to dash to Mars for expensive, unsustainable stunts – will keep us locked into our current predicament.

The space program needs rethinking

It is the mindset of the space program that needs rethinking – not the next destination, not the next launch vehicle, and not the next spacecraft. How do we exit this endless discussion loop? First, we need to understand and articulate true choices so people can understand and evaluate the different approaches and requirements. Second, we need to develop architectural approaches that fit the requirements for fiscal and political "sustainability." Finally, we need to get such plans in front of the national leadership.

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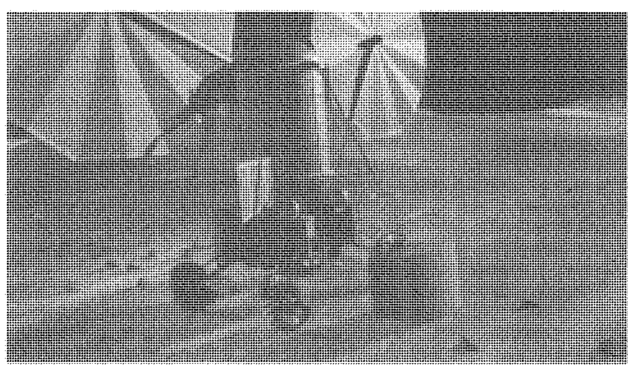


Right: Robotic spacecraft lands and delivers payload to lunar surface. Lander deploys solar arrays and becomes fixed surface power generation asset. Image credit: John Frassanito & Associates, reproduced with permission and thanks.

(Continued from page 8)

A cost-effective, sustainable human spaceflight program must be continuous, incremental and cumulative. It must continually expand our reach, creating new capabilities over time, while contributing to compelling national economic, scientific and security interests. Building a lasting and reusable space transportation system based around the development and use of lunar resources does that, whereas a series of singular destination missions will not. The original intended purpose of the Space Shuttle system was to incrementally move into the Solar System – first a Shuttle to-and-from LEO, then a Space Station as a jumping off platform, and then going beyond LEO into cislunar space. The Shuttle-derived heavy-lift cargo variant was always envisioned to go beyond LEO and on to the Moon. Decommissioning the Shuttle, the only proven operational heavy lift human launch capability, with no replacement in hand to get U.S. astronauts into and back from space was a mistake. The first step in rectifying that mistake is to use this crisis to adopt a new approach to the problem of human spaceflight.

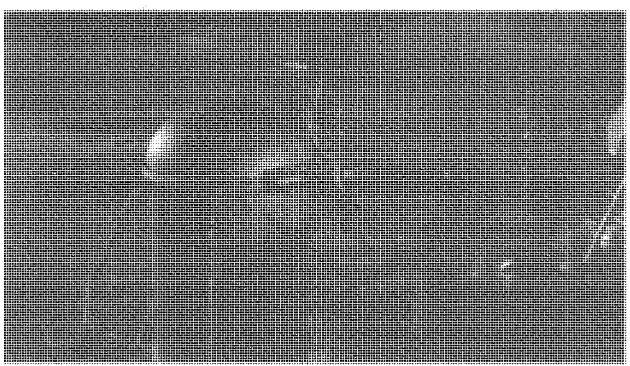
The right answer

The right answer is to adopt the principle that we are going somewhere with the purpose of gradually yet continuously expanding human reach in space. Initially, we develop an architecture using smaller launch vehicle assets, launching more frequently, and making these pieces work together to build up new and expanded capabilities throughout cislunar space. By taking these steps, America can fly spacecraft, create new commercial markets, access and protect the International Space Station and expand human reach beyond LEO.

It is not only important for America to lead in space, but to be seen to lead. Other space faring nations are pursuing expansion beyond LEO into cislunar space; some of these powers do not share our values or belief in free markets and democratic pluralism. If such economic and political paradigms do not exist on the new frontier, there is no assurance that they will emerge spontaneously. Having America actively involved in human expansion into space is likewise no guarantee that such values will prevail here, but such a system is more likely to develop and take hold if we are present and active in this grand and necessary endeavor. We may not worry about this now, but the future is always in question. By developing cislunar space next, our values and the societal paradigm of free markets, rule of law and democratic pluralism is much more likely to prevail on the new frontier of space.

To stand down the development of cislunar space for the better part of a decade is detrimental not only to our national interests, but to the future interests of the world and to generations yet unborn. By ceding this territory to others, we endanger our future by forfeiting technological advancement and economic development of the solar system to those who understand its potential and who are willing to lead.

For more information: www.cislunarnext.org



Left: Robotic servicing systems, teleoperated by controllers back on Earth, operate and maintain a propellant production plant on the Moon. Image credit: John Frassanito & Associates, reproduced with permission and thanks.

ARTICLE SUBMITTED BY DR. PAUL SPUDIS

Destination: Moon or Asteroid?
Operational, Scientific and Resource Utilization Considerations

By Paul D. Spudis

Reprinted from:

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August 31- September 2, 2011

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House Subcommittee on Space Hearing *Next Steps in Human Exploration to Mars and Beyond*

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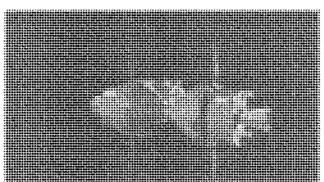

Lockheed-Martin's Plymouth Rock mission concept

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Paul D. Spudis is a Senior St
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Part I: Operational Considerations

The current controversy over the direction of our national space program has many dimensions but most of the discourse has focused on the means (government vs. commercial launch vehicles) not the ends (destinations and activities). Near-Earth objects (NEO, i.e., asteroids) became the next destination for human exploration as an alternative to the Moon when the Augustine committee advocated a "flexible path" in their 2009 report. The reason for going to an asteroid instead of the Moon was that it costs too much money to develop a lunar lander whereas asteroids, having extremely low surface gravity, don't require one. The administration embraced and supported this change in direction and since then, the agency has been studying possible NEO missions and how to conduct them.

On the surface, it might seem that NEO missions answer the requirements for future human destinations. NEOs are beyond low Earth orbit, they require long transit times and so simulate the duration of future Mars missions, and (wait for it)... we've never visited one with people. However, detailed consideration indicates that NEOs are not the best choice as our next destination in space. In this post and two additional ones to come, I will consider some of the operational, scientific and resource utilization issues that arise in planning NEO missions and exploration activities and compare them to the lunar alternative.

Most asteroids reside not near the Earth but in a zone between the orbits of Mars and Jupiter, the asteroid belt. The very strong gravity field of Jupiter will sometimes perturb the orbits of these rocky bodies and hurl them into the inner Solar System, where they usually hit the Sun or one of the inner planets. Between those two events, they orbit the Sun, sometimes coming close to the Earth. Such asteroids are called near-Earth objects and can be any of a variety of different types of asteroids. Typically, they are small, on the order of tens of meters to a few kilometers in size. As such, they do not have significant gravity fields of their own, so missions to them do not "land" on an alien world, but rather rendezvous and station-keep with it in deep space. Think "formation flying" with the International Space Station (ISS) without the option to dock.

The moniker "near Earth" is a relative descriptor. These objects orbit the Sun just as the Earth does and vary in distance to the Earth from a few million km to hundreds of millions of km, depending upon the time of year. Getting to one has nothing to do with getting to another, so multiple NEO destinations in one trip are unlikely. Because the distance to a NEO varies widely, we cannot just go to one whenever we choose – launch windows open at certain times of the year and because the NEO is in its own orbit, these windows occur infrequently and are of very short duration, usually a few days. Moreover, due to the distances between Earth and the NEO, radio communications will not be instantaneous, with varying time-lags of tens of seconds to several minutes between transmission and reception. Thus, the crew must be autonomous during operations.

Although there are several thousand NEOs, few of them are possible destinations for human missions. This is a consequence of two factors. First, space is very big and even several thousand rocks spread out over several billion cubic kilometers of empty space results in a very low density of objects. Second, many of these objects are unreachable, requiring too much velocity change ("delta-v") from an Earth departure stage; this can be a result of either too high of an orbital inclination (out of the plane of the Earth's orbit) or an orbit that is too eccentric (all orbits are elliptical). These factors result in reducing the field of possible destinations from thousands to a dozen or so at best. Moreover, the few NEOs that can be reached are all very small, from a few meters to perhaps a km or two in size. Not much exploratory area there, especially after a months-long trip in deep space.

That's another consideration – transit time. Not only are there few targets, it takes months to reach one of them. Long transit time is sold as a benefit by asteroid advocates: because a trip to Mars will take months, a NEO mission will allow us to test out the systems for Mars missions. But such systems do not yet exist. On a human mission to a NEO, the crew is beyond help from Earth, except for radioed instructions and sympathy. A human NEO mission will have to be self-sufficient to a degree that does not now exist. Parts on the ISS fail all the time, but because it is only 400 km above the Earth, it is relatively straightforward to send replacement parts up on the next supply mission (unless your supply fleet is grounded, as currently it has been). On a NEO mission, a broken system must be both fixable and fixed by the crew. Even seemingly annoying malfunctions can become critical. As ISS astronaut Don Pettit puts it, "If your toilet breaks, you're dead."

Crew exposure is another consequence of long flight times, in this case to the radiation environment of interplanetary space. This hazard comes in two flavors – solar flares and galactic cosmic rays. Solar

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flares are massive eruptions of high-energy particles from the Sun, occurring at irregular intervals. We must carry some type of high-mass shielding to protect the crew from this deadly radiation. Because we cannot predict when a flare might occur, this massive solar "storm shelter" must be carried wherever we go in the Solar System (because Apollo missions were only a few days long, the crew simply accepted the risk of possible death from a solar flare). Cosmic rays are much less intense, but constant. The normal ones are relatively harmless, but high-energy versions (heavy nuclei from ancient supernovae) can cause serious tissue damage. Although crew can be partly shielded from this hazard, they are never totally protected from it. Astronauts in low Earth orbit are largely protected from radiation because they orbit beneath the van Allen radiation belts, which protect life on the Earth. On the Moon, we can use regolith to shield crew but for now, such mass is not available to astronauts traveling in deep space.

When the crew finally arrives at their destination, more difficulties await. Most NEOs spin very rapidly, with rotation periods on the order of a few hours at most. This means that the object is approachable only near its polar area. But because these rocks are irregularly shaped, rotation is not the smooth, regular spin of a planet, but more like that of a wobbling toy top. If material is disturbed on the surface, the rapid spin of the asteroid will launch the debris into space, creating a possible collision hazard to the human vehicle and crew. The lack of gravity means that "walking" on the surface of the asteroid is not possible; crew will "float" above the surface of the object and just as occurs in Earth orbit, each touch of the object (action) will result in a propulsive maneuver away from the surface (reaction).

We need to learn how to work quickly at the asteroid because we don't have much time there. Loiter times near the asteroid for most opportunities are on the order of a few days. Why so short? Because the crew wants to be able to come home. Both NEO aud Earth continue to orbit the Sun and we need to make sure that the Earth is in the right place when we arrive back at its orbit. So in effect, we will spend months traveling there, in a vehicle with the habitable volume of a large walk-in closet (OK, two walk-in closets maybe), a short time at the destination and then months for the trip home. Is it worth it? That will be the subject of my next post.

Destination: Moon or Asteroid?

Part II: Science Considerations

Part III: Resource Utilization Considerations

Posted By: Paul D. Spudis — Lunar Exploration,Lunar Resources,Lunar Science,Space and Society,Space Politics,Space Transportation | Link | Comments (33)

33 Comments

1. Can you really pick a destination if the question of "why go?" has not been even properly discussed yet ?

   You will get a bunch of different people coming into the discussion with a ton of different assumptions about that, without any hope of understanding .. which keeps being the case in space advocacy circles.

   Comment by kert — August 31, 2011 @ 10:46 am

2. *Can you really pick a destination if the question of "why go?" has not been even properly discussed yet ?*

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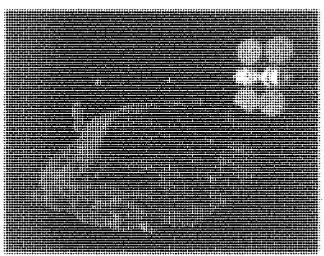
September 1, 2011

Destination: Moon or Asteroid? Part II: Scientific Considerations



People at an asteroid: What will they do there?

Part II: Scientific Considerations

In my last post, I examined some of the operational considerations associated with a human mission to a near Earth asteroid and how it contrasted with the simpler, easier operations of lunar return. Here, I want to consider what we might do at this destination by focusing on the scientific activities and possible return we could expect from such a mission. Some of the operational constraints mentioned in the previous post will impact the scientific return we expect from a human NEO mission.

Asteroids are the left over debris from the formation of the Solar System. Solid pieces of refractory (high melting temperature) elements and minerals that make up the rocky planets have their precursors in the asteroids. We actually have many pieces of these objects now -- as meteorites. The rocks that fall from

- About

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the sky are overwhelmingly from the small asteroids that orbit the Sun (the exception is that in meteorite collections, some come from larger bodies, including the Moon and Mars).

Moreover, we have flown by almost a dozen small bodies, orbited two, impacted one and "landed" on two others. Thousands of images and spectra have been obtained for these rocky objects. The chemical composition of the asteroids Eros and Vesta have been obtained remotely. We have catalogued the craters, cracks, scarps, grooves and pits that make up the surface features of these objects. We have seen that some are highly fragmental aggregates of smaller rocks, while others seem to be more solid and denser. In addition to these spacecraft data, thousands of asteroids have been catalogued, mapped and spectrally characterized from telescopes on the Earth. We have recognized the compositional variety, the various shapes, spin rates and orbits of these small planetoids. We now know for certain that the most common type of meteorite (chondrite) is derived from the most spectally common type of asteroid (S-type) as a result from the Hayabusa mission, the world's first asteroid sample return.

In short, we know quite a bit about the asteroids. What new knowledge would we gain from a human mission to one?

Although we have (literally) tons of meteorites, extraterrestrial samples without geological context have much less scientific value than those collected from planetary units with regional extent and clear origins. Many different processes have affected the surfaces of the planets and understanding the precise location and geological setting of a rock is essential to reconstructing the history and processes responsible for its formation and by inference, the history and processes of its host planet.

Most asteroids are made up of primitive, undifferentiated planetary matter. They have been destroyed and re-assembled by collision and impact over the last 4.5 billion years of Solar System history. The surface has been ground-up and fragmented by the creation of regolith and some details of this process remain poorly understood. But in general terms, we pretty much know what asteroids are made of, how they are put together, and what processes operate upon their surfaces. True enough, the details are not fully understood, but there is no reason to suspect that we are missing a major piece of the asteroid story. In contrast, planetary bodies such as the Moon have whole epochs and processes that we are just now uncovering – in the case of the Moon, water has been recently found to be present inside, outside and in significant qnantity at the poles, relations that have enormous implications for lunar history and about which we were nearly totally ignorant only a couple of years ago.

Most NEOs will be simple ordinary chondrites – we know this because ordinary chondrites make up about 85% of all meteorite falls (an observed fall of a rock from the sky). This class of meteorite is remarkable, not for its diversity but for its uniformity. Chondrites are used as a chemical standard in the analysis of planetary rocks and soils to measure the amounts of differentiation or chemical change during geological processing. In themselves, chondrites do not vary (much) except that they show different degrees of heating subsequent to their formation, but not enough heatiug to significantly change their chemical composition.

Some NEO asteroids are pieces of bigger objects that experienced chemical and mineral change or differentiation. Vesta (not a NEO, but a main belt asteroid) has reflection spectra similar to known, evolved meteorites, the eucrite group. These rocks suggest that some asteroids are small, differentiated planetoids, having volcanic activity that dates from the very beginning of Solar System history. Moreover, since we have pieces of the Moon and Mars as meteorite fragments, some NEOs may consist of material blasted off these planets. However, given that most NEOs are inaccessible to human missions, the

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likelihood that we could visit one of planetary derivation is small (curious that the most interesting of the NEOs appear to be those derived from some bigger (planet-sized) object.) In broad terms of meteorite science, multiple small samples from a variety of asteroid types are preferable to many bigger samples of a single specimen, exactly the opposite of what a human mission will provide.

What specifically would a crew do during a NEO visit? An astronaut on a planet typically would explore the surface, map geological relations where possible, collect representative samples of the units and rock types that can be discerned, and collect as much mapping and compositional data as possible to aid in the interpretation of the returned samples. In the case of a NEO, many of these activities would not be particularly fruitful. The asteroid is either a pile of rubble or a single huge boulder. Chondritic meteorites are uniform in composition, so geological setting is not particularly instructive. We do have questions about the processes of space weathering, the changes that occur in rocks as a result of their exposure to space for varying lengths of time. Such questions could be addressed by a simple robotic sample collector, as the recently approved OSIRIS mission plans to do.

One question that could be addressed by human visitors to asteroids is their internal make-up and structure. Some appear to be rubble piles while others are nearly solid – why such different fates in different asteroids? By using active seismometry (acoustic sounding), a human crew could lay out instruments and sensors to decipher the density profile of an asteroid. Understanding the internal structure of an asteroid is important for learning how strong such objects are; this could be an important factor in devising mitigation strategies in case we ever have to divert a NEO away from a collision trajectory with the Earth. As mentioned in my preceding post, the crew had better work quickly – loiter times at the asteroid will probably be short, on the order of a few days at most.

Although we can explore asteroids with human missions, it seems likely that few significant insights into the origins and processes of the early Solar System will result from such exploration. Such study is already a very active field, using the samples that nature has provided us – the meteorites. Sample collection from an asteroid will yield more samples of meteorites, only without the melted fusion crusts that passage through the Earth's atmosphere creates. In other words, from this mission, scientific progress will be incremental, not revolutionary.

In contrast, because they yield information on geological histories and processes at planet-wide scales, sample collection and return from a large planetary body such as the Moon or Mars could revolutionize our knowledge of these objects in particular and the Solar System in general. Many years prior to the Moon missions, we had meteorites that showed impact metamorphic effects but the idea of impact-caused mass extinctions of life on Earth only came after we had fully comprehended the impact process recorded in the Apollo samples from the Moon. The significance of impact-related mineral and chemical features were not appreciated until we had collected samples with geological context to understand what the lunar samples were telling us.

Of course, science being unpredictable, some major surprise that could revolutionize our knowledge may await us on some distant asteroid. But such surprises doubtless await us in many places throughout the Solar System and the best way to assure ourselves that we will eventually find them is to develop the capability to go anywhere in space at any time. That means developing and using the resources of space to create new capabilities. I will consider that in my next post.

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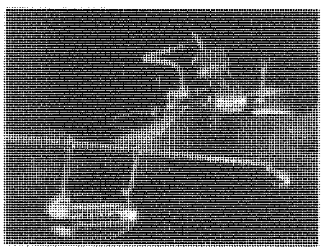
Destination: Moon or Asteroid? Part III: Resource Utilization Considerations



Setting up a mining operation on an asteroid may be difficult (from Howstuffworks.com)

Part III: Resource Utilization Considerations

In Part I and Part II of this series, I examined some of the operational and scientific issues associated with a human mission to a near Earth asteroid (NEO) and contrasted them with the simpler operations and greater scientific return of a mission to the Moon. To continue the discussion of what we might do at an asteroid, I will now consider using the local resources offered by asteroids, how they differ from those of the Moon, and offer some practical considerations on accessing and using them.

To become a truly space faring species, humanity must learn how to use what we find in space to survive and thrive. Tied to the logistics chain of the Earth, we are now and always will be limited in space

- About

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capability. Our ultimate goal in space is to develop the capability to go anywhere at any time and conduct any mission we can imagine. Such capability is unthinkable without being able to obtain provisions from resources found off-planet. That means developing and using the resources of space to create new capabilities.

One of the alleged benefits of asteroid destinations is that they are rich in resource potential. I would agree, putting the accent on the word "potential." Our best guide to the nature of these resources comes from the study of meteorites, which are derived from near Earth asteroids. They have several compositions, the most common being the ordinary chondrite, which makes up about 85% of observed meteorite falls. Ordinary chondrites are basically rocks, rich in the elements silicon, iron, magnesium, calcium and aluminum. They contain abundant metal grains, composed mostly of iron and nickel, widely dispersed throughout the rock.

The resource potential of asteroids lies not in these objects, but in the minority of asteroids that have more exotic compositions. Metal asteroids make up about 7% of the population and are composed of nearly pure iron-nickel metal, with some inclusions of rock-like material as a minor component. Other siderophile (iron-loving) elements including platinum and gold make up trace portions of these bodies. A metal asteroid is an extremely high-grade ore deposit and potentially could be worth billions of dollars if we were able to get these metals back to Earth, although one should be mindful of the possible catastrophic effects on existing precious metal markets – so much gold was produced during the 1849 California Gold Rush that the world market price of gold decreased by a factor of sixteen.

From the spaceflight perspective, water has the most value. Another type of relatively rare asteroid is also a chondrite, but a special type that contains carbon and organic compounds as well as clays and other hydrated minerals. These bodies contain significant amounts of water. Water is one of the most useful substances in space – it supports hnman life (to drink, to use as radiation shielding, and to breath when cracked into its component hydrogen and oxygen), it can be used as a medium of energy storage (fuel cells) and it is the most powerful chemical rocket propellant known. Finding and using a water-rich NEO would create a logistics depot of immense value.

A key advantage of asteroids for resources is a drawback as an operational environment – they have extremely low surface gravity. Getting into and out of the Moon's gravity well requires a change in velocity of about 2380 m/s (both ways); to do the same for a typical asteroid requires only a few meters per second. This means that a payload launched from an asteroid rather than the Moon saves almost 5 km/s in delta-v, a substantial amount of energy. So from the perspective of energy, the asteroids beat the Moon as a source of materials.

There are, however, some difficulties in mining and using asteroidal material as compared to lunar resources. First is the nature of the feedstock or "ore." We have recently found that water at the poles of the Moon is not only present in enormous quantity (tens of billions of tons) but is also in a form that can be easily used – ice. Ice can be converted into a liquid for further processing at minimal energy cost; if the icy regolith from the poles is heated to above 0° C, the ice will melt and water can be collected and stored. The water in carbonaceous chondrites is chemically bound within mineral structures. Significant amounts of energy are required to break these chemical bonds to free the water, at least 2-3 orders of magnitude more energy, depending on the specific mineral phase being processed. So extracting water from an asteroid, present in quantities of a few percent to maybe a couple of tens of percent, requires significant energy; water-ice at the poles of the Moon is present in greater abundance (up to 100% in certain polar craters) and is already in an easy-to-process and use form.

The processing of natural materials to extract water has many detailed steps, from the acquisition of the feedstock to moving the material through the processing stream to collection and storage of the derived product. At each stage, we typically separate one component from another; gravity serves this purpose in most industrial processing. One difficulty in asteroid resource processing will be to either devise techniques that do not require gravity (including related phenomena, such as thermal convection) or to create an artificial gravity field to ensure that things move in the right directions. Either approach complicates the resource extraction process.

The large distance from the Earth and poor accessibility of asteroids versus the Moon, works against resource extraction and processing. Human visits to NEOs will be of short duration and because radio time-lags to asteroids are on the order of minutes, direct remote control of processing will not be possible. Robotic systems for asteroid mining must be designed to have a large degree of autonomy. This may become possible but presently we do not have enongh information on the nature of asteroidal feedstock to either design or even envision the nse of snch robotic equipment. Moreover, even if we did fully understand the nature of the deposit, mining and processing are highly interactive activities on Earth and will be so in space. The slightest anomaly or miscalculation can cause the entire processing stream to break down and in remote operations, it will be difficult to diagnose and correct the problem and re-start it.

The accessibility issue also cuts against asteroidal resources. We cannot go to a given asteroid at will; launch windows open for very short periods and are closed most of the time. This affects not only our access to the asteroid but also shortens the time periods when we may depart the object to return our products to near-Earth space. In contrast, we can go to and from the Moon at any time and its proximity means that nearly instantaneous remote control and response are possible. The difficulties of remote control for asteroid activities have led some to suggest that we devise a way to "tow" the body into Earth orbit, where it may be disaggregated and processed at our leisure. I shudder to think about being assigned to write the environmental impact (if you'll pardon the expression) statement for that activity.

So where does that leave us in relation to space resource access and utilization? Asteroid resource utilization has potential but given today's technology levels, uncertain prospects for success. Asteroids are hard to get to, have short visit times for round-trips, difficult work environments, and uncertain product yields. Asteroids do have low gravity going for them. In contrast, the Moon is close and has the materials we want in the form we need it. The Moon is easily accessible at any time and is amenable to remote operations controlled from Earth in near-real time. My perspective is that it makes the most sense to go to the Moon first and learn the techniques, difficulties and technology for planetary resource utilization by manufacturing propellant from lunar water. Nearly every step of this activity – from prospecting, processing and harvesting – will teach us how to mine and process materials from future destinations, both minor and planetary sized-bodies. Resource utilization has commonality of techniques and equipment, the requirement to move and work with particulate materials, and the ability to purify and store the products. Learning how to access and process resources on the Moon is a general skill that transfers to any future space destination.

There was a reason that the Moon was made our first destination in the original Vision for Space Exploration. It's close, it's interesting, and it's useful. Establishing a foothold on the Moon opens up cislunar space to routine access and development. It will teach us the skills of a space faring people. It makes sense to go there first and create a permanent space transportation system. Once we have that, we get everything else.

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- nasaengineer.com
- National Space So
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