# LUNAR SCIENCE AND RESOURCES: FUTURE OPTIONS

## HEARING

BEFORE THE

SUBCOMMITTEE ON SPACE AND AERONAUTICS
COMMITTEE ON SCIENCE
HOUSE OF REPRESENTATIVES
ONE HUNDRED EIGHTH CONGRESS

SECOND SESSION

APRIL 1, 2004

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# LUNAR SCIENCE AND RESOURCES: FUTURE OPTIONS

## THURSDAY, APRIL 1, 2004

House of Representatives,
Subcommittee on Space and Aeronautics,
Committee on Science,
*Washington, DC.*

The Subcommittee met, pursuant to call, at 1:00 p.m., in Room 2318 of the Rayburn House Office Building, Hon. Dana Rohrabacher [Chairman of the Subcommittee] presiding.

**SUBCOMMITTEE ON SPACE AND AERONAUTICS**
**COMMITTEE ON SCIENCE**
**U.S. HOUSE OF REPRESENTATIVES**
**WASHINGTON, DC 20515**

**Hearing on**

***Lunar Sciences & Resources: Future Options***

Thursday, April 1, 2004
1:00 p.m.
2318 Rayburn House Office Building

## WITNESS LIST

**Dr. Paul Spudis**
Senior Staff Scientist
Johns Hopkins University Applied Physics Laboratory
Visiting Scientist
Lunar and Planetary Institute

**Dr. Daniel F. Lester**
Research Scientist
McDonald Observatory
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**Dr. Donald Campbell**
Professor of Astronomy
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National Astronomy and Ionosphere Center (NAIC)
Cornell University.

**Dr. John S. Lewis**
Professor of Planetary Sciences
Co-Director
Space Engineering Research Center
University of Arizona.

**Dr. Timothy Swindle**
Professor of Geosciences and Planetary Sciences
University of Arizona.

HEARING CHARTER

## SUBCOMMITTEE ON SPACE AND AERONAUTICS
## COMMITTEE ON SCIENCE
## U.S. HOUSE OF REPRESENTATIVES

# Lunar Science and Resources: Future Options

THURSDAY, APRIL 1, 2004
1:00 P.M.–3:00 P.M.
2318 RAYBURN HOUSE OFFICE BUILDING

### 1. Purpose

On Thursday, April 1, 2004 at 1:00 p.m., the Subcommittee on Space and Aeronautics will hold a hearing to examine current thinking about the suitability of the Moon for scientific and commercial activities.

The hearing is not meant to focus on whether to go to the Moon, but rather is intended to examine the suitability of using the Moon for an extended—perhaps permanent—presence to conduct space science and resource-extraction activities.

### 2. Witnesses

- **Dr. Paul Spudis** is a Senior Staff Scientist at the Johns Hopkins University Applied Physics Laboratory and Visiting Scientist at the Lunar and Planetary Institute in Houston, Texas.
- **Dr. Daniel F. Lester** is a Research Scientist at the McDonald Observatory, University of Texas at Austin.
- **Dr. Donald Campbell** is a Professor of Astronomy and associate director of the National Astronomy and Ionosphere Center (NAIC) at Cornell University.
- **Dr. John S. Lewis** is a Professor of Planetary Sciences and Co-Director of the Space Engineering Research Center at the University of Arizona.
- **Dr. Timothy Swindle** is Professor of Geosciences and Planetary Sciences at the University of Arizona.

### 3. Overarching Questions

1. Is the Moon a uniquely useful site to base deep-space radio, infrared and optical telescopes or other science instruments?
    a. Can space science be conducted using instruments on the Moon more reliably and cheaply than it could be done from Earth or using satellite-based instruments? What other fields of science (i.e., astrobiology, cosmology) would benefit from using a Moon-based laboratory?
2. Does the Moon contain minerals, isotopes, or other materials that one day may be commercially exploitable? How much certainty is there about the presence and quantity of these resources? How readily extractable are they?
    a. What additional technologies, if any, must we first develop before these resources can be made useful?

### 4. Background

On January 14, 2004, President Bush announced his Space Exploration Initiative, putting in motion a major new NASA program to send astronauts to the "Moon, Mars and beyond." Among other goals, the plan states: "The extended human presence on the Moon will enable astronauts to develop new technologies and harness the Moon's abundant resources to allow manned exploration of the challenging environments.. . . Experience and knowledge gained on the Moon will serve as a foundation for human missions beyond the Moon, beginning with Mars.”[1]

The Space Exploration Initiative calls for the first launch of a robotic probe to the Moon in 2008 to begin mapping and reconnaissance studies. At least one probe will be launched each year thereafter, either an orbiter or lander, with the goal that the first manned Moon mission would occur between 2015 and 2020. While the Space Exploration Initiative establishes a goal of going back to the Moon, it does not specify what we would do once we get there (i.e., lunar geology, space telescopes, mining).

The initiative is silent on whether the U.S. would attempt to establish a permanent human presence on the Moon. But proponents of such a presence believe the time is ripe to advocate lunar bases—robotic or human tended—as a logical next step of any U.S. effort to return to the Moon.

Some members of the lunar science and astronomy communities have long viewed the Moon as a base from which to operate telescopes and other science instruments.

The Moon offers several clear advantages—and disadvantages—as a base for astronomical observatories. Advantages include the lack of an atmosphere, its ability to shield instruments from radio and thermal pollution of Earth, lack of a magnetic field, a solid surface, and, in lunar craters at the poles, the capability of keeping infrared telescopes operating at optimally cold temperatures.

Disadvantages include dust, the need to install power sources to run instruments, and the risk of landing payloads safely on the Moon. Human-tended operations pose challenges that are far greater, such as assuring a reliable supply of food, water and oxygen; developing a suitable shelter; high background radiation; the risks of launching and landing; working in a cold vacuum; and the prolonged effects of operating in a low-gravity (one-sixth of Earth’s) environment.

Some scientists believe the Moon contains large deposits of minerals and isotopes that one day may be commercially exploitable. Of most interest is the possible presence of water, and the presence of helium-3, which theoretically could be used on Earth to generate energy using fusion reactors.

The attached article from the March 12, 2004 edition of *Science Magazine* outlines the debate on possible activities that could be conducted on the Moon.

### 5. Issues

- **How much water is on the Moon and how difficult would it be to extract?** In 1994, the U.S. lunar orbiter *Clementine* found indications of frozen water at the Moon’s poles. Scientists disagree on whether water is actually present, and, if it is, whether it exists in significant quantities. Obviously, water would be a boon to any human activities on the Moon because it could be used to sustain human life and to produce hydrogen fuel and oxygen. If no readily accessible source of water is found, lunar astronauts would need to transport their own water, significantly adding to the logistics burden and possibly limiting the amount of other materials they could bring along, as well as limiting the time they could remain on the Moon.

  Water can be transformed into fuel (hydrogen) and oxygen, but exploiting this opportunity requires launching heavy processing equipment from Earth, safely landing and assembling it on the lunar surface, and providing power for its operation. Would benefits of this approach outweigh the costs of simply launching fuel and oxygen from Earth? Would the lack of easily extractable lunar ice prove to be an insurmountable obstacle to long-term human habitation?

- **Do the advantages outweigh the disadvantages of using the Moon as a base for astronomical observatories? How does the Moon compare with other alternatives?** Scientists disagree about the benefits of using the Moon as a site for operating science instruments that are designed to look into deep space. Astronomical observatories located on the Moon’s far side, or at its poles, hold many advantages over Earth-based observatories. Having no atmosphere eliminates a major source of aberrations common to Earth-based telescopes and it permits viewing objects at all wavelengths (Earth’s atmosphere filters out ultraviolet, x-ray, and gamma ray wavelengths). The Moon would also act as a shield against radio and thermal pollution from Earth sources. Its uniformly low temperatures at the lunar poles provide an excellent location to site infrared telescopes.

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[1] “President Bush Announces New Vision for Space Exploration Program.” www.whitehouse.gov/news/releases/2004/01/20040114–1.html

Disadvantages include the threat of lunar dust settling on, and obstructing telescope optics. Dust may be kicked up during landing, assembly, or repair. The risk of safely landing the telescope is substantial. Providing power to run the instruments will require construction of solar arrays or the use of a small nuclear-electric generator at a location far enough away to avoid interference. Relying on lunar astronauts to assemble the observatory raises significant risk factors, especially if they are expected to work at the bottom of a deep, cold crater.

Some scientists advocate free-flying telescopes (such as Hubble, the Chandra Observatory, and the newly commissioned Spitzer Infrared Observatory) as a more cost-effective, less risky alternative than lunar-based telescopes. With the exception of Hubble, none of the observatories are designed to be serviced or repaired, eliminating any need for human tending. Free flyers can be launched to high Earth orbits or libration points, removing a large source of thermal and radio interference. Guidance, pointing and tracking technologies are extremely accurate, negating any advantage of using a stable lunar surface.

- **Is it commercially practical to mine lunar-based minerals and isotopes?** Scientists disagree about the amounts and types of valuable ores that may be found on the Moon. A related issue is whether commercial enterprises can overcome the huge costs associated with launching, landing and assembling foundries and fabrication facilities to mine and process any ores, and transport finished products to Earth or use them to support missions to other parts of the Solar System. Once again, the availability of lunar ice (water) would affect the success of such activities.

  Harvesting resources on the Moon would also raise several important legal questions (about which the Committee intends to hold a future hearing). The United States is a signatory to four multinational treaties concerning the use of outer space, two of which expressly mention the Moon. The Treaty on Principles Governing the Activities of States in the Exploration of the Use of Outer Space, including the Moon and Other Celestial Bodies was codified in 1967 and ratified by the United States, Russia and 96 other nations. Among other things, the treaty provides that the Moon is “not subject to national appropriation.” The United States is not a signatory to the Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (“the Moon Treaty”). Codified in 1979 and ratified by only seven nations, the Moon Treaty states in relevant part that the Moon is “the common heritage of all mankind,” and that the Moon’s natural resources may not become the property of any person. The treaty further provides for an international regime to govern the “exploitation of the natural resources of the Moon.”

- **How practical is it to consider extracting helium-3 for power generation facilities on Earth?** Helium-3 is a scarce isotope on Earth but lunar samples returned by Apollo missions suggests that it is more abundant on the Moon’s surface. While it may more plentiful, extracting large amounts of helium-3 from lunar soil is likely to prove difficult. Physicists believe helium-3 will one day be used as a fuel for specially designed fusion reactors on Earth, but development of such reactors is decades away.

### 6. Questions to Witnesses

In his letter of invitation to appear as a witness, Dr. Spudis was asked to address the following questions in his testimony:

- What science can be conducted on the surface of the Moon that cannot be duplicated by Earth-based research or free-flying satellites?
- What minerals, elements and isotopes exist on the Moon in sufficient quantities that they could contribute to expanding the reach of human exploration of the solar system? What is the basis of your estimate and how widely shared is it? How soon after a human return to the Moon would it be possible to begin exploiting resources?
- How much water do you believe is trapped on the lunar surface, and what is the basis of your estimates? How confident are you of these estimates? Based on current observations, is the water concentrated in various pockets on the lunar surface, or is it widely distributed?
- Do you believe that long-term human habitation on the Moon is necessary to conduct science and lunar resource extraction activities? What role would robotics play?

In his letter of invitation to appear as a witness, Dr. Lewis was asked to address the following questions in his testimony:

- What minerals, elements and isotopes exist on the Moon in sufficient quantities that they could contribute to expanding the reach of human exploration of the solar system? What is the basis of your estimate and how widely shared is it? How soon after a human return to the Moon would it be possible to begin exploiting resources?
- What are the advantages to human exploration of the solar system by siting fabrication and processing facilities on the Moon? Can lunar-based fabrication be done more effectively than using Earth-bound facilities?
- How would you characterize the possibility that extraction of Moon materials may one day be commercially viable?

In his letter of invitation to appear as a witness, Dr. Campbell was asked to address the following questions in his testimony:

- How much water do you believe is trapped on the lunar surface, and what is the basis of your estimates? How confident are you of these estimates? Based on current observations, is the water concentrated in various pockets on the lunar surface, or is it widely distributed?
- How important is finding water to exploiting the Moon for scientific or economic purposes?
- What kinds of instruments need to be flown on upcoming lunar probes to try to resolve questions about water on the Moon?
- What other minerals, ores, or elements do you believe may be present in the lunar soil that may hold interest for future exploitation?

In his letter of invitation to appear as a witness, Dr. Lester was asked to address the following questions in his testimony:

- What space science can be conducted on the surface of the Moon that cannot be duplicated by Earth-based research or free-flying satellites?
- Is the Moon an appropriate site for astronomical observatories? What advantages and disadvantages does the Moon pose as a base for telescopes?
- As NASA begins to launch lunar robotic probes to survey the Moon's resources, what instruments should be flown on the probes that can be used to serve the Space Exploration Initiative as well as inform lunar scientists about the suitability of using the Moon as a base for long-term science activities?
- What are your views about the practicality of establishing long-term human bases on the Moon to conduct science? Will robotics be able to carry out the same science missions without the presence of humans on the Moon?

In his letter of invitation to appear as a witness, Dr. Swindle was asked to address the following questions in his testimony:

- What are the most pressing questions in lunar science? To what extent do they require human lunar missions to be pursued? To what extent can they be pursued from Earth?
- What minerals, elements and isotopes exist on the Moon in sufficient quantities that they could contribute to expanding the reach of human exploration of the solar system? What is the basis of your estimate and how widely shared is it? How soon after a human return to the Moon would it be possible to begin exploiting resources?
- Specifically, how much helium-3 do you believe is on the Moon, and what is the basis of your estimate? Based on current observations, is the helium-3 concentrated in various pockets on the lunar surface, or is it widely distributed? How much ore would have to processed to refine useful amounts of helium-3, and how technologically difficult would it be to accomplish? How long after a human return to the Moon would production of helium-3 likely be viable? How close are we to developing technologies that could make use of helium-3?

## 7. Attachment

"Moon's 'Abundant Resources' Largely an Unknown Quantity," *Science Magazine,* March 12, 2004

# Moon's 'Abundant Resources' Largely an Unknown Quantity

**Will we find enough raw materials, in accessible enough places, to power Bush's proposed lunar base?**

It's 2014. Forty-five years after the Apollo 11 landing, humans return to the moon to set up the lunar base that President George W. Bush proposed a decade earlier. Which will they be: homesteaders or campers?

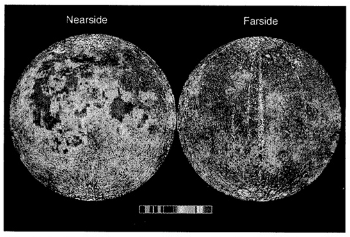
Apollo astronauts, who roved the lunar surface for tens of hours, could easily bring with them enough food, water, and air for a short visit. Under NASA's ambitious new plans for lunar exploration, however, astronauts will live on the moon for weeks or months at a time—and the longer they stay, the more difficult and expensive it becomes to supply them from Earth. Some space boosters, the president included, suggest that part of the solution lies in living off the land. "The moon is home to abundant resources," Bush stated in his 14 January speech announcing NASA's new vision. Scientists agree that potentially useful chemicals, such as water ice and various gases, are indeed locked up in lunar soil. But when it comes to estimating how abundant they are and how practical it would be to extract them, one resource still in short supply is information.

**Water.** More valuable than gold to a lunar base, water can be used for drinking or it can be split to create oxygen to breathe—or oxygen and hydrogen for rocket fuel. A few tons of hydrogen-oxygen fuel could send a rocket off the surface of the moon and into space. That's why moon buffs such as Paul Spudis, a planetary scientist at Johns Hopkins University's Applied Physics Laboratory in Laurel, Maryland, think the most important lunar resource is likely to be water from ice.

In theory, ice from crashed comets may linger in cold, dark niches at the lunar poles, from which it could relatively easily be extracted and distilled. But scientists disagree about how much of it is trapped there. In 1996, a Department of Defense satellite called Clementine bounced radar waves off the moon's surface and back to radar telescopes on Earth. Spudis and colleagues noticed that reflections from shadowy nooks near the lunar south pole could be interpreted as signatures of multiple scattering within crystals of water—an indication that about 1.5% of the lunar soil in those regions is water ice.

Similar results came when the Lunar Prospector satellite, launched in 1998, used a spectrometer to count neutrons bouncing off the moon in energy ranges known to interact with hydrogen—presumably in water ice. The answer: Patches of polar lunar soil were about 0.5% to 1% ice by weight—less water than Clementine found, but still enough to make a polar base attractive.

On the other hand, Donald Campbell, a physicist at Cornell University, and colleagues twice bounced radio waves off the moon from the Arecibo telescope in Puerto Rico but saw no signs of water ice. "We don't believe that the radar data supports" the large amounts of ice that the Clementine analysis would imply, Campbell says. And when the Lunar Prospector crashed into the moon's south pole at the end of its mission, scientists didn't see water in the resulting plume of debris. Spudis thinks a more energetic crash would have splashed up water vapor, but for now, lunar water remains an open question.



**Orb of plenty?** Titanium minerals mapped by the Clementine orbiter (red areas) may contain useful amounts of oxygen and helium.

CREDIT: CLEMENTINE/NASA

**Trapped gases.** Even if there's little water on the moon, astronauts might be able to make it and other useful chemicals from more-abundant raw materials: light elements such as nitrogen, oxygen, and carbon, manufactured by nuclear fusion inside the sun and blown to the lunar surface on the solar wind. These trace elements are present in the lunar soil, or regolith, at levels of parts per million, so it would take a huge amount of mining to get usable quantities. The good news is that they are extremely easy to extract: Just heat soil up (using the base's solar or nuclear power source) and the gases escape, yielding nitrogen, carbon monoxide, carbon dioxide, methane, and hydrogen that can be converted into air or water. Water, in turn, can be used to strip oxygen from a common iron-titanium lunar mineral known as ilmenite.

**Helium.** Even more valuable in the long run may be a much rarer legacy of the solar wind, helium-3. Only Earth-bound humans would benefit, however, and even its enthusiasts acknowledge that it's a long shot.

Helium-3 is attractive because it can fuel an advanced fusion reactor. A helium-3 atom combined with a hydrogen-2 (deuterium) atom or with another helium-3 releases a great deal of energy with relatively little radioactive waste. "If we replaced all the electrical power plants in the United States with [helium-3/deuterium] reactors, you'd need only 40 metric tons to produce all the electricity needed in 2004," says Gerald Kulcinski, a physicist at the University of Wisconsin, Madison. Only a few hundred kilograms of helium-3 are accessible on Earth, he says, but the lunar regolith harbors millions of tons of it.

Several factors make mining helium-3 a dicey proposition. For one, most of the solar wind strikes the lunar farside, which faces the sun when the moon's orbit takes it upwind of Earth's magnetic shadow. But ilmenite, the only lunar mineral that traps helium-3 effectively, is more common on the moon's nearside. Wherever it crops up, even helium-3–rich lunar soil won't contain much of the gas. "It'll be a little better than 10 parts per billion by weight," says Timothy Swindle, a geochemist at the University of Arizona in Tucson. "To make a dent in the world's energy needs, you're going to have to mine a large fraction of the surface of the moon." Physicists will also have to create a working helium-3 reactor—no easy task, considering that decades of research have yet to produce a fusion power plant of any sort. And, of course, someone will have to ship all the helium back to Earth.

The bottom line: Before investing in helium futures or moon air and water rights, wait for scientists to figure out how much of these resources there are and where they reside. NASA's 2005 budget contains money to begin exploring the moon with robot missions—including, presumably, prospectors. Their work will reveal whether visiting astronauts will be able to eke out an existence from the lunar soil, or whether the rest of us will have to foot a literally astronomical delivery bill.

–Charles Seife

Chairman ROHRABACHER. I hereby call this meeting of the Space and Aeronautics Subcommittee to order. Without objection, the Chair will be granted the authority to recess this committee at any time. Hearing no objections, so ordered.

Thirty years ago, the end of the Apollo era signaled the beginning of a much more narrow, scaled-back agenda for human space flight. Unfortunately, President Bush—or should I say fortunately, not unfortunately. Fortunately, President Bush has made the decision to recommit this nation to its heritage of human exploration, and then pushing it beyond, human exploration of the universe. The question now is not whether we will return to the Moon, but what things might be done there in the name of science and economic development. Today's hearing will focus on the Moon. What are the key lunar minerals and ores there on the Moon and what is the Moon's potential as a scientific-industrial laboratory.

And I share the belief that the Moon affords us the opportunity to pursue exploration, perhaps in the tradition of Lewis and Clark. The Moon is a way station, that is right. That is true. But, further than that, it could well be a destination in and of itself. Some question whether resources on the Moon are adequate enough to be commercially exploitable, and some argue whether or not the Moon is a proper destination in and of itself. Some question the validity of going to the Moon even for a visit. Measurements made by Defense Department's Clementine and NASA's Lunar Prospector probes have suggested the presence of water on the Moon. Now, there is some debate within the scientific community whether or not the water is sufficient for sustaining some type of a lunar operation. Resolving this issue is, of course, one of questions that needs to be answered.

And NASA's plan to map lunar resources, however, holds the promise of informing us how people can live and work on the Moon. In this regard, we must ensure that the technology, equipment, and instruments that NASA plans to use for mapping the lunar resources are the right ones for the task. Is NASA's planned series of lunar robotic missions adequate? What input from the private sector has NASA received in making the determinations as to what its goals will be? And, that said, we have assembled a panel of expert witnesses that will provide us their insight and analysis on these issues.

I believe that Americans must continue to be the leading force in exploring space. But we must know why we are going to be sending human beings on particular missions, and especially that dealing with the Moon. We must be identifying critical lunar exploration activities and what they could be and what they couldn't be. What are our limitations? All this will determine what role we will play as a country as a leader, as I say, in the exploration of space.

Mr. Lampson, you may proceed with your opening statement.

[The prepared statement of Mr. Rohrabacher follows:]

## PREPARED STATEMENT OF CHAIRMAN DANA ROHRABACHER

Thirty years ago, the end of the Apollo era signaled the beginning of a much more narrow, scaled-back agenda for our human space flight program. Fortunately, President Bush made the decision to recommit this nation to its heritage of human exploration beyond Earth's orbit. The question now is not whether we will return to the Moon, but what things might be done there in the name of science and economic development. Today's hearing will focus on the Moon's suitability in these areas for enabling a permanent human presence on the lunar surface. Utilizing key lunar minerals and ores is critical if the Moon's potential as a scientific and industrial laboratory in Earth's neighborhood is to be realized.

I share the belief that the Moon affords us the opportunity to pursue exploration in the tradition of the Lewis and Clark expedition. Exploration of a new frontier then aided our nation in laying the groundwork for settling the American Northwest. Similarly, the Moon offers us the potential to establish lunar human settlements in the future. Some question whether resources on the Moon are adequate or commercially exploitable. For example, measurements made by the Defense Department's Clementine and NASA's Lunar Prospector probes have suggested the presence of water on the Moon. There is some debate within the science community whether water is sufficiently abundant for sustaining lunar-based operations. Resolving this fundamental issue is key for successfully returning people to the Moon.

NASA's plan to map lunar resources, however, holds the promise of informing us how people can live and work on the Moon. In this regard we must ensure that the instruments NASA plans to use for mapping lunar resources are the right ones for the task. Is NASA's planned series of lunar robotic missions adequate? What input from the private sector has NASA received in making these determinations? That said, we have assembled a panel of expert witnesses that will provide us with their insight and analysis of these issues.

I believe Americans must continue to explore space, but we must know why we are sending humans there. Identifying critical lunar exploration activities will have major implications for our future role as a leader in space.

Mr. LAMPSON. Thank you, Mr. Chairman. And the only thing that was wilder than your announcement about the civilization on the Moon is when I got a phone call this morning from a local television station telling me that I had been selected by John Kerry to be his running mate. And the only thing that I could think of that the only thing that would have been wilder than that was if it had been George Bush.

Chairman ROHRABACHER. Well, there you go.

Mr. LAMPSON. It is a—thank you very much, both for the time, and for calling this hearing. I am certainly pleased to welcome our witnesses today, and look forward to all of the testimony that you have to bring us. We do have a distinguished panel of scientists appearing before the Subcommittee, and I am anxious to hear all of your views.

A return to the Moon by U.S. astronauts is a central feature of the Space Initiative proposed by the President in January of this year, and that makes sense to me. I have long believed, as I know Dana has—Chairman Rohrabacher has, that the exploration of our Solar system should involve a number of interesting destinations, including the Moon. However, an important question is what we will do on the Moon. Will we have a limited presence there for just as long as it takes to test the systems and techniques needed for human missions to Mars, or will we establish a long-term presence on the Moon, using it for scientific, operational, or even commercial purposes?

So our witnesses will present a range of viewpoints regarding potential scientific opportunities on the Moon. And they will also discuss the arguments for and against the likelihood of significant extraction and utilization of lunar resources. This hearing will help the Subcommittee understand just what the Moon has to offer to us as we move out into the Solar system. And so I hope that we will have more such hearings, and I hope that we will have a chance to hear from some of the folks at the Johnson Space Center who have been working on some of these issues, also, for a very long period of time. There is a great deal for us to learn, and when we have the opportunity to hear it from the people who are living it, it makes a big difference for me, so I come to this hearing eager to learn from our witnesses.

Again, I want to welcome you, and I look forward to listening to the testimony.

Chairman ROHRABACHER. All right. Thank you very much. Mr. Bartlett—or Dr. Bartlett, I should say. Excuse me.

Mr. BARTLETT. Thank you very much. I look forward to this hearing. I have never shied away from the President's commitment to return humans to the Moon and on to Mars. In addition to the benefits that our society will get from pushing the envelope to do that, our country desperately needs something that captures the imagination of our people, and inspires our young people to go into careers of math, science, and engineering. Maybe this will do that. When we made that commitment to put a man on the Moon, that really did that.

We now have our best and brightest students in this country going into careers other than science, math and engineering. As a matter of fact, far too many of them are going into destructive pursuits. They are becoming lawyers and political scientists. Though we need a few of each of those, and we have got more than a few of each of those.

For the short-term, our economic superiority is at risk if we don't turn out more scientists, mathematicians, and engineers, and for the longer-term, our national security is at risk. We will not continue to have the world's best military unless we turn out scientists, mathematicians and engineers, well-trained, and in adequate numbers. And hopefully returning then to the Moon and on to Mars will provide the stimulus that encourages our young people to move into these careers that keep us the premiere economic nation in the world and the premier military nation in the world.

So I think that this is an investment that will pay very well for our society. That is why I look forward to this hearing, and thank you all very much.

Chairman ROHRABACHER. Mr. Feeney, do you have a one-minute statement? All right. Without objection, the opening statements of other members will be put in the written record so we can get right to the testimony. Hearing no objection, so ordered.

I also ask unanimous consent to insert in the appropriate place in the record the background memorandum prepared by the Majority Staff for this hearing. Hearing no objection, so ordered.

We have a distinguished panel with us today to provide their unique perspectives to these issues. We have asked them to summarize their testimony to five minutes so that we can get right to a dialogue, and I have encouraged them to be as aggressive in promoting their ideas or attacking ideas that they disagree with, as they see fit.

Our first witness is Dr. Paul Spudis, who is a senior staff scientist at Johns Hopkins University's Applied Physics Laboratory. Dr. Spudis is also a member of the Aldridge Commission, but he is appearing before this committee today as a recognized expert on lunar science, and his testimony will represent his personal views and opinions. I understand that he is not appearing on behalf of the Aldridge Commission, and it is nice to see you again, and you may proceed.

## STATEMENT OF DR. PAUL D. SPUDIS, SENIOR STAFF SCIENTIST, JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY, VISITING SCIENTIST, LUNAR AND PLANETARY INSTITUTE, HOUSTON, TEXAS

Dr. SPUDIS. Mr. Chairman and Members of the Committee, thank you for inviting me here today to testify on the subject of lunar science, resources, and the U.S. Space Program.

Recently, President Bush articulated a new strategic direction for America in space, one that includes a return to the Moon, and the development and use of off-planet resources. The value of the Moon as a space destination has not escaped the notice of other countries. At least four new robotic missions are currently being flown, or prepared for flight, by Europe, India, Japan, and China. And advance planning for human missions in many of these countries is already under way. I believe that our nation needs to return to the Moon, and that this return should take place now rather than later.

While you have my full written testimony, in the time available, I would like to make the following points, and answers to the questions posed to me by the Committee.

Point 1: the Moon is a unique scientific resource on which important research, ranging from planetary science to astronomy and high-energy physics, can be conducted. The Moon is a small planet of surprising complexity. The period of its most active geological evolution, between three and four billion years ago, corresponds to a missing chapter of Earth's history. The processes that work on the Moon—impact, volcanism, the deformation of its crust—are the same ones that affect all the rocky bodies of the inner solar system, including the Earth. Because the Moon has no atmosphere or running water, its ancient surface is preserved in nearly pristine form, and its geological story can be read with clarity and understanding. As Earth's companion in space, the Moon retains the unique record of this history of this corner of the solar system, particularly the history of impacts, vital knowledge unavailable on any other planetary object.

Telescopes on the Moon possess many advantages over both Earth-based and space-based instruments. The Moon's stable base permits the construction of optical interferometers with multiple-kilometer baselines. Such an instrument could image the disks of terrestrial planets orbiting nearby stars. The Moon's environment is well characterized. Dust accumulation can be controlled, and presents no intractable difficulties to the establishment and maintenance of service telescopes.

The Moon offers astronomers many environmental advantages with its far side blocking the Earth's radio noise, dark polar craters to cool infrared detectors, and a solid mounting base that requires no pointing gyros as do free-space telescopes.

Point 2: we already know that the Moon possesses the resources needed to create a space-faring transportation infrastructure in cislunar space. Cislunar space is the volume of space between Earth and Moon.

As usable commodities, lunar materials offer many possibilities. Because of its high abundance, oxygen production is likely to be an important early product. The production of oxygen from the Moon involves breaking the very tight chemical bonds in lunar minerals between oxygen and various metals, including iron, aluminum, and titanium. Many different techniques to accomplish this task have been developed. All are based on common industrial processes easily adapted for use on the Moon.

The most important use of oxygen in its liquefied form is to make rocket fuel oxidizer. Coupled with extraction of hydrogen from the soil, this processing can make rocket fuel the most important and profitable commodity of a new lunar economy. Once processing is established, lifting fuel off the Moon for use in space will be like driving a tanker truck away from an oil refinery.

Point 3: hydrogen, probably in the form of water ice, exists at the poles of the Moon in quantity, and can be extracted and processed into rocket propellant and life support consumables.

Our current estimate of the amount of water on the Moon comes from two orbital measurements. The Clementine bistatic experiment indicates that an area of about 135 square kilometers of pure ice exists within an observed area of about 45,000 square kilometers, corresponding to a concentration level of 0.3 percent. This estimate is consistent with observations from Earth-based radio observatories, including Arecibo and Goldstone, which show small, scattered areas of high radar backscatter within the sun-dark regions of the poles. The Lunar Prospector neutron spectrometer found a concentration level of about 1.5 weight-percent water over an area of approximately 12,000 kilometers in extent. Because of the observing geometry between Earth and Moon, Clementine and Earth-based radar could only examine about ¼ to ⅓ the total dark area of the south pole, while Lunar Prospector in orbit around the Moon collected data from 100 percent of the dark area. It is estimated that over 10 billion metric tons of water exist at the lunar poles, an amount equal in volume to Utah's Great Salt Lake. We do not know how widely disseminated this ice is. We must survey the poles from orbit to understand this distribution in detail.

We have identified several areas near both north and south poles of the Moon that offer near-constant Sun illumination. An outpost or establishment in these areas will have the advantage of being in sunlight for the generation of electric power via solar cells, and a benign thermal environment, because the Sun is always at grazing incidence angles. The poles of the Moon are inviting oases in near-Earth space, easily accessible from the L–1 Point or polar orbit, both possible staging areas for lunar missions.

Point 4: by allowing us to travel at will with people throughout the Earth-Moon system, a return to the Moon to use lunar resources gives the Nation a challenging mission, and creates capability for the future. Returning to the Moon to use its resources will establish a robust transportation infrastructure, one 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, working with ore bodies of small concentration under difficult conditions. The unique polar environment of the Moon, with its zones of near-permanent illumination and permanent darkness, provides its own challenges, but also offers extraordinary advantages. For humanity to have a future beyond low-Earth orbit, we must learn to use the materials and conditions available off-planet. Otherwise, we will always be mass- and power-limited to only those payloads that we can lift out of Earth's deep gravity well. Investment in a few robotic precursor missions would be greatly beneficial and help ensure the success of our efforts.

We should map the polar deposits of the Moon from orbit using imaging radar and an advanced neutron spectrometer to determine the extent, purity, and thickness of the ice in these dark regions. We can use this information to select sites to land small robotic probes, conduct chemical analyses of the polar deposits, and radio the results to Earth. Although we expect water ice to dominate, these deposits made from cometary cores may also contain methane, ammonia, and organic molecules, all potentially useful resources. We need to inventory these species, determine their chemical and isotopic properties as well as their physical nature and setting.

Finally, we should land a series of demonstration experiments designed to test various techniques and methods of lunar resource extraction. Ultimately, both people and machines are needed on the Moon to fully realize its potential as an off-planet logistics and industrial base.

Point 5: this mission will create routine access to cislunar space, which directly relates to important national economic and strategic goals. Learning space survival skills close to home, we create new opportunities for exploration, utilization, and wealth creation. Space will no longer be a hostile place that we tentatively visit for short periods, instead it becomes a prominent part of our world.

Achieving freedom of cislunar space makes America more secure by enabling and maintaining cheaper assets in orbit, and more prosperous by opening an economically limitless frontier. Creating this infrastructure, we will have a system that can take us to the planets.

Point 6: timing is everything. It is important for America to undertake this mission now rather than later. Many nations have recently indicated an interest in the Moon. The possible collection and use of lunar resources raises some interesting political and economic issues. Our initial return to the Moon would be an engineering and scientific research and development project. We undertake our studies of the extraction of lunar resources to ascertain the best methods to harvest and use these materials. Our presence on the Moon does not give us title to it. However, a strong and continuing American presence on the Moon can help establish de facto the broad legal framework and economic paradigm of democratic free-market capitalism off the Earth. It is not clear that other nations will be similarly inclined.

America must have a challenging and vigorous space program. A mission that inspires, educates and enriches. It must relate to important national needs, yet push the boundaries of the possible and serve larger national concerns beyond scientific endeavors. The

President's program fulfills these goals. A return to the Moon is a giant step into the solar system.

Thank you for your attention, and I will be happy to answer any questions that you may have.

[The prepared statement of Dr. Spudis follows:]

## PREPARED STATEMENT OF PAUL D. SPUDIS

Mr. Chairman and Members of the Committee, thank you for inviting me here today to testify on the subject of lunar science, resources, and the U.S. space program.

Recently, President Bush articulated a new strategic direction for America in space, one that includes a return to the Moon and the development and use of off-planet resources. Although we conducted our initial visits to that body over 30 years ago, we have recently made several important discoveries that indicate a return to the Moon offers many advantages and benefits to the Nation. In addition to being a scientifically rich object for study, the Moon offers abundant material and energy resources, the feedstock of an industrial space infrastructure. Once established, such an infrastructure will revolutionize space travel, assuring us of continuous, routine access to cislunar space (i.e., the space between and around Earth and Moon) and beyond. The value of the Moon as a space destination has not escaped the notice of other countries—at least four new robotic missions are currently being flown or prepared for flight by Europe, India, Japan, and China and advanced planning for human missions in many of these countries is already underway. Additionally, at least two of these future planned missions (India and China) have advanced their launch dates considerably within the last month, indicating that these nations recognize both the importance and value of the Moon and the urgency of establishing a presence there.

The points below elaborate on WHY the Nation needs to return to the Moon and why that return should take place NOW rather than later.

### (1) The Moon is close, accessible with existing systems, and has resources that we can use to create a true, economical space-faring infrastructure.

The inclusion of the Moon as the first destination in the President's new vision was no accident. The Moon is both a scientific bonanza and an economic treasure trove, easily reachable with existing systems and infrastructure that can revolutionize our national strategic and economic posture in space and at home. The dark areas near the poles of the Moon contain significant amounts (at least 10 billion tons) of hydrogen, most probably in the form of water ice. This ice can be mined to support human life on the Moon and in space and to make rocket propellant (liquid hydrogen and oxygen). Moreover, we can return to the Moon using existing infrastructure of evolved-expendable and Shuttle-derived launch systems for only a modest increase in the space budget within the next five years.

The Moon is also a testing ground, a small nearby planet where we can learn the techniques of the strategies and operations we need to explore the solar system. The "mission" of this program is to go to the Moon to learn how to use off-planet resources to make space flight easier and cheaper in the future. Rocket propellant made on the Moon will permit routine access to cislunar space by people and machines, vital to the servicing and protection of national strategic assets and for the repair and refurbishing of commercial satellites. The availability of refueling capability in low-Earth orbit would completely change the way engineers design spacecraft and the way companies and the government think of investing in space assets. This capability will serve to dramatically reduce the cost of space infrastructure to both the government and to the private sector, thus spurring economic investment (and profit).

### (2) The Moon is a unique scientific resource on which important research, ranging from planetary science to astronomy and high-energy physics, can be conducted.

Generally considered a simple, primitive body, the Moon is actually a small planet of surprising complexity. The period of its most active geological evolution, between four and three billion years ago, corresponds to a "missing chapter" of Earth history. The processes that work on the Moon—impact, volcanism, and tectonism (deformation of the crust)—are the same ones that affect all of the rocky bodies of the inner solar system, including the Earth. Because the Moon has no atmosphere or running water, its ancient surface is preserved in nearly pristine form and its geological story can be read with clarity and understanding. Because the Moon is Earth's companion in space, it retains a record of the history of this corner of the Solar System—vital knowledge unavailable on any other planetary object.

Of all the scientific benefits of Apollo, appreciation of the importance of impact (the collision of solid bodies) in planetary evolution must rank highest. Before we went to the Moon, we had to understand the physical and chemical effects of these collisions, events completely beyond the scale of human experience. Of limited application at first, this new knowledge turned out to have profound consequences. We now believe that large-body collisions periodically wipe out species and families on Earth, most notably, the extinction of dinosaurs 65 million years ago. The telltale residue of such large body impacts in Earth's past is recognized because of knowledge we acquired about impact from the Moon. Additional knowledge still resides there; while the Earth's surface record has been largely erased by the dynamic processes of erosion and crustal recycling, the ancient lunar surface retains this impact history. Although other planets display craters, only the Moon resides in our vicinity of the solar system, records the same impact flux that has struck Earth over the geologic past and retains a unique record that cannot be read on any other body. When we return to the Moon, we will examine this record in detail and learn about its evolution as well as our own.

Because the Moon has no atmosphere and is a quiet, stable body, it is a premier place to observe the universe. Telescopes erected on the lunar surface will possess many advantages over both Earth-based and space-based instruments. The Moon's level of seismic activity is orders of magnitude lower than that of Earth, permitting the construction of interferometers with multiple-kilometer baselines. Such an instrument can image the disks of terrestrial-sized planets orbiting nearby stars. The lack of an atmosphere permits clear viewing, with no spectrally opaque windows to contend with; the entire electromagnetic spectrum is visible from the Moon's surface. Its slow rotation (one lunar day is 708 hours long, about 28 terrestrial days) means that there are long times of darkness for observation. Even during the lunar day, brighter sky objects are visible through the reflected surface glare. The far side of the Moon is permanently shielded from the din of electromagnetic noise produced by our industrial civilization. Unique electromagnetic windows on the sky, such as low-frequency shortwave radio (~10–100 m), can be mapped only from the lunar far side. There are areas of perpetual darkness and sunlight near the poles of the Moon. The dark regions are very cold, only a few tens of degrees above absolute zero and these natural "cold traps" can be used to passively cool infrared detectors. Thus, telescopes installed near the lunar poles can see both entire celestial hemispheres at once with infrared detectors, cooled courtesy of the cold traps.

Recent suggestions that lunar dust poses unsolvable problems and difficulties for telescopes on the Moon are incorrect; lunar dust does not "coat" surfaces if left undisturbed. The Apollo astronauts became covered in dust because in some cases, they fell, knelt, or had to literally wallow in dust to pick up the samples they wanted to return. The best evidence that lunar dust creates no long-term problems comes from the performance of the Laser Ranging Retroreflectors (LRRR), which were deployed by Apollo astronauts at four different sites. These passive arrays of glass cubes are used as mirrors to reflect laser pulses sent from Earth in order to precisely measure the Earth-Moon distance. After over 30 years of continuous use and exposure to the lunar dust environment, they show no degradation of photon return whatsoever.

### (3) We already know the Moon possesses the resources needed to create a space-faring transportation infrastructure in cislunar (Earth-Moon) space.

The return of the Apollo lunar samples taught us the fundamental chemical make-up of the Moon. The Moon is a very dry, chemically reduced object, rich in refractory elements but poor in volatile elements. The composition of the Moon is rather ordinary, made up of common Earth minerals such as plagioclase (an aluminum, calcium silicate), pyroxene (a magnesium, iron silicate), and ilmenite (an iron-titanium oxide). The Moon is approximately 40 percent oxygen by weight. Light elements, including hydrogen and carbon, are present, but in small amounts—in a typical lunar mare soil, hydrogen makes up between 50 and 90 parts per million by weight. Soils richer in titanium appear to be also richer in hydrogen, thus allowing us to infer the extent of hydrogen abundance from the global titanium concentration maps returned by both the Clementine and Lunar Prospector missions.

As usable commodities, lunar materials offer many possibilities. Because radiation is a serious problem for human space flight beyond low-Earth orbit, the simple expedient of covering surface habitats with soil can protect future lunar inhabitants from both galactic cosmic rays and even solar flares. Lunar soil can be sintered by microwave into very strong building materials, including bricks and anhydrous glasses that have strengths many times that of steel. When we return to the Moon, we will have no shortage of useful building materials.

Because of its high abundance in lunar materials, oxygen production is likely to be an important early lunar product. The production of oxygen from lunar materials is not magical, but simply involves breaking the very tight chemical bonds between oxygen and various metals in lunar minerals. 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 liquefied form is to make 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.

The Moon has no atmosphere or global magnetic field, so the solar wind, the tenuous stream of gases emitted by the Sun (mostly hydrogen), are directly implanted onto the dust grains of the Moon. Although this solar wind hydrogen is present over most of the Moon in very small quantities, it too can be extracted from soil. Soil heated to about 700°C releases more than 90 percent of its adsorbed solar wind gases. Such heat can be obtained from collecting and concentrating solar energy using focusing mirrors on the lunar surface, a readily available form of energy on the Moon. Collected by robotic processing rovers, solar wind hydrogen can be harvested from virtually any location. Additionally, recent discoveries by space probes of the 1990's suggest that special areas exist where this material is present in much greater abundance, making its collection and use much easier.

**(4) Hydrogen, probably in the form of water ice, exists at the poles of the Moon in quantity and can be extracted and processed into rocket propellant and life-support consumables.**

The joint DOD–NASA Clementine mission was flown in 1994. Designed to test sensors developed for the Strategic Defense Initiative (SDI), Clementine was an amazing success story. This small spacecraft was designed, built, and flown within the short time span of 24 months for a total cost of about $150 M (FY 2003 dollars), including the launch vehicle. Clementine made global maps of the mineral and elemental content of the Moon, mapped the shape and topography of its surface with laser altimetry, and gave us our first good look at the intriguing and unique polar regions of the Moon. Clementine did not carry instruments specifically designed to look for lunar water, but encouraged by an interesting result from Arecibo radar data that suggested interesting deposits near the Moon's south pole, an ingenious improvisation used the spacecraft communications antenna to beam radio waves into the polar regions; radio echoes were observed using the Deep Space Network dishes. Results indicated that material with reflection characteristics similar to ice are found in the permanently dark areas near the south pole. This major discovery was subsequently confirmed in 1998 by a different experiment flown on NASA's Lunar Prospector spacecraft.

The Moon contains no internal water; all water is added to it over geological time by the impact of comets and water-bearing asteroids. Dark areas near the poles are very cold, only a few tens of degrees above absolute zero. Thus, any water that gets into these polar "cold traps" cannot get out so over time, significant quantities accumulate. Our current best estimate of the amount of water on the Moon comes from two orbital measurements. The Clementine bistatic experiment indicates that an area of about 135 $km^2$ of pure ice exists within an observed area of about 45,000 $km^2$, corresponding to a concentration level of about 0.3 percent. This radar estimate is consistent with observations from Earth-based radio observatories, including Arecibo and Goldstone, which show small, scattered areas of high radar backscatter within the sun-dark regions of the lunar poles. The Lunar Prospector neutron spectrometer found a concentration level of about 1.5 percent water over an area approximately 12,000 $km^2$ in extent. It should be noted that because of the observing geometry between Earth and Moon, Clementine and Earth-based radar can only examine about a quarter to a third of the total dark area of the lunar south pole, whereas Lunar Prospector collected data from 100 percent of the dark region. This difference in part may explain the discrepancy. In all, we estimate that over 10 billion metric tons of water exist at the lunar poles, an amount equal to the volume of Utah's Great Salt Lake—without the salt! Lunar polar water has the advantage of already being in a concentrated useful form, simplifying scenarios for lunar return and habitation. Water from the lunar cold traps advances our space-faring infrastructure by creating the first space "filling station" on the solar system highway.

The poles of the Moon are useful from yet another resource perspective—the areas of permanent darkness are in proximity to areas of near-permanent sunlight. Because the Moon's axis of rotation is nearly perpendicular to the plane of the ecliptic, the sun always appears on or near the horizon at the poles. If you're in a hole, you never see the Sun; if you're on a peak, you always see it. We have identified several areas near both the north and south poles of the Moon that offer near-constant sun illumination. Thus, 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 (the sun is always at grazing incidence); such a location never experiences the temperature extremes (from 100° to −150°C) found on the lunar equator. These properties make the poles of the Moon an inviting oasis in near-Earth space.

**(5) By allowing us to travel at will, with people, throughout the Earth-Moon system, a return to the Moon to use lunar resources gives the Nation a challenging mission and creates capability for the future.**

Implementation of this objective for our national space program would have the result of establishing a robust transportation infrastructure, one 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 is a challenging technical task. We must learn to use machines in remote, hostile environments, working with ore bodies of small concentration under difficult conditions. The unique polar environment of the Moon, with its zones of near-permanent illumination and permanent darkness, provides its own challenges. But for humanity to have a foothold beyond low-Earth orbit, we must learn to use the materials available off-planet. We are fortunate that the Moon offers a nearby, "safe" laboratory for our first steps in using space resources. Initial blunders in mining tactics or feedstock processing are better practiced three days from Earth than from Mars, located many months of space travel away.

A mission learning to use these lunar resources is scalable in both level of effort and the types of commodities to be produced. We begin by using the resources that are the easiest to extract. Thus, a logical first product is water derived from the lunar polar deposits. Water is producible there regardless of the nature of the polar volatiles—ice of cometary origin is easily collected and purified while molecular hydrogen on lunar dust from the solar wind can be combined with oxygen extracted from rocks and soil (through a variety of processes) to make water. Water is easily stored for use as a life-sustaining substance for people or broken down into its constituent hydrogen and oxygen for use as rocket propellant.

Although we currently possess the minimal information to plan a lunar return, investment in a few robotic precursor missions would be greatly beneficial. We should map the polar deposits of the Moon from orbit using imaging radar to determine the extent, purity, and thickness of the ice in these dark regions. A camera and associated instrument to make a high resolution global topographic map (e.g., radar or laser altimetry) is also needed on this orbital mission to make high quality maps for future explorers and miners. The next step will be to land small robotic probes to conduct chemical analyses of the polar deposits and radio results to Earth. Although we expect water ice to dominate the deposit, impact deposits from cometary cores are made up of many different substances, including methane, ammonia, and organic molecules, all potentially useful resources. We need to inventory these species, determine their chemical and isotopic properties, and their physical nature and environment. Just as the way for Apollo was paved by such missions as Ranger and Surveyor, a set of robotic precursor missions, conducted in parallel with the planning of manned expeditions, can make subsequent human missions safer and more productive.

After these robotic missions have documented the nature of the deposits, focused engineering research efforts should be undertaken to develop the techniques and machinery needed to be transported to the lunar base as part of future human expeditions. There, the processes and principles of resource extraction will be established and validated, thus paving the way to automation and commercialization of the mining, extraction and production of lunar hydrogen and oxygen.

**(6) This new mission will create routine access to cislunar space for people and machines, which directly relates to important national economic and strategic goals.**

By learning space survival skills close to home, we create new opportunities for exploration, utilization, and wealth creation. Space will no longer be a hostile place that we tentatively visit for short periods; it becomes instead a permanent part of our world. Achieving routine freedom of cislunar space makes America more secure (by enabling larger, cheaper, and routinely maintainable assets in orbit) and more prosperous (by opening an economically limitless new frontier).

As a nation, we rely on a variety of government assets in cislunar space, from weather satellites to GPS systems to a wide variety of reconnaissance satellites. In addition, commercial spacecraft continue to make up a multi-billion dollar market, providing telephone, Internet, radio and video services. America has invested billions of dollars in this infrastructure. Yet at the moment, we have no way to service, repair, refurbish or protect any of these spacecraft. They are vulnerable with no bulwark against severe damage or permanent loss. It is an extraordinary investment in design and fabrication to make these assets as reliable as possible. When we lose a satellite, it must be replaced and this process takes years.

We cannot now access these spacecraft because it is not feasible to maintain a human-tended servicing capability in Earth orbit—the costs of launching orbital transfer vehicles and propellant would be excessive (it costs around $10,000 to launch one pound to low-Earth orbit). By creating the ability to refuel in orbit, using propellant derived from the Moon, we would revolutionize our national space infrastructure. Satellites would be repaired, rather than written off. Assets would be protected rather than abandoned. Very large satellite complexes could be built and serviced over long periods, creating new capabilities and expanding bandwidth (the new commodity of the information society) for a wide variety of purposes. And along the way, we will create new opportunities and make ever greater discoveries.

Thus, a return to the Moon with the purpose of learning to mine and use its resources creates a new paradigm for space operations. Space becomes a part of America's industrial world, not an exotic environment for arcane studies. Such a mission ties our space program to its original roots in making us more secure and more prosperous. But it also enables a broader series of scientific and exploratory opportunities. If we can create a space-faring infrastructure that can routinely access cislunar space, we have a system that can take us to the planets.

**(7) Timing is everything: It is important for America to undertake this mission NOW, rather than later.**

Many nations have recently indicated an interest in the Moon. The possible collection and use of lunar resources raises some interesting political and economic issues. Currently, the 1967 United Nations Treaty on the Peaceful Uses of Outer Space prohibits claims of national sovereignty on the Moon or any other object. However, it is not clear that private claims are likewise prohibited under this treaty. The 1984 United Nations Moon treaty specifically prohibits private ownership of lunar assets, but the United States, Russia, and China are not signatories to that treaty, ratification of which was specifically rejected by the United States Senate.

Our initial return to the Moon would be an engineering and scientific research and development project. We undertake our studies of the extraction of lunar resources to ascertain the best methods to harvest and use these materials. Our presence on the Moon does not give us title to it. However, a strong and continuing American presence on the Moon can help establish de facto the broad legal framework and economic paradigm of democratic, free-market capitalism off the Earth. It is not clear that other nations would be similarly inclined. In short, regardless of impressions, we are indeed in a race to the Moon—not a race comparable to the 1960's Cold War race to the Moon between America and the Soviet Union, but a race no less important in establishing future socio-economic stability. History has shown that our economic-political system produces the most wealth and freedom and highest quality of life for the most people in the shortest time. America needs to continue to lead in space, ensuring an open economic and self-determining, democratic framework is established off-Earth.

**(8) The infrastructure created by a return to the Moon will allow us to travel to the planets in the future more safely and cost effectively.**

This benefit comes in two forms. First, developing and using lunar resources can enable movement throughout the Solar System by permitting the fueling of interplanetary craft with materiel already in orbit, thereby saving the enormous costs of launch from Earth's surface. Second, the processes and procedures that we learn on the Moon will be applied to all future space operations. To successfully mine the Moon, we must learn how to use machines and people in tandem, each taking advantage of the other's strengths. The issue isn't "people or robots?" in space, it's "how can we best use the combination of people and robots in space?" People bring the unique abilities of cognition and experience to exploration and discovery; robots possess extraordinary stamina, strength, and sensory abilities. We can learn on the Moon how to best combine these two complementary skill mixes to maximize our exploratory and exploitation abilities.

A return to the Moon will give us operational experience on another world. Activities on the Moon will make future planetary missions less risky as we gain valuable experience in an environment close to Earth, yet on a distinct and unique alien world. Systems and procedures can be tested, vetted, revised and re-checked. By learning to live and work on the Moon, we gain both experience and confidence in planetary exploration and surface operations.

The Moon provides a nearby laboratory and industrial test-bed where we can hone our exploratory skills and lay the foundations for a future space-based economy. Human expansion to the Moon will provide new opportunities and horizons for the American entrepreneur, our businesses, and our workforce. Developing new technologies has always led to new markets and increased our general prosperity. Expansion of the economy is vital to our national health and security. Who will capitalize on this opportunity and become the next Rockefeller, Carnegie, Ford, Getty, or Gates?

America needs a challenging, vigorous space program. It must present a mission that inspires, educates, and enriches. It must relate to important national needs yet push the boundaries of the possible. It must serve larger national concerns beyond scientific endeavors. The President's program fulfills these goals. It is a technical challenge to the Nation. It creates security for America by assuring access and control of our assets in cislunar space. It creates wealth and new markets by producing commodities of great commercial value. It stimulates and inspires the next generation by example. A return to the Moon is a giant step into the Solar System.

Thank you for your attention.

### BIOGRAPHY FOR PAUL D. SPUDIS

PAUL D. SPUDIS is a Senior Staff Scientist at the Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland and Visiting Scientist at the Lunar and Planetary Institute in Houston, Texas. He was formerly with the Branch of Astrogeology, U.S. Geological Survey in Flagstaff, Arizona and the Lunar and Planetary Institute. He is a geologist who received his education at Arizona State University (B.S., 1976; Ph.D., 1982) and at Brown University (Sc.M., 1977). Since 1982, he has been a Principal Investigator in the Planetary Geology and Geophysics Program of the NASA Office of Space Science, Solar System Exploration Division, specializing in research on the processes of impact and volcanism on the planets. He has served on NASA's Lunar and Planetary Sample Team (LAPST), which advises allocations of lunar samples for scientific research, the Lunar Exploration Science Working Group (LEXSWG), that devised scientific strategies of lunar exploration, and the Planetary Geology Working Group, which monitors overall directions in the planetary research community. He has also been a member of the Committee for Planetary and Lunar Exploration (COMPLEX), an advisory committee of the National Academy of Sciences, and the Synthesis Group, a White House panel that in 1990–1991, analyzed a return to the Moon to establish a base and the first human mission to Mars. He was Deputy Leader of the Science Team for the Department of Defense Clementine mission to the Moon in 1994. He is a member of the President's Commission on the Implementation of U.S. Space Exploration Policy, whose report is due in June of 2004. He is the author or co-author of over 150 scientific papers and three books, including *The Once and Future Moon,* a book for the general public in the Smithsonian Library of the Solar System series, and *The Clementine Atlas of the Moon,* published in 2004 by Cambridge University Press.

Chairman ROHRABACHER. Thank you very much. Our next witness is Dr. Daniel Lester, who is a research scientist at McDonald Observatory, University of Texas at Austin. Dr. Lester, you may proceed.

## STATEMENT OF DR. DANIEL F. LESTER, RESEARCH SCIENTIST, MCDONALD OBSERVATORY, UNIVERSITY OF TEXAS, AUSTIN

Dr. LESTER. Thank you. Mr. Chairman, Members of the Committee, I want to thank you also very much for inviting me to testify before you today. I am an astronomer at McDonald Observatory, University of Texas, and I am going to use my five minutes to talk a little about telescopes in space and on the Moon in particular.

I want to start out by saying that space—the vacuum of space—is a tremendously enabling place for astronomical telescopes. We do very well with telescopes on the Earth, but those telescopes on the Earth, which are much easier to build and cheaper to build than telescopes in space, look through the Earth's atmosphere, and the Earth's atmosphere blocks a lot of the light that we would like to be able to see from the stars and galaxies beyond.

So the question becomes where do we put telescopes in space? Do we put them in orbit around the Earth? Do we put them in orbit around the Sun? Or, perhaps, do we put them down on the surface of a body that doesn't have any atmosphere, like the Moon? What we have to ask ourselves at this point is what the Moon offers to us.

Now, I want to backtrack just a moment and say that 20 or 30 years ago, my community, the astronomical community, was very excited about the idea of putting telescopes on the Moon. I, too, invested a lot of effort in going in that direction. Now, you have to understand that at that time, 20 or 30 years ago, we had virtually no high-capability free-flying telescopes in space, and we had people walking around on the Moon. So at that time, it seemed like a very credible thing to do. We are going to have people walking around the Moon, thanks to the new initiative, but we now have a tremendous amount of experience in making observatories in free space, much like the Hubble Space Telescope, work very well. A long time ago, we were worried about whether we could point telescopes in free space—telescopes floating around. How would we be able to keep them to track on the stars we were looking at? We now understand how to do that extremely well using what is now off-the-shelf technology.

So one can ask what does the Moon have that free space doesn't? And the way I and my colleagues look at it is that the Moon has dirt and the Moon has gravity. And so the question becomes are dirt and gravity enabling to astronomy, and my contention is that they are not for the following reasons.

Dirt, while we will hear about the use of dirt for lunar resources, and I think that is a wonderful thing to think about, astronomers tend to look at dirt as a pollutant for our telescopes. Dirt that gets on our telescopes, gets on the optics, prevents the light from getting through them, and actually, for infrared telescopes which I use a lot of, adds to the background enormously, reducing the sensitivity. That dirt has strongly abrasive properties. That dirt will get in gears. It will get in bearings. And will make maintenance of telescopes quite challenging on the Moon compared to free space.

Now, gravity is no friend of telescopes. Gravity—of course, the Earth has plenty of gravity and we have telescopes on the Earth and we manage to avoid having problems with gravity. Of course, the problems that we have are where a telescope looks in this part of the sky, gravity is pulling down on it. When the telescope then goes over and looks in this part of the sky, gravity is pulling down in a different way. Gravity bends the telescopes. It doesn't bend it very much, but it doesn't take very much to get the telescopes out of alignment.

Now, our approach to that for ground-based observatories is very simple. We make them very stiff and very strong and very massive. We throw a lot of steel at them. That is not a good strategy for deciding what to do with telescopes in space. Now, it is true that the lunar gravity is only $\frac{1}{6}$ of the Earth, but nevertheless—and so it in principle is easier to make telescopes that will work well on the Moon compared to making telescopes that will work well on the Earth. But free space has no gravity at all, and so the kinds of structural complexity that we need to hold together a telescope in alignment in free space is very much lower.

Finally, gravity is a risk. When we are sending equipment to the Moon from the Earth, it has to survive. It has to survive the soft landing. The retrorockets have to work. Parachutes don't work. And so we look at that as a risk factor that we don't have for telescopes in free space.

Now, in conclusion, I would just say that one of the big advantages that one can look at by having telescopes on the Moon is that there will be people there. I want to make it very clear to the Committee that myself and many of my colleagues look ahead to the new initiative involving humans and astronauts in astronomical activities is profoundly highly enabling. We are very excited about that. We are looking forward to looking into that.

For example, the very biggest telescopes that we hope to make—telescopes far bigger than Hubble Space Telescope—these telescopes are too big to be put into a rocket already unfolded. If I want to build a ten-meter telescope and I only have a five-meter rocket shroud, I have got a big problem, unless that telescope is folded up. We fold the telescope up, we shoot it up, and then we cross our fingers, and the hinges and motors, then they get deployed, have to work. If they don't work, we are in trouble. Now, in a situation like this, having an astronaut there with a screwdriver in one hand and a wrench in the other hand and the ability to give something a pull where it needs to be pulled, can be fantastically enabling for us, so we are really looking forward to that.

I would just like to say in summary that we would very much hope that the technologies that we develop to put people back on the Moon, and to the experience that we gain in doing that, can be used to optimally service and aide astronomy in free space. Thank you.

[The prepared statement of Dr. Lester follows:]

### PREPARED STATEMENT OF DANIEL F. LESTER

Mr. Chairman and Members of the Committee, thank you for this opportunity to appear and give testimony concerning future options for using the Moon to do science. As a member of the space astronomy community, I have been asked to express current thinking about the advantages and disadvantages of the Moon for doing astronomy and, in particular, whether the Moon is an appropriate site for astronomical telescopes. The importance of space telescopes both to fundamental science and to the excitement that the public has about our national efforts in space, combined with the key role that the Moon plays in the President's new space initiative, give special importance to this issue. In summary, and upon careful recent review of lunar observatory concepts that have been presented over the years, my colleagues and I find that the opportunities for lunar-based astronomy offer much less value, compared to observatories in free space, than had been anticipated several decades ago. While the lunar surface is not a highly enabling site for an astronomical observatory, development of the Moon would need many technologies that would substantially advance telescopes in free space.

**Space Astronomy as a National Priority**

I want to begin this testimony by reviewing the reasons that we do astronomy—answering some of the most far-reaching and exciting scientific questions that challenge our nation. While studies of our own solar system are increasingly dominated by actual visits by robotic craft, and soon humans, studies of the universe beyond depend entirely on telescopes that detect energy coming from it. While our solar system provides us with clues about the formation of our Earth and the way that life formed upon it, the universe beyond offers insights into extremes of the physical world that are impossible to replicate in our laboratories. We seek to understand the structure and evolution of the cosmos on both the largest scales, reaching back to its earliest times, and on the smallest scales, in the vicinity of black holes. We want to learn how galaxies, stars, and planetary systems form and evolve, their cycles of matter and energy, and understand the diversity of worlds beyond our own. We want to search those worlds for those that might harbor life. Such explorations provide us with not just intellectual satisfaction and national pride in scientific accomplishment, but with new understanding that is the foundation for future technologies. By looking at our universe far away, we better understand the physical world nearby.

### Space as an Enabling Site for Astronomical Telescopes

But why do we go into space to do it? Large telescopes are ubiquitous on terrestrial mountaintops, and with roads, power lines, and air to breathe such telescopes are much easier to build and operate than those in space. For several different reasons, it is the vacuum of space that is extraordinarily enabling for astronomy. The atmosphere of the Earth, while essential for life here, distorts and blocks much of the light that comes from the cosmos. That our atmosphere effectively blocks gamma rays, x-rays, and ultraviolet light is critical to our survival, but makes direct studies of black holes and supernovae difficult. That our atmosphere contains water vapor that blocks most infrared light makes studies of star and planet formation especially challenging, though such water is crucial to our existence. In the vacuum of space there is no such impediment. The sky from space is profoundly clear, and this clarity has been utilized by the Compton and Chandra observatories to explore the universe at high energies, the recent Spitzer observatory in the infrared, as well as the Hubble telescope for visible light. For infrared telescopes in particular, in which cryogenic operation offers a dramatic increase in sensitivity, such operation is impossible in the presence of an atmosphere, which would freeze out on a cold telescope. So the vacuum of space offers important thermal advantages.

### Astronomical Observatories and the Lunar Surface

Some forty years ago, the Moon was first proposed by astronomers as a prime site for large telescopes. The lack of an atmosphere offered an unobscured view of the cosmos, and the lunar surface offered a “platform” on which to anchor big structures. At this time, the concept for observatory operation was strongly human-intensive, modeled on the operations plan for ground-based telescopes of the era. Humans would be needed, it was thought, not just to handle the (now obsolete) photographic plates that were the sensor-of-choice in that era, but to look through an eyepiece to point and guide the telescope! With a facility firmly anchored to the lunar surface, astronauts could inhabit the observatory and go about their jobs without jiggling the telescope. One or two decades later, with astronauts actually walking and doing science on the Moon, this idea of lunar telescopes gained credibility in the science community. Then, and to this day, astronomical telescopes on the Moon were understood to offer vastly greater capabilities than they would on the surface of the Earth. If the surface of the Moon and the surface of the Earth were the only places able to host large astronomical telescopes, and if cost were not an object, the Moon would win handily in science potential.

Within the last two decades, however, there has been a revolution in our capabilities to autonomously deploy, stabilize, and point satellites in the vacuum of free space. This understanding was gained from both military and commercial (Earth resources) surveillance investments, as well as from the communication satellite industry. Telescopes in free space now track with a precision that is far higher than can telescopes on the ground. Even for arrays of widely separated telescopes that are optically coupled, and offer big advantages in image clarity, implementation strategies have been designed for free space that offer low risk. Finally, information is now returned electronically, rather than on material media, such as photographic plates. While human involvement has been in at least most contemporary cases unnecessary for startup, the Hubble telescope proved that astronaut roles in mission assurance and servicing could be highly enabling for astronomy. Our space program, as well as that of other countries, has achieved huge successes in astronomy from telescopes in free space.

### Dirt and Gravity are No Friends to Telescopes

In comparison to zero-g sites in free space the Moon, as a telescope platform, offers mainly dirt and gravity. While dirt has been viewed by some as providing harvestable resources, it also translates into serious performance liabilities. Surface dust kicked up by both meteorites and activity near the telescope (whether blast waves from rockets or footsteps of astronauts) will degrade optical surfaces. This will result in a reduction of sensitivity and a sharp increase in background light that suppresses the faintest infrared light from distant stars and extra-solar planets. It also dramatically enhances scattered light that will interfere with studies of solar systems in the vicinity of bright stars. This dust, the deleterious properties of which are well understood from Apollo efforts, can be assumed to increase wear and reduce performance of loaded mechanical bearings, on which such lunar telescopes would critically depend for precision motions.

Compared to the weightless environment of free space, even the 1/6g of the Moon will threaten the precise optical alignment of telescopes as they move across the sky. In order to achieve the stiffness needed to avoid such gravity deformations, a lunar telescope will have to be much more massive, and concomitantly more expensive, than a similar telescope in free space. Consider, for example, that the six meter diameter James Webb Space Telescope (JWST), now being designed for free space, will have a mass of about six metric tons. Similar sized telescopes on Earth each have about three hundred metric tons of material that has to move, almost an order of magnitude larger than JWST when scaled to the lowered lunar gravity. Finally, gravity is something that lunar surface telescope builders would need to fight. All parts and subsystems brought from the Earth must survive soft landing on the Moon, a requirement that involves considerable added expense and risk. In short, we should ask whether dirt and gravity offer any general value to astronomy. The answer, I believe, is no.

Concepts for lunar telescopes have been proposed that take advantage of special properties of the Moon. The orbit of the Moon is such that telescopes within craters at the lunar pole would never have sunlight shining on them. These telescopes would naturally be extremely cold, perhaps 40–50K, and in this respect could offer excellent infrared performance without expendable cryogens or costly refrigeration. While noteworthy, this property of the Moon is no longer particularly enabling, as such temperatures are achievable in free space, using lightweight reflective shields to block the sunlight. The Spitzer Space Telescope is at least partly passively cooled using such sun shields, and the thermal performance actually realized for that observatory is identical to engineering predictions. JWST will use shields with more layers, and these models predict achievable telescope temperatures of 35K. We can do even better. The Single Aperture Far Infrared telescope (SAFIR) is a cold telescope facility even larger than JWST, roadmapped as a Vision Mission candidate for the next decade. I am the Principal Investigator on a concept study for SAFIR. Our team believes that with lessons learned from JWST, and optimized shielding, even lower temperatures can be realized passively. The lunar poles are indeed very cold places but with sunlight properly screened, free space is as well.

The far side of the Moon is also claimed to be scientifically noteworthy as a radio-quiet site. On this hemisphere of the Moon there is never a line-of-sight to the Earth, so the strong human radio traffic and natural radio emission from our planet cannot interfere with astronomical observations there. While this is potentially enabling, the scientific need for such a radio quiet site has never been entirely persuasive. The potential of this site was discussed, but never included explicitly, in the Decadal Study of astronomical priorities by the National Academy of Science. Recent significant developments in strategies for radio frequency noise mitigation may also pertain to this.

### It's Not Humans versus Robots

A final advantage that has been ascribed to the Moon for space astronomy is that it is where people will be. I believe I speak for my community in saying that the involvement of astronauts in space astronomy has enormous potential. We look ahead even in the near-term to telescopes that do not fit, fully deployed, into launcher shrouds (c.f. JWST). Such telescopes need to be packed, unfolded, locked tight, aligned, and verified, all carrying significant risk if done autonomously. The advantages of in situ astronauts holding screwdrivers and wrenches who are there to deploy and assemble large space telescopes, and rescue these expensive assets in the event of a technical failure (c.f. HST) cannot be dismissed. But if astronauts are going to be based on the Moon, and if we believe they will visit Mars, we will certainly have the capability to put these astronauts to use in free space to advance astronomy, whether in low-Earth orbit as for HST, or farther out. For example, the semi-stable Earth-Moon and Earth-Sun Lagrange (or libration) points in free space are understood to offer huge advantages to astronomy, and current plans call for a whole squadron of science missions at the latter site within the next two decades. No credible discussion of space astronomy can be had without considering the impressive science potential of these Lagrange points in the Earth-Moon system. As a result, it would be truly unfortunate if astronaut involvement in the future of space science was limited to opportunities with dirt underfoot.

The new space initiative is a bold vision that promises rich payoffs, and gives our nation a defining challenge. National leadership to accrue from this vision and the sustainability with which is it pursued will depend upon careful consideration and strategic pursuit of science opportunities. Such opportunities are founded in curiosity and the spirit of exploration, which are historically established parts of our national heritage and very much key national needs. The Moon offers many such opportunities, but for space astronomy the real value of lunar development will come from how well such development serves observatories elsewhere.

### BIOGRAPHY FOR DANIEL F. LESTER

Daniel F. Lester is a Research Scientist at the McDonald Observatory of the University of Texas. His research specialty is infrared studies of star formation in galaxies. His is the author of more than eighty refereed papers in professional journals. Dr. Lester earned his Ph.D. at the University of California at Santa Cruz with the Lick Observatory, followed by postdoctoral work at the NASA Ames Research Center, and as a staff scientist at the University of Hawaii Institute for Astronomy. He worked closely on the conceptual development of the Stratospheric Observatory for Infrared Astronomy (SOFIA), and has been active in community strategic planning and policy development for space astronomy. Dr. Lester is currently Principal Investigator and team leader for the Single Aperture Far Infrared (SAFIR) vision mission study, now being funded by NASA. He is active in K–12 science education and public outreach efforts.

Chairman ROHRABACHER. Thank you very much for your testimony. Our next witness is Dr. Donald Campbell, who is a professor of astronomy and Associate Director of the National Astronomy and Ionosphere Center at Cornell University. Dr. Campbell, you may proceed.

## STATEMENT OF DR. DONALD B. CAMPBELL, PROFESSOR OF ASTRONOMY, ASSOCIATE DIRECTOR, NATIONAL ASTRONOMY AND IONOSPHERE CENTER (NAIC), CORNELL UNIVERSITY

Dr. CAMPBELL. Thank you, Mr. Chairman, Members of the Committee, and thank you for inviting me to testify on the subject of lunar science and resources. I have been specifically asked to address the issue of the possible presence of water on the surface of the Moon and how we should proceed in determining whether it is or is not present in recoverable quantities.

There is no doubt that accessible, significant, and recoverable deposits of water on the Moon would greatly facilitate the setting up of a lunar base. The lunar surface is rich in a variety of minerals, such as iron, titanium oxides, and these minerals could provide resources such as oxygen to sustain an extended human presence on the Moon. However, recoverable amounts of one vital commodity, hydrogen, needed to produce water and possibly rocket fuel, are in short supply on the lunar soil. For this reason, the idea that the lunar polar regions may have water ice, which was so suggested 40 years ago, continues to be of great interest.

There are two remote sensing techniques currently used to look for water: radar and neutron spectrometry. Radar is sensitive to thick deposits of relatively pure water ice. This was demonstrated by the discovery by Alpha Earth-based radars of water ice deposits in the very cold bottoms of permanently shaded impact craters at the poles of Mercury. Neutron spectrometers are sensitive to the presence of hydrogen, which may or may not be incorporated in water molecules. The power of this technique was dramatically demonstrated with the recent discovery of large quantities of ground ice on Mars.

Suggestions from radar observations from the Clementine Orbiter in 1994, that there are thick ice deposits in one crater at the lunar South pole, were not confirmed by radar observations using the National Science Foundation's Arecibo telescope. As you can gather that Dr. Spudis have some disagreement in terms of the interpretation of those—the Clementine data and the Arecibo radar data. However, it is important to understand that both these radars had a very poor view of the polar region. They had almost identical views of the polar regions, and looking from a very low angle in the sky—they are only about six degrees above the horizon, so there were large areas of the lunar surface which they could not, in fact, view very adequately, the shadow effect away from the radar.

The neutron spectrometer—yeah, I don't know—I should say that this result does not in anyway preclude, because of the poor visibility, the possibility there may be thick deposits of ice, although it makes it somewhat unlikely. The neutron spectrometer on the 1998 Lunar Prospector Orbiter had a clear view of all of the surface in the polar regions. As reported by Dr. William Feldman, the principle investigator for the instrument, and his colleagues—and I should emphasize that I was not involved in this particular work—there is a general increase of a factor of about three in the hydrogen concentration in the upper three feet of the lunar soil in the polar regions, compared with the equatorial regions. They also found much higher hydrogen concentrations associated with several large, permanently-shaded impact craters at the south pole. At the north pole, the shaded craters are smaller than the 30-mile best resolution of the neutron spectrometer. It was not possible to look at individual craters, but there was an increased hydrogen content associated with groups of small shaded craters. The hydrogen may be in the form of free hydrogen implanted into the lunar soil surface by the solar wind, water in the form of ice, or hydrated minerals in which water molecules are chemically bound to the minerals.

If all the excess hydrogen in the polar regions is in the form of water, it would correspond to about two billion tons. That sounds like a lot, but you have got to understand that the concentration in the lunar surface would be extremely small, and it would be so low, it is probably not feasible to recover it. Of a lot more interest are the high hydrogen concentrations coincident with the large impact craters of the south poles. The bottom of these craters are in permanent shadows and are very cold, acting as traps for hydrogen or water molecules. If it is in the form of water ice, the enhanced hydrogen concentration of these craters would correspond to about 1.5 percent water ice, getting up to be a significant concentration of potentially—would be recoverable amounts of water without too much effort. It is probably in the form of grains or crystals mixed into the upper few feet of the lunar soil. The radar experiments on the Clementine orbiter, or from Arecibo, would not have been sensitive to that form of water ice, small crystals and grains mixed into the soil.

Given the size of these craters, this concentration of water ice corresponds to about 200 million tons of water, a significant amount if it can be recovered. However, one has to keep in mind that the craters are deep, very cold, and dark, and so devising a recovery method will not be easy.

Because of its importance as a resource, we need to settle the question as to whether there is any accessible and usable quantities of water at the poles. To do so, a lunar polar orbiter should be equipped with a suitable set of instruments. And, as you already heard, you know, those instruments should include a high resolution advanced neutron spectrometer. It is my understanding that a 3-mile surface resolution is feasible, about 10 times better than the 30-mile resolution of the Lunar Prospector orbiter. That would allow mapping of the hydrogen concentration of relatively small scales, and looking into much smaller craters to see if there are concentrations of water there that may be more accessible than in the big craters.

A mapping synthetic aperture radar system to search for thick ice deposits possibly buried under the lunar soil. The SAR would also allow detailed images to be obtained of the areas at the lunar poles that are in permanent shadow. These cannot be imaged with normal cameras.

We also need an instrument to measure the altitudes of the polar terrains, including the depths and wall slopes of the craters that may harbor ice deposits. This could be an interferometric SAR as an expansion of the radar SAR system mentioned in item 2, or it could be a LASER altimeter system.

We would like to know the temperatures at the bottom of these craters, and so there should be an infrared system for measuring temperatures in the interior of the craters with shadowed bottoms.

There should obviously be a high-resolution camera for investigating suitability of possible landing sites, and for the part of the route illuminated by the Sun, the ease or difficulty of access to possible water ice deposits.

And finally, if there is some evidence for water ice deposits in the shadowed craters, clearly we want in situ measurements, and probably the most simple way to do that is to, initially at least, is put penetrators into the surface to directly examine the composition of the surface itself.

Thank you very much.

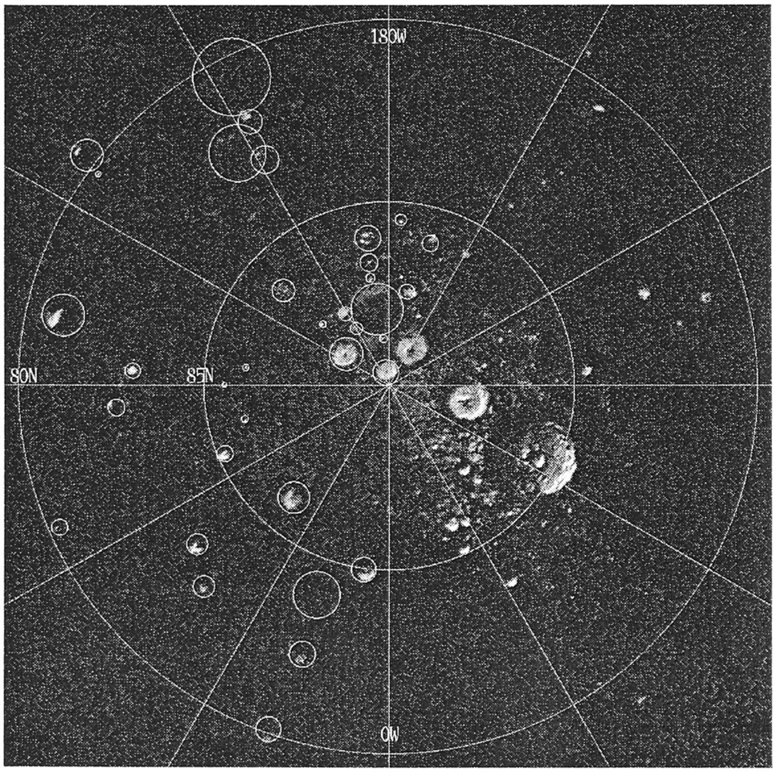
[The prepared statement of Dr. Campbell follows:]

## PREPARED STATEMENT OF DONALD B. CAMPBELL

Mr. Chairman and Members of the Committee, thank you for inviting me here today to testify on the subject of lunar resources.

The lunar surface is rich in a variety of minerals such as oxides of iron and titanium and it is possible that these minerals can be utilized to provide resources such as oxygen to sustain an extended human presence on the Moon. Recoverable amounts of one vital commodity, hydrogen, needed to produce water and possibly rocket fuel, appear to be in short supply in the lunar soil. Consequently, the idea that the polar regions of the Moon may harbor ice deposits, first suggested over 40 years ago, continues to be of great interest. In the early 1990s the idea was given further impetus by the discovery of apparent ice deposits in the cold, permanently shaded bottoms of impact crater at the poles of the planet Mercury. The discovery and investigation of these ice deposits were made using powerful radar systems on one of NASA's Deep Space Network (DSN) Goldstone antennas and on the NSF's Arecibo telescope (operated by Cornell University under a cooperative agreement with the NSF) in Puerto Rico. Ice at low temperatures has unusual radar reflection properties—it “lights up” under the radar illumination very much like a highway sign at night and the reflected radar signal has different polarization properties than for rock or soil—but only if it is in the form of thick, relatively pure deposits. As can be seen in radar image of the north polar region of Mercury made at the NSF’s Arecibo Observatory in Puerto Rico, the ice deposits stand out very brightly on Mercury.

Figure: A radar image of the north pole of Mercury showing the bright radar echoes from what are thought to be thick deposits of ice on the shadowed floors of impact craters. The circles show the sizes and locations of known impact craters from images taken in 1974 from the Mariner 10 spacecraft. The ice stands out so brightly because it is a good retro-reflector. The radar echoes from the surrounding terrain are so weak that they cannot be seen. The image was made with the NSF’s Arecibo telescope (courtesy of J. Harmon).

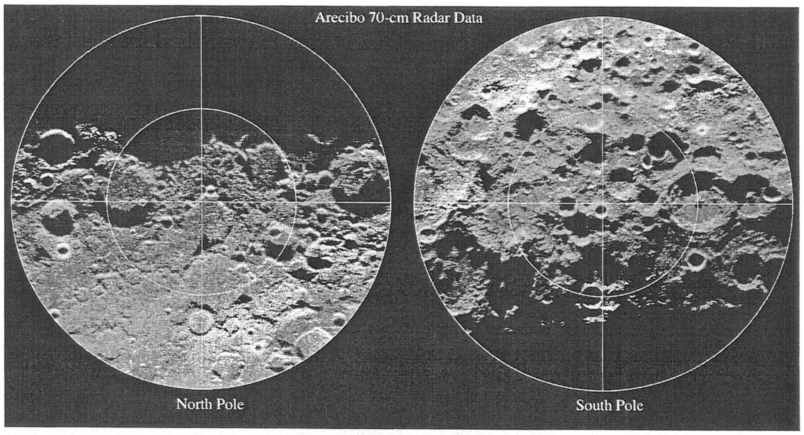


Ice can also be identified by using a neutron spectrometer to map the properties of cosmic ray produced neutrons that scatter in the top few feet of a planetary surface with the nature of the scattering being very sensitive to the presence of the nuclei of hydrogen atoms and, hence, water ice if the hydrogen is incorporated in water molecules. The ability of neutron spectrometers to detect the presence of water ice was dramatically demonstrated by the recent discovery of considerable ground ice deposits on Mars.

**How much water may be trapped on the lunar surface?**

Over the past decade there has been evidence from instruments on lunar orbiting spacecraft suggestive of the presence of water ice in the polar regions. Results from bi-static radar observations using the Clementine orbiter—the radar signal was transmitted from the spacecraft and the echo received by one of NASA's DSN antennas—were interpreted as indicating the presence of thick deposits of ice in a crater at the south pole. The interpretation of the Clementine results has been debated in the scientific literature and, as can be seen from the figure, imaging radar observations using the NSF's Arecibo Observatory have not found any evidence for ice deposits on the Moon similar to those seen at the poles of Mercury. However, since neither the Clementine nor the Arecibo observations were able to view some or all of the shaded bottoms of the impact craters at the lunar poles, these observations cannot be regarded as definitive. While perhaps unlikely, the possibility still exists that there are thick ice deposits in the bottoms of some shaded impact craters at the lunar poles.

Figure: Radar images of the poles of the Moon made with the NSF's Arecibo telescope. Much of the area close to the poles themselves, especially at the south pole, is in shadow from the Sun and cannot be seen in optical images. The radar on the Earth is higher above the horizon than the Sun so can "see" some of these shaded areas. There are no bright radar echoes similar to those for Mercury indicating no thick deposits of clean water ice. Only some of the shaded areas can be seen with the radar and it is possible that ice may be present in locations yet to be investigated. (Image courtesy of B. Campbell.)



Measurements from the Lunar Prospector orbiter are not open to this level of uncertainty. Its neutron spectrometer looked directly down so could view all of the polar terrain. As discussed above, this instrument is sensitive to the presence of hydrogen atoms and it discovered significant concentrations of hydrogen in the lunar polar regions. Its best spatial resolution on the Moon's surface was about 30 miles. As reported by William Feldman of the Los Alamos National Laboratory and colleagues, near the south pole there is a small general increase in the hydrogen concentration compared with the equatorial regions and there are significant concentrations associated with large impact craters with shaded bottoms. In the north there is a similar general increase in the average concentration of hydrogen. However, most of the impact craters with shaded bottoms are small, so that the hydrogen deposits cannot be uniquely associated with individual shadowed craters and it is not possible to say whether there are areas with significant concentrations. There are definitely higher concentrations of hydrogen at the lunar poles compared with other areas of the Moon but both its origin—cometary impacts or solar wind implanted hydrogen—and its current form—hydrogen, ice or hydrated minerals—is a topic of considerable discussion in the relevant scientific community.

If all of the hydrogen at the lunar poles is in the form of ice, then an analysis of the Lunar Prospector results by Dr. Feldman and colleagues has shown that the total inventory of water ice in the upper three feet or so would be about two billion tons. Considering just the shaded areas at the south pole, where the only economically recoverable deposits discovered so far seem to reside, they concluded that the weight concentration of water ice in the upper three feet would be about 1.5 percent. Taking our best estimates of the total shaded area at the south pole, this translates into about two hundred million tons of water equivalent. This water is likely distributed as ice grains or crystals in the lunar soil and would not have been observable by either the Clementine orbiter or Earth-based radars. Because of the poor spatial resolution of the neutron spectrometer on the Lunar Prospector orbiter, it is not possible to say from current data whether there are small areas where there may be even higher concentrations of ice.

### Is finding water important for exploiting the Moon for scientific or economic purposes?

Accessible deposits of water on the Moon would profoundly affect the economics and viability of a human presence on the Moon. Water is, literally, the stuff of life. For a permanent or reusable base a local supply would be invaluable both for human needs in the form of water and oxygen, and for production of rocket fuel. A viable base would enable both further exploration of the Moon and, as Dr. Spudis and others have pointed out, has the potential to allow exploitation of lunar resources.

However, the need is for accessible deposits. Unfortunately, the only recoverable deposits are likely to be in the polar regions probably in the bottoms of very cold, permanently dark craters. It is likely, but not certain, that any deposits are well mixed into the lunar soil at about the one percent level of concentration. Recovering water from these deposits will not be an easy task.

Before we spend too much time making plans for exploiting water resources on the Moon, we should determine whether there are any recoverable deposits of water, in what form—distributed at low concentrations in the lunar soil or in concentrated deposits—of what type—ice or hydrated minerals—and how accessible. To do this we need to send one or more missions with these specific objectives.

### Instruments needed to resolve the water issue.

Detecting water ice in the cold, dark bottoms of impact craters in the lunar polar regions is extremely difficult especially if the ice is covered by, or imbedded in, the lunar soil. Two remote sensing techniques that we have available, imaging radars and neutron spectrometers, offer the best hope. If the ice is in the form of thick sheets, then it is possible that a radar system on an orbiter would detect the associated strong radar reflection properties even if the ice lies beneath a surface covering of lunar soil. Depending on its frequency of operation, a radar system could probe many feet into the lunar surface to search for buried deposits. According to Dr. Feldman, neutron spectrometers with about ten times the spatial resolution of the instrument on the Lunar Prospector orbiter appear to be feasible and would allow searches on about three mile or better scales for those areas with the highest concentration of hydrogen. *In situ* searches would be the most definitive but could only be made in a very small number of locations. Such sampling could be achieved by using instrumented penetrators or, ultimately, rovers to investigate the most likely sites to harbor water based on results from previous searches using a high resolution neutron spectrometer and imaging radar.

A possible suite of instruments on one or more lunar polar orbiters would be:

1. A high resolution neutron spectrometer. Three mile surface resolution appears to be possible, 10 times better than that of the Lunar Prospector neutron spectrometer, allowing mapping of the hydrogen concentration at this scale.
2. A mapping synthetic aperture radar system (SAR) to search for thick ice deposits possibly buried under lunar soil. A SAR would also allow detailed images to be obtained of the areas at the lunar poles that are in permanent shadow and, hence, cannot be imaged with normal cameras.
3. An instrument to measure the altitudes of the polar terrains including the depths and wall slopes of the craters that may harbor ice deposits. This could be an interferometric SAR as an expansion of the SAR system of item 2, or a LASER altimeter.
4. An infrared system for measuring the surface temperatures over the polar regions and, especially, in the interiors of the craters with shadowed bottoms.
5. A very high resolution camera for investigating the suitability of possible landing sites and, for the part of the route illuminated by the Sun, the ease or difficulty of access to possible water ice deposits.
6. Suitably instrumented penetrators on a follow up mission to investigate locations that the earlier measurements indicate may harbor water in useful concentrations and directly determine its presence and form.

**What other useful minerals, ores or elements may be present in the lunar soil?**

Many useful materials are present in significant concentrations in the minerals present in the lunar soil and rocks. Mare basalts have high concentrations of oxygen, silicon, ion, magnesium, titanium and the lunar highlands have significant amounts of aluminum and calcium. The major issue is how to recover these materials or make use of the minerals themselves using relatively simple automated processes suitable for use on the lunar surface.

Thank you for your attention.

## BIOGRAPHY FOR DONALD B. CAMPBELL

**Education:**

University of Sydney—BS (Physics); MS (Physics, Radio Astronomy)

Cornell University—Ph.D. (Astronomy and Space Sciences) 1971

**Positions Held:**

1993–Present—Associate Director, National Astronomy and Ionosphere Center, Cornell University
1992–1993—Interim Director, National Astronomy and Ionosphere Center, Cornell University
1988–Present—Professor, Department of Astronomy, Cornell University
1983–1987—Adjunct Professor, Department of Astronomy, Cornell University
1981–1987—Director of the Arecibo Observatory, National Astronomy and Ionosphere Center, Cornell University
1976–1987—Senior Research Associate, Cornell University (NAIC)
1974–1976—Research Associate, Cornell University (NAIC)
1973–1974—Staff Scientist, Haystack Observatory, MIT
1971–1973—Research Associate, Cornell University (NAIC)
1966–1971—Research Assistant and Graduate Student, Cornell University

**Professional Societies:**

International Astronomical Union

American Geophysical Union

American Astronomical Society and its Division of Planetary Sciences

International Union for Radio Science

American Association for the Advancement of Science

**Honors:**

1984—NASA Medal for Exceptional Scientific Achievement
1992—NASA Group Achievement Award
1994—NASA Group Achievement Award
2003—Fellow, American Association for the Advancement of Science

**Professional Activities:**

1984–1988—Member of the Radar Investigation Group for the Venus Radar Mapper Mission
1989–1994—Co-Investigator, NASA's Magellan Mission Radar Investigation Group
1992–1995—Vice President, American Astronomical Society
1993–1996—Advisory Committee, NASA-sponsored Venus Geologic Mapping Project
1994–1996—NASA's Planetary Geology & Geophysics Proposal Review Panel
1994–1997—Nat'l. Academy of Sciences, U.S. Nat'l. Committee for the Int'l. Astronomical Union
1995–1999—Member of the Visiting Committee for the National Radio Astronomy Observatory
1998–1999—Chair, Visiting Committee for the National Radio Astronomy Observatory

1999–2000—Radio and National Centers Panels of the Astronomy and Astrophysics Survey Committee's Decadal Review

2003—Steering Committee for the Canadian SKA Project.

2003—Member, Executive Management Board for NASA's Deep Space Mission System

**Some Relevant Publications:**

Arecibo Radar Mapping of the Lunar Poles: A Search for Ice Deposits, N.J.S. Stacy, D.B. Campbell, and P.G. Ford, *Science,* 276, 1527–1530, [April 1997].

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Long Wavelength Probing of the Lunar Poles, B.A. Campbell, D.B. Campbell, J.F. Chandler, A.A. Hine, M.C. Nolan and P.J. Perillat, 2003, *Nature,* 426, 137–138, 13 Nov. 2003.

Chairman ROHRABACHER. Very well. There it is. Thank you very much. Our next witness is Dr. John Lewis, Professor of Planetary Sciences and Co-Director of the Space Engineering Research Center at the University of Arizona. Mr. Lewis, you may proceed.

## STATEMENT OF DR. JOHN S. LEWIS, PROFESSOR OF PLANETARY SCIENCES, CO-DIRECTOR, SPACE ENGINEERING RESEARCH CENTER, UNIVERSITY OF ARIZONA

Dr. LEWIS. Mr. Chairman, Members of the Committee, I will assume that the remarks by the gentlemen to my right have said have registered upon your consciousness and I need not repeat many of the points that they have made, with which I agree. I would like to cut to the chase and talk specifically about the space resource value of the Moon, both locally and for external use.

First of all, let us take the case of local use of lunar resources on the Moon. The most elementary use is simply to take lunar dirt and use it as radiation shielding for human habitats on the surface of the Moon. The radiation environment is very challenging in space, and indeed, it will be very challenging on the way to Mars and back. On the surface of the Moon, we have that unprocessed lunar dirt, ilmenite, available as a radiation shielding.

We also have the various minerals that contain oxygen on the surface of the Moon. I would say that it would be actually quite feasible to design and build a device for extracting oxygen-bearing minerals and extracting the oxygen from them in an unmanned lander starting today. The technologies are well-understood for many of these schemes. I would not pretend to know which is the best scheme, but I would claim there are approximately a dozen competing schemes, any one of which may be made to serve under these circumstances. The extraction of oxygen from the surface of the Moon would be principally useful for making life-support materials and rocket propellant for local mobility on the Moon.

Local mobility, you often think of rovers running around on the surface of the Moon. I think in terms of devices that have the ability to hop over obstacles. If you want to get around anywhere besides on the Mauri bottoms of the Moon, you would probably need to have that ability to take off and land. Being able to manufacture rocket propellants in situ on the surface, the Moon would be a great advantage for that kind of functionality. Also, that oxygen's available for the return of human beings and of samples to Earth, and plays a very important role there.

The urgent scientific goals that Dr. Spudis talked about concerning the history and evolution of the Moon contain many issues that could be closely linked to the science we need to know in order to design these processing and extraction experiments. The science is urgent. There is much unfinished scientific business on the Moon, and the best question I could raise at this point is how can those resources assist in the developing, understanding, and exploration of the Moon. Mobility is very high on my list of reasons why local resource utilization is valuable.

I should also point out that once you have the chemistry to extract oxygen from minerals, such as ilmenite on the surface of the Moon, they leave behind a residue that contains ultra-high purity iron metal. Ultra-high purity iron metal is not usually thought of as a first generation product, but the, so to speak, slag from the oxygen extraction process, will contain many percent by weight of ultra-pure iron, and that ultra-pure iron has the unusual feature that it has the chemical resistance, corrosion resistance, and strength of stainless steel, so it is an ideal material for use in fabricating anything from wires to habitats on the surface of the Moon.

Now I would like to address the issue of export of lunar resources to Earth. Many of these resources have been extensively mentioned, in very different contexts usually with very little cross-reference. One of these is helium-3 extraction for uses of fusion fuel on Earth. There are a number of issues involving that characterization of helium-3 that Professor Swindle will be addressing in his remarks, and I will tell you in advance, unless he has changed his testimony, I have read and approve of the remarks that he will make on that subject and will not duplicate them now.

There are many science issues involved in characterizing that helium-3 occurrence and in extraction of it. I, frankly, am quite skeptical whether it can be made to be economical, but I don't know. We don't have the answers to those questions yet, and many of those fundamental questions can be answered relatively inexpensively by cleverly designed scientific missions in the regions of the Moon that human beings are likely to visit anyhow, in the Mauri basins of the nearest sunlight.

Water from the polar deposits on the Moon—let me say that I am far from convinced that this has any economic significance whatsoever. Even if we had high concentrations—higher concentrations of water ice than has been suggested by the experiments to date, we would find ourselves in the very difficult position of mining in total darkness at a temperature less than 100 Kelvin, 100 degrees above Absolute Zero, in virtually inaccessible places in crater bottoms near the poles. If something goes wrong there, how do you fix it?

Will something go wrong there? One: mining permafrost under any circumstances, even here on Earth, is extremely demanding. The Army Cold Regions Research Engineering Laboratory has books and books on what you do with permafrost, and piece of advice number one is if it is there, leave it alone. Mining permafrost is extremely difficult. We are talking here about a mixture of abrasive glass particles frozen in a frozen ice matrix that is so cold that it has the strength of granite or of steel. Mining that stuff is not easy. Second, the mining equipment we will be bringing from Earth is made of metal, and metals at 100 Kelvin tend to be as brittle as glass. So I find this to be an extremely daunting series of technological issues, and I am far from willing to endorse the economic potential of lunar polar ice at this time. On the other hand, I have learned—I think I learned in kindergarten—that there are things I don't know, and when new information comes along, I may be willing to change my mind. Let us go after that critical information. Let us characterize those deposits. The scientific value of knowing what is in those lunar polar ice deposits—I say ice here as an assumption. I think it is probably mostly water ice, but I can't prove it. The other materials in there are tracers of the common asteroid bombardment history of the Moon, and may have considerable scientific interest in their own right.

The third item for import from the Moon is solar power. This has been discussed by Professor David Criswell of the University of Houston. He proposes manufacturing solar cells on the surface of the Moon and beaming electric power from those solar cells down to Earth. The up-front investment for this is gigantic and daunting, but it appears that once the system is installed, it might be economically feasible. And indeed, the chemical processes needed to manufacture those solar cells on the Moon seem plausible from present knowledge, and I would strongly recommend that the Committee think in terms of looking further at that technology.

The broader significance and utility of lunar resources and solar system exploration, I would boil down to a three-point argument here, sort of starting with a left jab. The Moon is not halfway to Mars. The Moon is not even on the road to Mars. If we imagine the Dutch sitting around in the 17th Century trying to decide whether to trade in the East Indies or the West Indies, they did not decide to go to New Amsterdam and set up a base for trading with Indonesia. They decided to go to both places. And I sincerely hope that in the wisdom of this committee, they will understand that both of these goals are worthy and they aren't necessarily closely linked.

Further, I should point out that the Dutch, when they went to New Amsterdam, did not come here to settle and colonize all of North America. One fact, if you have a vehicle departing from

Earth to travel to either the Moon or Mars, that vehicle can deliver more payload to Mars if it goes direct to Mars than it can if it just lands on the Moon, because of the energy cost of landing on the Moon. The notion of landing on the Moon in order to refuel in order to go to Mars makes absolutely no sense.

And I guess the—there are certain common technologies that I would strongly recommend for exploration that support both lunar and Mars missions. One: lowering launch costs. This can be done by using some of the new technology launch vehicles that are out there on the market. Lowering those launch cost supports the most innovative segments of the Earth-space industry, and is a highly desirable thing because it makes the missions approximately 10 times as affordable as they are now.

Number 2: use local resources locally, and I am referring here to lunar resources used on the Moon where they are high utility, and on the way to Mars, near-Earth asteroids, Phobos and Deimos, Martian satellite resources, or Martian resources may be extremely useful.

And finally, a great value would be an appropriate transportation system architecture to provide maximum accessibility to the Moon and Mars that would involve a refueling station in a highly eccentric Earth orbit, from low-Earth orbit ranging out to approximately the Moon and back. That might serve to be a location where lunar oxygen could be accumulated for use to service Mars missions, and although I can't promise that that will work out economically, that is far more attractive than the other scenarios for staging missions to Mars from the Moon.

Mars need not wait for the Moon. And the basic science and the technology testing needed to develop these resource extraction schemes can be begun immediately without having to wait for human beings on the Moon. So the possibility that a commercial oxygen generation plant on the Moon could be there when the first men land should be considered.

Thank you, Mr. Chairman.

[The prepared statement of Dr. Lewis follows:]

## PREPARED STATEMENT OF JOHN S. LEWIS

### Abstract

Use of materials native to the Moon can play an important role in facilitating both unmanned and manned exploration of the lunar surface, most notably in the form of oxygen extracted from lunar minerals for use in life support and rocket propellants. Lunar metals may also play a valuable role in local construction activities.

Lunar resources are of no obvious utility for other exploration activities, such as missions to Mars. In general, the prospects for economically sensible export of lunar-derived commodities are limited by the unattractive composition of the lunar surface and the substantial energy requirements for landing on and taking off from the Moon.

The three lunar commercial options that seem most plausible are the collection and transmission of solar power to Earth, the extraction of helium-3 as a fuel for terrestrial fusion power plants, and manufacture of rocket propellants from lunar polar ice deposits. All three of these schemes require substantial fundamental scientific and engineering research in the lunar environment before their economic potential can be fully assessed. At the moment, lunar Solar Power Stations appear to be the most promising of the three.

Chairman Rohrabacher, Members of Congress, ladies and gentlemen: It is my pleasure to offer some remarks concerning the role of the Moon and its mineral resources in the future pursuit of lunar science and exploration. I shall also address the potential role of lunar resources in support of wider human exploration of the Solar System, and their potential economic importance to Earth.

The resources of nearby space can be exploited for two major purposes; either for local use in space, or for return to Earth. The most immediate utility of lunar materials lies in their use to support manned and unmanned activities on the lunar surface and to facilitate the return of astronauts and scientific samples to Earth. The easiest such scheme to implement would be that requiring the least-complex handling and processing. Even raw, unprocessed lunar surface material can be readily utilized to provide radiation shielding for lunar camps and base modules.

Most lunar resource utilization schemes, however, entail both the beneficiation (extraction and enrichment) of specific ores and their chemical processing. A variety of extraction schemes and target ores have been suggested. It is premature to select the "best" targets for extraction, but it is already clear that as many as a dozen different proposed schemes for extraction of oxygen from lunar minerals may be practical. Oxygen makes up 90 percent of the mass of the high-performance hydrogen/oxygen propellant combination. Even if hydrogen propellant for use on the Moon were imported from Earth, the energy requirements for delivery of propellants to the Moon would be reduced by a factor of ten. In any return to the Moon, it would be a serious oversight to ignore the great benefits of lunar oxygen production for providing both life-support materials for crews on the Moon and propellants for lunar-surface mobility and return to Earth.

Demonstration, and even practical use, of oxygen extraction technologies need not wait for human presence on the Moon. Lunar-derived propellants can play valuable roles in providing mobility for unmanned missions on the lunar surface (using brief rocket firings to hop over obstacles) and in returning scientific samples to Earth. It is possible to envision small processing units, dealing with kilogram quantities, on automated, unmanned spacecraft carrying out mineral extraction and processing at a low level of complexity. Such an experiment might, for example, react hydrogen gas brought from Earth with lunar minerals containing iron oxides to extract water vapor from them, leaving behind a residue containing high-purity iron metal. Electricity generated from sunlight by means of photovoltaic cells would then be used to separate water into hydrogen and oxygen by electrolysis. The hydrogen would be recycled, and the oxygen accumulated for use. Successful demonstration of this process would encourage scaling the equipment up to ton quantities to serve the need of a manned expedition or base, and would as a bonus permit recovery of ton quantities of ultra-pure iron metal from the extraction residue. That metal, which exhibits the strength and corrosion resistance of stainless steel, could be used for fabrication of beams and girders, nuts and bolts, wire and cables, and even the shells of habitat modules. Technologies for the extraction and purification of iron could be based on the gaseous carbonyl (Mond) process, which has over a century of industrial use on Earth.

One especially interesting lunar resource is the sunlight that impinges on its surface. Prof. David Criswell of the University of Houston has proposed that solar cell "farms" deployed on the lunar surface could collect vast amounts of solar power, convert that power into electricity, and beam that power back to Earth as microwave beams. Criswell argues that the installation cost of such a system could be slashed dramatically by fabricating its principal components on the Moon from lunar materials. A variety of chemical schemes for manufacturing solar cells, wire, and other system components have already been explored, and small-scale testing of these processes could be started at an early date. It is my opinion that the brightest prospect for profitable export of any commodity from the Moon to Earth is power from such a Lunar Solar Power Station.

Export of actual lunar materials for use elsewhere, especially on Earth, has rarely been suggested because of two major deterring factors. First, the overall composition of the lunar surface is strikingly similar to that of the slag discarded in metal smelting operations on Earth. Few native lunar materials may be of sufficient abundance, accessibility, and value to merit their extraction and export. Second, the gravity field of the Moon, although substantially less than that of Earth (an escape velocity of about a quarter of Earth's and a surface gravity about one sixth of Earth's) is still quite substantial. Given the propulsion requirements for escape from the Moon and return to Earth, and the complete absence of ready-to-use propellants on the Moon, the cost of retrieval of lunar materials is certain to be very high, rendering the return of almost any lunar-derived product to Earth prohibitively expensive. Of the materials known or suspected to exist on the Moon, only one appears to offer any hope of economic benefit: that is the isotope helium-3, a potential fuel for fusion reactors. I have reviewed Prof. Swindle's testimony on this subject and concur with his assessment that many questions (such as the actual abundance, distribution, and recoverability of helium-3 on the Moon and the feasibility of commercial fusion reactors) need to be answered before we can conclude that helium-3 extraction from the Moon is economically sensible. A renewed program of lunar exploration must address these scientific and technical unknowns. Much of the needed research can be done by unmanned missions.

A second lunar resource, ice from permanently deep-frozen crater bottoms near the lunar poles, has also sometimes been suggested as appropriate for export either to the lunar equator or to space stations or vehicles off the Moon. I regard this suggestion with deep skepticism because of the immense technical difficulty of mining steel-hard and highly abrasive permafrost under conditions of permanent darkness, at the bottom of steep and rugged craters, at temperatures so low that most metals in the mining equipment are as brittle as glass. Further, the location of the hydrogen-bearing deposits (almost certainly dominated by water ice) at the poles is the most remote from sensible locations for a lunar base of any place on the Moon.

The lunar ice deposits are of great scientific interest for the stories they can tell about comet and asteroid bombardment of the lunar surface. Scientific investigation of these deposits need not, and arguably should not, involve human presence. With such composition data in hand, and with a greatly improved knowledge of the extent, concentration, and purity of the lunar ice, a more realistic assessment of the utility of these deposits could be made.

Specifically, the use of lunar-derived propellants, whether oxygen extracted from iron-bearing minerals such as ilmenite and olivine or hydrogen and oxygen made from polar ice, to support expeditions to Mars makes no logistic sense. The Moon is not "between" Earth and Mars; it is a different destination, poorly suited to function as a support base for travel to Mars. Water extraction from the martian moons Phobos and Deimos or from near-Earth asteroids may offer great advantages to Mars-bound expeditions, more profound than lunar water could even if the Moon had no gravity to fight. In any location, development of extraction and fabrication technologies should, like low-cost space launch services, be conducted as a commercial endeavor.

There are clear advantages to the use of lunar resources in support of both manned and unmanned activities on the Moon. Direct benefits to Earth from lunar resource exploitation are certainly conceivable, but will remain conjectural until substantial further research on *in situ* fabrication of solar cells and on the abundance and distribution of helium-3 and polar ice has been done on the Moon.

### BIOGRAPHY FOR JOHN S. LEWIS

John S. Lewis is Professor of Planetary Sciences and Co-Director of the Space Engineering Research Center at the University of Arizona. He was previously a Professor of Planetary Sciences at MIT and Visiting Professor at the California Institute of Technology. His research interests are related to the application of chemistry to astronomical problems, including the origin of the Solar System, the evolution of planetary atmospheres, the origin of organic matter in planetary environments, the chemical structure and history of icy satellites, the hazards of comet and asteroid bombardment of Earth, and the extraction, processing, and use of the energy and material resources of nearby space. He has served as member or Chairman of a wide variety of NASA and NAS advisory committees and review panels. He has written 15 books, including undergraduate and graduate level texts and popular science books, and has authored over 150 scientific publications.

Chairman ROHRABACHER. Well, thank you. And I know there will be more discussion. And our final witness is Dr. Timothy Swindle from—he is a Professor of Geosciences and planetary Sciences at the University of Arizona. Dr. Swindle, you may proceed.

## STATEMENT OF DR. TIMOTHY D. SWINDLE, PROFESSOR OF GEOSCIENCES AND PLANETARY SCIENCES, UNIVERSITY OF ARIZONA.

Dr. SWINDLE. Here we go. Thank you. Chairman Rohrabacher and Members of the Committee, and ladies and gentlemen, thank you for the invitation to talk about issues regarding lunar science and lunar resources. Today, I wish to address one very good science reason to go the Moon, and one proposed lunar resource that would be very difficult to utilize.

First the science reason: we can go to the Moon to learn about the environment on the early Earth at the time when life was forming. Furthermore, much of what we can learn about the Earth from the Moon, we cannot learn from the Earth itself. One of the dominant processes occurring on the Moon is—has always been the impact of comets and asteroids. The large circular dark features that you can see from Earth without a telescope are lava flows that fill basins, which were formed by impacts larger than any that have occurred on Earth in the three billion years. Surprisingly, the vast majority of Moon rocks formed by these big impacts are virtually the same age, not quite four billion years old. We don't know whether that is because the last one or two or five of these impacts plastered the limited region that we sampled with Apollo, or whether there really was a half a billion years before that, where there were relatively few impacts. There are older Moon rocks, though not formed by impacts. To solve this puzzle, we would need to go back to the Moon and carefully select certain rocks from areas that we didn't visit before. So why is that interesting?

The last well-dated impacts on the Moon are about the same age as the oldest rocks of any kind on Earth, which is also the time when the first evidence for life on Earth appears. Since Earth has nothing more than fragments of any rocks older than this, learning anything about what happened on Earth before then from the terrestrial record will be very difficult. However, we can learn how many impacts the Moon was suffering before this, and even something about whether these impacts were comets or asteroids. And if we know what was hitting the Moon, we instantly know something about what was hitting the Earth. Since if the Moon was taking a pounding, the Earth was getting hit by the same kinds of things, only by more of them.

These could have provided the water or the organic materials for life, or their impacts could have continually frustrated the start of life on Earth. Learning about the Moon, we learn about the Earth. However, we need carefully selected rocks from the Moon, and by far the best way to do that is to send humans. During the Apollo missions, the astronauts looked at far more samples than they brought back, and they judiciously chose what were almost the best samples they could have. Robotic technology, unfortunately, is still far from being able to separate out the subtleties that a human easily can.

Now, let me switch gears and talk about something very different, a suggested lunar resource. As Professor Lewis mentioned, it has been proposed that we should go to the Moon to mine helium-3 as a fuel for clean burning fusion reactors. Helium, and particularly helium-3, is extremely rare on the Earth. Heilum-3 makes up less than one-trillionth of our atmosphere. It is somewhat more abundant on the Moon. That is because the solar wind, the flow of particles expelled by the Sun, includes quite a bit of helium-3. The solar wind hits the Moon's surface, it gets implanted into the outer ten millionth of a meter of grains that are at the very surface of the lunar regolith or the lunar soil.

Small impacts then stir this regolith so that the helium-bearing grains on the surface get mixed to greater depths. We know quite a bit about the distribution of helium-3 on the Moon, but two things we don't know are how deeply those grains from the surface get mixed down, and whether the fact that the Earth's magnetic field can shield parts of the Moon's surface from the solar wind at certain times will make a difference at some spots. These two rather small uncertainties make a difference of a factor of ten in our total estimates of the amount of helium-3 on the Moon.

We do know this, though, mining helium-3 from the Moon would be a massive, difficult operation. At the most promising locations, helium-3 makes up no more than about one part in 100 million, and it is almost exclusively found in the upper ten meters of the regolith, perhaps the upper three meters. Thus, to mine one ton of helium-3 per year, which one group suggested as a goal to fuel a working fusion reactor, we would have to move 100 million tons of dirt, which is comparable to some of the largest terrestrial mines. It is difficult to imagine this being a robotic operation. The minimum amount of the Moon that would have to be mined to match that one ton a year is about seven square kilometers per year, and it wouldn't take very many years to mine enough of the Moon that you could see the Moon—the mine from Earth with binoculars.

I would stress that at present, a full assessment of the feasibility of mining helium-3 is far cheaper and simpler than actually trying to mine it. The assessment would include learning more about the lunar regolith at various depths at various locations around the Moon, determining the relative value of helium-3-based fusion reactors, the cost of other potential sources of helium-3, not to mention developing and testing mining techniques. Also, I would point out that there are many other lunar resources for which extraction would require far less ambitious projects.

So, my three main points: First, the Moon holds valuable clues as to the early history of the Earth at a time when life was forming. Second, helium-3 is a potentially valuable resource, but extracting it from the Moon is a difficult process. There should be more basic assessment before attempting to implement anything. And finally, the work I have talked about will be accomplished far more easily with humans on the Moon than without.

Thank you.

[The prepared statement of Dr. Swindle follows:]

## PREPARED STATEMENT OF TIMOTHY D. SWINDLE

Chairman Rohrabacher, Members of the Committee, ladies and gentlemen: Thank you for the invitation to talk about issues regarding lunar science and lunar resources. Today, I wish to address one topic in each. First, we are beginning to understand that lunar science is important because the Moon contains clues to the earliest history of Earth, perhaps even of the start of life on Earth. Second, there are aspects of fundamental lunar science that we need to understand better to be able to assess whether it would be worthwhile to try to exploit the Moon for certain resources that might be used on Earth. In specific example of helium-3, while it is clear that it is a prodigious undertaking, we need more information to know the real magnitude of the task.

The first evidence of life on Earth comes in rocks that are approximately 3.8 billion years old. The evidence is ambiguous, and it is unlikely that we will be able to use terrestrial rocks to learn much more about what was happening then, or earlier, because there are so few rocks this old or older. Could we use the Moon to understand what was going on on Earth?

The large circular dark features on the Moon that we see from Earth are dark lava flows that fill basins, which were formed by impacts larger than any that have occurred on Earth in the last three billion years. Perhaps surprisingly, analysis of the rocks returned by the Apollo program showed that the vast majority of impact-derived rocks are roughly the same age, between 3.8 and 4.0 billion years old. Few are younger than 3.8 billion years old; none are older than 4.0 billion. Although a number of rocks older than 4.0 billion years were brought back, extending back to the age of the Moon itself nearly 4.5 billion years ago, none of the older rocks were the types formed in large impacts.

Two possibilities have been suggested to explain the tight clustering in ages of the impact rocks from the Apollo collection. One is that the Moon actually had not had many, if any, large impacts in the previous 0.5 billion years, and then had a cataclysmic bombardment. The biggest problem with the idea of a late cataclysm is that we do not understand where the objects causing the bombardment could have been stored for that length of time before suddenly being released on the inner Solar System. The other possibility suggested is that there were many large impacts all along, but the rocks formed in the earlier impacts were all destroyed in the final few impacts, the terminal portion of this heavy bombardment. The biggest problem with the idea of a terminal heavy bombardment is the difficulty with destroying the old rocks produced in impacts while leaving intact many other rocks formed in that same period.

The question of the early impact history of the Moon has important implications for the early history of Earth. If the Moon suffered several large impacts in any given period of time, Earth probably suffered many more, since Earth is nearby (in solar system terms), but larger. This is probably why we find no intact rocks on Earth older than the time of the final basin-forming events on the Moon, whether it was a cataclysm or a terminal heavy bombardment.

Assuming that the lunar basins were only the last in a continuous string of large impacts, the end of a heavy bombardment, some scientists have suggested that there was an “impact frustration” of life. Life may have arisen long before the first evidence we find, and perhaps may have even begun more than once, but was wiped out, or “frustrated,” as one impact after another hit the Earth with enough energy to boil the oceans. In this scenario, life began on Earth virtually as soon as it became possible.

On the other hand, if there was a cataclysmic bombardment, then there may have been a long, relatively peaceful period on Earth in which life could have started. In this scenario, life might have been more abundant when the cataclysm began, but it could only have survived in some niches away from the oceans and away from the Earth’s surface. There are some primitive organisms even today that might be suitable candidates for such survival. In this scenario, it is also possible that it took hundreds of millions of years of clement conditions for life to start, reducing the chances of finding life on a planet like Mars, whose climate was only pleasant for a brief period of time.

These two alternatives provide fundamentally different expectations about the formation of life on Earth, and its likelihood elsewhere.

There is also the question of where and when Earth got its water. Water is crucial for life as we know it, but in many models of the formation of the Earth, the planet formed from material that would have lacked water because that material came from too close to the Sun. Hence, the water may have been added at some later time by the impacts of comets or water-rich asteroids. There are few clues available on Earth to address these questions, but the Moon does contain clues. The rocks formed in lunar impact basins often contain rare elements that can serve as tracers for the bodies that impacted. As we learn more about the compositions of more of the bodies that impacted the Moon, we learn more about the bodies that impacted Earth, and hence we learn more about how much material of what kind was added to Earth, and when it was added.

Although we continue to try to address these problem in a variety of ways, we are hampered by the fact that the only lunar rocks we have from known locations are the Apollo samples, and the Apollo samples all come from a rather restricted region on the near side of the Moon where the more recent basin-sized impacts occurred. One of the arguments for going back to the Moon is to try to decipher the Moon’s early impact history by studying rocks from a variety of known locations that are not near the latest basins. We can do this robotically, and it would be a great improvement over the suite of samples currently available, but having humans present is far superior. During the Apollo missions, the astronauts looked at far more rocks than they returned, and judiciously chose what were almost certainly the best samples available. Robotic technology is still far from being able to separate out the subtleties that a human easily can.

Exactly how and when life started on Earth is one of the great scientific questions of the 21st Century. Understanding the history of the bombardment of the Moon will not tell us how life started on Earth, but it will tell us far more about what the conditions were on Earth when life did start. Furthermore, the record stored within the rocks on the Moon is of times and events whose record no longer exists on Earth.

Going from the distant past to the near future, understanding basic lunar science is also crucial to understanding whether certain ideas for using lunar resources are even feasible, much less how to implement them. As an example, Gerald Kulcinski, Harrison Schmitt, and co-workers have proposed the use of the rare helium-3 from the Moon as a fuel for clean-burning fusion reactors.

Helium, and particularly its lighter stable isotope helium-3, is rare on Earth. Helium is light enough that any atom currently in the atmosphere is likely to escape from Earth's gravity at some time over the next million years or so. Earth's atmosphere is gaining some helium from Earth's interior or by trapping it from space, but it is in tiny amounts, only about 10 kg per year: helium-3 is less than one part per trillion of the atmosphere by mass, and extraction is clearly extremely difficult.

There is, however, a body in the Solar System with huge reserves of helium-3—the Sun itself. The Sun contains a total of about $1.4 \times 10^{26}$ kg of helium-3, a larger mass than the entire mass of the Earth. Going to the Sun to get that potential fuel is far beyond our presently imagined capabilities, but the Sun expels some of its outer layer in a rather steady flow of particles, the solar wind. The solar wind flux at the distance of the Earth from the Sun is about 0.005 g of helium-3 per $km^2$ per year. The Earth's magnetic field deflects virtually all of this solar wind, but the Moon has no magnetic field or atmosphere of its own, so the solar wind is implanted into the surface of the Moon, except during the portion of the month when the Moon is shielded by the Earth's magnetic field.

Kulcinski and Schmitt have suggested the possibility of mining the Moon for helium-3, and have suggested one ton per year as a target amount. In 1990, I was part of a group at the University of Arizona that evaluated the potential of this idea. We considered how much helium-3 the Moon actually contains, how well we know that amount, and how we might mine it. Although there have been some advances in lunar science since then that have caused us to revise our estimates slightly, we still have not been able to learn anything more definitive about the two most critical parameters, the distribution of helium-3 with depth in the lunar regolith and the distribution of helium-3 with location on the Moon. Our estimates of the total helium-3 contained in the lunar regolith (the lunar "soil") ranged from 450,000 to 4.6 million tons, based just on plausible variations in these two factors.

The amount varies with depth within the regolith because solar wind is implanted only 0.1 to 0.2 microns deep (a micron is one millionth of a meter). Small impacts stir the regolith, so that helium-bearing grains on the surface can get mixed to greater depths. However, models of regolith formation predict that the amount of solar wind should generally decrease with depth, because deeper layers should have fewer grains that have spent time at the surface. At present, we have no samples from any deeper than three meters (the depth of the longest drill core taken by the Apollo astronauts), and the predicted trend is not really seen. If the abundance changes little with depth to the bottom of the regolith (typically 10 to 15 meters), then approaches to mining helium-3 would clearly need to be different than if the helium-3 is concentrated in the upper two to three meters.

The amount of helium-3 varies with location as a result of two factors, one of which we understand, and one of which we don't. One factor is the chemical composition: helium atoms are so small, and so light, that they can escape from many minerals, even if they are implanted. Some minerals will retain less than one percent of the helium-3 implanted. By far the best, in terms of retention, is the mineral ilmenite, which also happens to be the mineral that contains most of the element titanium on the Moon. Hence, by mapping the abundance of titanium (something that has been accomplished by orbiting spacecraft), we can predict where helium might be retained well.

The other factor is the amount of helium received. Since Earth's magnetic field shields the Moon from the solar wind during part of the month, the portion of the Moon facing the Sun at that time each month (the Near Side of the Moon) is exposed to less solar wind than the portion of the Moon that faces the Sun when the Moon is not within Earth's magnetic field. But even though some portions are exposed to more solar wind, we do not know whether they actually receive more—it is possible (and has been suggested, based on some experiments) that individual grain surfaces become saturated, reaching a state where no more can be implanted, even if the surface is exposed to more solar wind. By far the best way to test this is to analyze samples from a variety of locations on the Moon, which we cannot do at present.

We also need to know more about the general properties of the lunar regolith if we are going to attempt to mine the Moon for helium-3. For example, a mining engineer would clearly need to know how common intact rocks are, and what sizes they are likely to be, as one moves deeper into the regolith, and if and how the properties of the deeper regolith differ from those of the surface layers studied by the Apollo missions.

It is worth noting that in any scenario, mining helium-3 from the Moon will be a massive, difficult operation. Even with our most optimistic estimates of the abundances and distribution, we found that at the most promising sites, helium-3 makes up only one part in 100 million of the regolith (by mass), so extracting one ton of helium-3 would require mining 100 million tons of regolith, even if the extraction were perfect, which it will not be. This is comparable to the annual work of some of the largest terrestrial mines. Adding in the fact that only the top few meters of the regolith contain any helium-3 at all, to mine one ton per year would require digging up seven square kilometers of the Moon's surface each year, at the most promising site under the most optimistic set of assumptions, so it would not take many years for the mine to become large enough to be visible from Earth with even a small pair of binoculars. Although massive mining operations are increasingly mechanized, humans are still the best way to make decisions, diagnose equipment problems, and make repairs.

There are several other potential resources, most notably oxygen, whose extraction would require far less ambitious mining projects. However, they typically share the common property that we would need to know more about the basic science of the lunar regolith to be able to properly implement them, or even to properly evaluate their potential.

Once again, while it is certainly possible to imagine ways to attack these basic science questions robotically, it would require a level of sophistication far in advance of any mechanisms yet launched into space, though well within the reach of human-conducted exploration. Furthermore, in the case of helium-3, it is worth stressing that at present, a full assessment of the feasibility is far cheaper and simpler than an attempt at implementation.

In summary, the Moon holds valuable clues to the early history of Earth, at the time when life was forming, and may hold valuable resources for the future of Earth. But to evaluate either properly, there is lunar science that would need to be done, and the way to do that lunar science best is with human beings.

### BIOGRAPHY FOR TIMOTHY D. SWINDLE

Dr. Timothy D. Swindle is a Professor of Planetary Sciences and Geosciences at the University of Arizona. He received a Ph.D. in Physics from Washington University in St. Louis in 1986. Prof. Swindle's main area of research has been using the noble gases, such as helium, argon and xenon, to study meteorites and lunar samples. His lunar work has included studies of the impact bombardment history of the Moon and the incorporation of gases into the lunar regolith. His current research emphases are on the chronology of the Moon and on constructing instrumentation to be used on robotic spacecraft to determine the ages of rocks on bodies where human exploration is not yet possible.

## DISCUSSION

Chairman ROHRABACHER. Well, thank you very much. We have just been called to a vote, and so what I would suggest is if we took the vote and then come right back and begin the—I think it is one vote—come back and conduct the questions right afterwards.

Mr. FEENEY. Mr. Chairman, with your indulgence, I am going to have go to the White House after this. I appreciated all the testimony, and I would like to ask some questions now—well, no, I just wanted to leave one simple statement because I am not a scientist by background. But 100 years ago, most people thought that about 98 percent of the surface of Florida was practically unusable so we have got to learn, I think, is what I learned from the witnesses.

Chairman ROHRABACHER. Thank you very much.

Mr. FEENEY. But that was before air conditioning, which is just as vital in practical terms as water and oxygen to humans in Florida, anyway.

Chairman ROHRABACHER. All right. We have several major issues to discuss, and so when we come back, we will get right to them, and this committee is in recess for 15 minutes.

[Recess.]

## HELIUM-3

Chairman ROHRABACHER. All right. This hearing is called to order. Thank you very much for waiting. We have had some very fine testimony today. I would like to ask the panel a question. For those who would like to, several panelists have mentioned helium-3. Isn't it the case that helium-3 has no value now and we are only talking about something that has value if it is—if we can perfect fusion energy? Is there some other value that I am missing there? So, please feel free to jump in.

Dr. SWINDLE. I would agree with that assessment. The fusion reactors are coming, perhaps, but perhaps. They are not there yet.

Chairman ROHRABACHER. I would say a big perhaps. I will let you know.

Dr. SWINDLE. And there is no other reason to mine helium-3 that I have heard suggested.

Chairman ROHRABACHER. All right. Dr. Lewis, is that—does anyone disagree with that assessment? Nobody disagrees with that assessment.

Dr. LEWIS. Mr. Chairman?

Chairman ROHRABACHER. Yes?

Dr. LEWIS. We shouldn't discount fusion reactors. It is a perpetual truth that they are 30 years away.

Chairman ROHRABACHER. And they always will be.

Dr. LEWIS. It has been true since 1960.

Chairman ROHRABACHER. Right.

Dr. LEWIS. But there is an interesting application, which is that when a new fusion reactor is first built, during the test runs of it, they use helium-3-deuterium mixtures to test the reactor because that fuel combination is very clean. It doesn't induce radioactivity in the reactor, but that is not a commercial-level activity. That is done in very tiny quantities.

## SOLAR ENERGY ON THE MOON

Chairman ROHRABACHER. Yes. Several years ago, I made a study of how successful we have been in developing fusion, and I came to the conclusion that it is the least successful of all of our scientific endeavors was trying to—but it promoted—but it actually employed more people with less success than any other of our scientific endeavors. Also, we are talking about the concept of solar power on the Moon. I believe Mr. Lewis was talking about that, and beaming energy—this is something that I think has much more potential than fusion energy.

Dr. LEWIS. That is correct if we are talking about economic impact on Earth on a foreseeable time scale. Fusion energy could be made to work at any time, and then might become a big player, but the Sun does exist. We do know how to make electricity from it. We do know how to convert that electricity into microwave power. And, I would strongly recommend that at the very least, your staff get in contact with Professor David Criswell at——

Chairman ROHRABACHER. Well——

Dr. LEWIS.—the University of Houston and——

Chairman ROHRABACHER. Oh, yes.

Dr. LEWIS.—get his slant on this.

Chairman ROHRABACHER. Why would it be better to have the solar system on the Moon rather than orbiting?

Dr. LEWIS. The advantages and disadvantages pile up pretty much like this: if you install the—a system in, say, geosynchronous orbit around the Earth, that system has to be lifted in its entirety from the surface of the Earth. But, if you install the system on the surface of the Moon, you can make the structures and the solar cells themselves out of local lunar materials, so you don't have to transport nearly as much mass. You bring up a small factory.

Chairman ROHRABACHER. And——

Dr. LEWIS. However, there is a downside.

Chairman ROHRABACHER. Okay.

Dr. LEWIS. The downside is that to get that power back to the surface of the Earth, you need a much larger transmitter on the Moon than you do in geosynchronous orbit, so that would have to be made out of lunar resources, and that means you would need a fairly large-scale up-front industrial base on the Moon to manufacture these items. If you see your way through that up-front cost in installing such a system, then the economy of the system seems hard to avoid. It is just that the up-front investment is enormous.

Chairman ROHRABACHER. Enormous as in billion?

Dr. LEWIS. Oh.

Chairman ROHRABACHER. Tens of billions?

Dr. LEWIS. Tens of billions.

Chairman ROHRABACHER. Hundreds of billions?

Dr. LEWIS. Yeah.

Chairman ROHRABACHER. No, not hundreds.

Dr. SWINDLE. Could I make a comment on that?

Chairman ROHRABACHER. Yes, sir.

## IN SITU RESOURCES

Dr. SPUDIS. It is certainly true that when Dave Criswell talks about this concept, he is envisioning giga-watt production for use, basically, to electrify and industrialize the third world, and that is certainly the goal of this. But you could start with doing proof-of-concept and demonstration experiments with a very minimal return to the Moon. For example, Professor Alex Ignatiev from the University of Houston has developed a miniature rover that rolls around and actually manufactures amorphous silica solar cells in situ from lunar soil, and this has actually been built and is in test demonstrations. So you could land a robot payload on the Moon, develop—let us set it out. Let it make solar cells, connect them together, and demonstrate that the concept is feasible without investing billions of dollars in industrial infrastructure. So you can start small and then ramp up as you get more.

Chairman ROHRABACHER. And you could do that with a robot—totally robotically?

Dr. SWINDLE. That is what he is looking at right at the moment, but that is just an initial test. It is not a production phase.

Chairman ROHRABACHER. All right. Any one else want to jump back or back——

Dr. LEWIS. Yes, just let me point out that there will be substantial power demands for a lunar base.

Chairman ROHRABACHER. Yes.

Dr. LEWIS. And there is no reason why one couldn't start with a facility of this sort to power the lunar base and then later add the ability to transfer part of that power to Earth.

Chairman ROHRABACHER. Okay. And we also had a suggestion that we could land some type of equipment on the Moon that would then be able to produce, I guess, a fuel from hydrogen so that once people got there, they could refuel. They would have a refueling operation that would be ready to go, or already operating. Now, who is it that suggested that? Somebody suggested that, or maybe I was just thinking that.

Dr. LEWIS. I mentioned it. You know, oxygen extraction from the Moon is the big attraction. The hydrogen——

Chairman ROHRABACHER. What about hydrogen?

Dr. LEWIS. The hydrogen concentration on most of the Moon is very low, so that you run into sort of a pale version of the helium-3 problem where you need to process huge quantities of dirt to get the hydrogen out. However, if you are asking—if you are considering a vehicle on the surface of the Moon about to bring a crew of astronauts back to Earth, the propellant that they need is 90 percent by mass oxygen and only 10 percent hydrogen.

Chairman ROHRABACHER. Oh, I see. Okay.

Dr. LEWIS. So one can imagine ferrying hydrogen to the Moon and then beefing that up with a huge quantity of lunar oxygen. One can imagine, in fact, running the rocket engines way over on the oxygen-rich side so that you are using lots of extra oxygen because it is relatively cheap on the Moon.

Dr. SPUDIS. But it is not impossible to extract hydrogen from any place on the Moon. It is just—he is right. It is very low concentration. But, if you have time and you have energy, you can set up a robotic system to roll across the surface and extract what it can and store it and let it operate autonomously, and when it is full, then you can go up and use it as fuel. That is certainly feasible. We are fortunate in the sense that the hydrogen on the lunar dust is put there by the solar wind. The solar wind hits the Moon, it implants these atoms on dust grains. Those atoms come off fairly easily. You have to heat the soil to about 700 degrees Centigrade and that gas comes off and it can be collected and then condensed and liquefied. So it is possible to do this, as long as you are willing to wait. It won't be something you can do immediately, but it is something you can do over a long period of time.

## POSSIBLE RETURN DATES TO THE MOON

Chairman ROHRABACHER. Well, this all is very exciting about then, and let me ask you this. Maybe you can just give me your own concept there, do you—just down the panel. How long do you think, and how much do you think, it will cost us to—before we can get back to the Moon with a human being and have some sort of manned operation on the Moon?

Dr. SPUDIS. Well, technically, there is no reason why we couldn't be on the Moon within five to seven years of the program start. Now the principle reason why the President's proposed initiative takes a slower pace is that the trade there is the difference between money and schedule, that if you fund it at pretty much the current NASA level, slightly augmented and growing with inflation——

Chairman ROHRABACHER. Uh-huh.

Dr. SPUDIS.—then we could be back on the Moon, with robots first in '08, and beyond and people starting as early as 2015, but that is based on the assumption of essentially constant funding, slightly augmented. If you wanted to accelerate that, you could. There is no technical reason why we couldn't be on the Moon within, let us say, 2010. It is possible.

Chairman ROHRABACHER. Is there——

Mr. SPUDIS. It is a money issue.

Chairman ROHRABACHER. Is there any disagreement with the panel on that? Okay, good. Well, I am going to let Mr. Lampson take over, and I may have a few more questions as we move on.

## TIMEFRAME FOR IN SITU RESOURCE DEVELOPMENT

Mr. LAMPSON. How long, Dr. Spudis, would it take, if you say you have time to wait, for the development of that fuel? What were you talking about? Were you talking amount minutes, days, years?

Dr. SPUDIS. Months. Basically, what you would want to do is you would want to set up a rover that was solar powered, basically, so you would only operate during the daytime. So in that scenario, it would operate for 14 days and then basically hibernate during the lunar night of 14 days, and it would basically go back and forth across the soil, collecting solar energy with a passive mirror—solar-thermal—concentrating it like a heating element onto the soil, taking evolved gasses, collecting evolved gasses that come off, and then processing those.

Mr. LAMPSON. So that is the direction in which we want to go, we want to do that pretty quickly——

Dr. SPUDIS. Well——

Mr. LAMPSON. Right?

Dr. SPUDIS.—I am not advocating this. I am saying that it is technically possible. I think the first step to going back to the Moon is to get a better understanding of where the ore deposits are. The problem with the equatorial sites is that those are fairly low-grade ores. The concentration levels are very low, just like Dr. Lewis says. We need to find out what is at the poles. What is going on there? How much is there? Where is it? What is the physical state? And then decide whether that is the answer to the problem or not.

## PRIORITIZATION OF LUNAR SCIENCE

Mr. LAMPSON. How would all of you prioritize the research that we want to do, or should be done on the Moon? I mean, what has the highest priority? Any or all of you?

Dr. SPUDIS. In terms of science?

Mr. LAMPSON. Uh-huh.

Dr. SPUDIS. I think that one of the most intriguing things is what I mentioned in my testimony and that—and also Tim Swindle mentioned too—and that is the impact history of the Earth-Moon system. Fundamentally, the biggest scientific accomplishment of Apollo was an appreciation for the importance of hypervelocity impact. That is something we didn't really appreciate before we went to the Moon, and yet, we found that it is fundamental to the evolution and history of life on Earth. The dinosaurs, for example, went extinct 65 million years ago because of a giant impact, and we now suspect that these impacts may occur occasionally in the geologic record, but we can't verify that because the Earth's record is incomplete. The Moon's record is complete. You can go back and recover and read that record, and it applies to the Earth because Earth and Moon are in the same part of the solar system. Tim, do you have any comments on that?

Mr. LAMPSON. Anybody else have a——

Dr. SWINDLE. No.

Mr. LAMPSON.—different priority or a different set of priorities? That is the most important thing. Are you going to list anything else?

Dr. LEWIS. Yes, the fundamental science that needs to be done to assess these various resource schemes. I would put that in the same list. And, incidentally, the apparatus and the personnel involved in doing those experiments overlap substantially with those who would be doing the basic science that Dr. Spudis is talking about. This is not a separate or conflicting or competing agenda, but it is part of the scientific assessment of the Moon. It is something that can be done substantially with unmanned probes. As I mentioned in my testimony, one can envision even producing tanks of liquid oxygen that would be available, sitting there on the Moon when the first——

## TIMEFRAME FOR A HUMAN RETURN TO THE MOON

Mr. LAMPSON. Much of this can be done robotically. At some point, you have to have humans involved——

Dr. LEWIS. Right.

Mr. LAMPSON.—and do you have a feeling as to when that might be?

Dr. LEWIS. Well, let us just break it into phases. There is a robotic phase where you are learning the basic principles and demonstrating the processes. Then, there is an industrial phase where you are actually doing it on a commercial scale. That first phase could be initiated this year, and could be flying missions within a couple of years. That is not a problem. People have thought a great deal about how to do these things. Many of the instruments involved already exist. The commercial phase, if one has a large liquid oxygen plant on the Moon, let us say just for purposes of concreteness, would almost certainly benefit from being attended by human beings from time to time for maintenance and repair and so on. So I suppose that you could say that within a few short years, we could have the ability to produce that first big commercial batch of oxygen, but beyond that point, you need the people there, A, to maintain the plant, and B, to use the product. And there is a synergism there. I would hate to see the landing of people on the Moon delayed because of inadequate attention to building infrastructure on the Moon to support them.

Mr. LAMPSON. Let me go on one different direction for a minute and we will come back on the—oh, I am sorry. Dr. Swindle.

Dr. SWINDLE. One other thing on the same topic, Professor Lewis was talking about the resource aspect. Let me address the same question from the science aspect which is to say that some robotic missions in terms of addressing the impact history would be very nice, and, in fact, I believe that Dr. Spudis and I are competitors on proposals for such a mission in for launch in 2007? Something like that.

Dr. SPUDIS. Right.

Dr. SWINDLE. And we will learn a huge amount by having a few samples from some places we haven't been. Beyond that, to really make progress, we need to have the advantage of having people who can look and pick up the one rock that you really needed out of that landscape that you can't really with just—even a good camera.

Mr. LAMPSON. Okay. Do you want to go ahead and then we will come all the way back.

Chairman ROHRABACHER. All right. Dr. Bartlett.

## OTHER POTENTIAL LUNAR FUELS

Mr. BARTLETT. Thank you very much. Are there other potential fuels on the Moon, other than hydrogen, that could be exploited?

Dr. LEWIS. Yes. Yes, there are a number, but they all require—they are all at the bottom of deep chemical potential energy wells. They need to be extracted at considerable cost, and part of that cost is in the complexity of the equipment needed to do it. An example would be extracting a metal from the lunar surface, such as aluminum, that can be burned in the oxygen. There are no completely satisfactory schemes for using powdered aluminum in oxygen right now. I have seen some that scare me to death and some that I don't think would work enough to scare me. But, indeed, there is a possibility of extracting metals to be burned with the oxygen. I would say that that research is in a very primitive state. How you would make an autonomous propulsion system on the Moon compared to the state of knowledge of how to extract oxygen.

Dr. SPUDIS. There are two other possibilities. It was looked at in the '80s of using lunar surface sulfur. There is sulfur in the lunar regolith, and that can actually be burned as a rocket fuel. You can actually make solid rockets on the Moon. That was looked at quite extensively by the Los Alamos group back in the early '80s, and that looked feasible. The other thing that we don't yet know about is we—if there is ice in the poles—the dark areas of the poles that was deposited by cometary cores, cometary cones contain methane, and there may be methane, there may be ammonia, in the floors of the polar craters, and both of those can be used as rocket propellant as well.

Mr. BARTLETT. Thank you. In spite of enormous insulation, the Moon is very cold because it is simultaneously radiating to space. If you put a piece of glass over it, of course, the incoming energy ends up, a lot of it, as infrared, which doesn't get back through the glass. What happens to lunar temperature if you put glass over it?

Dr. LEWIS. You——

Mr. BARTLETT. You would get a greenhouse effect, obviously.

Dr. LEWIS. You would get a greenhouse effect, but the numerical answer depends very sensitively on the exact on the exact transmission of the glass, wavelength dependent on transmission.

Mr. BARTLETT. Okay.

Dr. LEWIS. But you can easily bump the temperatures up by, you know, 20, 30 percent, absolute temperatures.

Mr. BARTLETT. It will get them up to habitable temperatures just by the greenhouse effect?

Dr. LEWIS. It will probably be easier to build a habitat and step inside it. Building a glass structure on the Moon invites a—becomes a very sensitive method of determining the rate at which meteoroids are striking the Moon, the rate at which your glass house crumbles. So, yes, you can indeed enhance temperatures that way. One can imagine small devices on the Moon that trap solar energy in that manner. One can also imagine producing electricity by using a device to trap sunlight, boil water, and drive a Ranking cycle generator and so on, but if you are talking about terraforming, trying to make Earth-like conditions on the Moon, the Moon is so utterly un-Earth-like that you better try to do it one square yard at a time, not think about it in terms of a global scale.

## MOBILE SOLAR STORES

Mr. BARTLETT. When you are thinking about transportation on the Moon, obviously the energy source that is continuously available is solar, and it is easy to imagine a solar ATV that goes wherever you can go with a solar ATV. What attention has been given to developing solar kangaroos? Something that just stores the energy and then hops over obstacles when enough has been stored?

Dr. LEWIS. On the Moon? I don't know, ultimately. I don't think a lot of attention has been given to that. It is assumed, in a lot of scenarios that when you go back there, you use solar energy. After that, it gets real fuzzy. Sometimes, you see big arrays that are laid out that are many football fields across and providing megawatts to the lunar base, but ultimately, you have got a problem, that on the Moon, you have got 14 days of night. And, in addition, 14 days of daylight, because it rotates once on its axis every 28 days. So you have to have something to get you through the night anyway. If you decide to go nuclear, then that provides the power that you would need day and night. So you don't have to worry about solar. If you don't go nuclear, you have to think of something else, either sub-battery, which could be very massive, or rechargeable fuel cells, which is the most likely possibility. The other possibility is that if you have established your outpost near the poles, there are areas near the poles that are in near constant sunlight because the Moon spins perpendicular on its axis and the Sun is always at grazing incidence. And in those areas, you could collect solar energy constantly. The problem you have got in all these things is that solar energy is not something that lends itself to powering mobile things. It is very massive. It has a very high kilogram per kilowatt cost. So, if you want to have mobile things that go around to different places to do jobs, you need to have a more concentrated energy source.

### GRAVITY GRADIENT STABILIZATION

Mr. BARTLETT. Is there any gravity gradient stabilization on the Moon?

Dr. LEWIS. On the Moon? The gravity of the Moon——

Mr. BARTLETT. Gravity gradient stabilization.

Dr. LEWIS. Well, if you were—that would be relevant only if you were in orbit around the Moon. If you were on the surface of the Moon, then the gravity gradient is what holds you on the Moon, so——

Mr. BARTLETT. Relative to Earth, is there gravity gradient stabilization?

Dr. LEWIS. It is possible for an object in low lunar orbit to be gravity gradient stabilized, but the——

Mr. BARTLETT. But the Moon is not?

Dr. LEWIS. Well, as a matter of fact, the fact that the Moon always keeps one side toward Earth is an example of gravity gradient stabilization.

Mr. BARTLETT. Okay. Which means that it will be light and dark because its gravity gradient stabilized to the Earth. Okay.

Dr. LEWIS. It means that one side will always face the Earth.

Mr. BARTLETT. Because its gravity gradient stabilized to the Earth, yes.

Dr. LEWIS. That is right. Mr. Bartlett?

Mr. BARTLETT. Yes?

### MOBILE SOLAR STORES II

Dr. LEWIS. Your question regarding the hoppers on the Moon, if I may have put a frivolous noun on it, has actually been studied in the case of Mars, where devices that use either nuclear or solar power, extract carbon dioxide from the atmosphere of Mars, separate it into oxygen and carbon monoxide and liquefy them, and then use them as rocket propellants to hop around the surface. So you can hop from one location to another until your tanks are empty, and then sit there and absorb sunlight and refill the tanks with oxygen and carbon monoxide.

Mr. BARTLETT. Well, couldn't one imagine a mechanical kind of thing. Gravity on the Moon is so low that, you know, you could hop quite a distance.

Dr. LEWIS. You could indeed, but you would have no control over your landing. You would have to know exactly where you are going to come down. You do not get an opportunity to think twice about landing on that sharp rock over there.

Chairman ROHRABACHER. Might hop right into the briar patch. As just a, you know, I am waiting for some learned environmentalist to step forward and tell us that they would be afraid to have all this mining going on on the Moon because it might affect our tides, but I will—believe me. That will happen. That will happen. It might happen 20 years from now, but we will note—you will note——

Mr. LAMPSON. What would that do to surfing?

## MOON AS A WAY STATION

Chairman ROHRABACHER. That is the point, right. Anyway, as I was just actually—was at a discussion with some people along the coast about desalinization, and one lady got up—a learned person got up to talk about, well, how do we know, you know, what effect desalinating the water so we can use it would have on the ocean, and, anyway, we won't go back to that. Mr. Lewis—or Dr. Lewis, you stated that it makes no sense whatsoever to use the Moon as a way station, and that is sort of the concept a lot of people have in mind. They have in mind that we go to the Moon and then—so they are a little hesitant about whether we are going to learn things there, or whether we use that as a jumping off point, and we have heard those phrases. But let me ask you this. We go the Moon, and we land on the Moon, what about if we find a way to refuel the system on the Moon?

Dr. LEWIS. Let us assume that we have done that.

Chairman ROHRABACHER. All right.

Dr. LEWIS. That we can manufacture cheap liquid oxygen on the surface of the Moon.

Chairman ROHRABACHER. Or whatever. Some kind of fuel——

Dr. LEWIS. Okay.

Chairman ROHRABACHER.—that we are going to get in that vessel that can——

Dr. LEWIS. Okay.

Chairman ROHRABACHER.—now go on to Mars.

Dr. LEWIS. Here is an expedition sitting at the space station in low orbit around the Earth and they take off. They have a choice. They can either go to, for example, establish an orbit around the Moon and then wait for oxygen to be brought up to them from the lunar surface to refuel their tanks to prepare them for travelling on to Mars, or they can depart directly to Mars. The amazing truth is that it requires almost identical amounts of fuel at the space station to do those two things. In other words, if you go to the refueling base, it costs you extra fuel that you could have used to go to Mars instead.

Chairman ROHRABACHER. But, what I mean—well, if you could manufacture the fuel on the Moon itself.

Dr. LEWIS. That is right.

Chairman ROHRABACHER. Then you don't have to haul it up in order to refuel.

Dr. LEWIS. You have to haul it up to where your expedition is in orbit around the Moon.

Chairman ROHRABACHER. Oh, in orbit around the Moon, I get it.

Dr. LEWIS. If you bring your expedition down to the surface of the Moon, you are deep into the red ink in the ledger, because the cost of landing and taking off completely erases any advantage you might have hoped to get.

Chairman ROHRABACHER. Dr. Spudis, do you have something to jump in on that point?

Dr. SPUDIS. Well, I think it is—I think there is a little confusion. The Moon's enabling role in Mars exploration is not to build a Cape Canaveral on the Moon and to launch the mission from there. It is to act as a logistics depot, and there have been a variety of mission scenarios looked at by the exploration people at Johnson Space Center where they stage all missions from Earth Moon L1, that is the point that is halfway between—well, it is not halfway, it is where the gravity points balance, and it co-orbits with the Moon, so it always hangs in space, it is always between Earth and Moon. And it turns out that if you build a staging node at that L1 location, a lot of things become very easy. You could have global access to the Moon with no penalty for going to different latitudes. You can stage returns to the Earth, so you can return exactly when the orbital plane, for example, of the space station, if you wanted to go to the space station, is in alignment, and it is a good place to stage these missions. What they did was they looked at the production of lunar rocket fuel, hydrogen and oxygen, and worked that into a scenario for Mars missions, and it turned out that if you did it for one Mars mission, it wasn't worth it, but if you continually went to Mars—basically, if you made a Mars launch at every opportunity to send a mission there, that lunar produced fuel actually ended up saving you a great deal of money because you were not lifting that fuel up from the gravity well of the Earth.

Chairman ROHRABACHER. That may well be too far out——

Dr. SPUDIS. It may be.

Chairman ROHRABACHER.—for people to think about.

Dr. SPUDIS. But the real significance for producing fuel on the Moon is not for the Mars trip, it is to have routine access to cislunar space, because right now, that is where all of our assets are. All of our communications satellites, all of our GPS resource satellites, all of our national security satellites, are in the volume of space between Earth and Moon, and right now, we have no way to access those. We launch them and they are gone. If one fails, we write it off and launch another.

## THE VALUE OF TELESCOPES ON THE LUNAR SURFACE

Chairman ROHRABACHER. Okay. One other point of contention that we had here was—two other points, and then I have got one question, but I will let colleagues go before my last question. There was some disagreement over the value of a telescope on the Moon, and I noticed that Dr. Lester and Spudis disagree. Maybe you can—you have each heard each other's testimony. Dr. Lester or Dr. Spudis, what is—who is right? Somebody is wrong.

Dr. SPUDIS. I am right. No, I think it is a matter—I don't think we disagree as much as it would appear. The question is not, all things considered, where are you going to build the biggest telescope we can, because nobody is asking the astronomers that question. The question is if you are on the Moon and you have some capability, does it make any sense to do any astronomy from there, and I think the answer to that question is yes. It may not be the ideal location, but it is a location where significant things can be done. In some cases, unique things. I think the dust issue is a completely solvable one. That was looked at 12 years ago when we did the SEI studies, and we have a lot of ways to mitigate that problem.

Chairman ROHRABACHER. So going to the Moon to do astronomy is not a good excuse to do astronomy. Once you are there, might as well do it. You think that is——

Dr. LESTER. I think it is a question of bang for the buck. If you want to spend a certain amount of money and you want to get the most science out of it astronomically, putting a telescope on the Moon is not necessarily the smartest thing to do. Now, if somebody was going to give me a billion dollars and say, Dan Lester, go put a telescope—would you want to go put a telescope on the Moon, I would say, well, as long as that billion dollars isn't being taken away——

Chairman ROHRABACHER. I see.

Dr. LESTER.—from doing astronomy somewhere else, I guess so. You could give me a billion dollars to put a telescope in Central Park and I would go put a telescope there and I could get some astronomy done from Central Park, but I don't think it is——

## AMOUNT OF WATER ON THE LUNAR SURFACE

Chairman ROHRABACHER. All right. I got your point. Now, there was one other disagreement with Dr. Spudis, this time by Dr. Campbell, over exactly how much water there is on the Moon, and it seems we have a disagreement here. Again, who is right? Who is wrong?

Dr. CAMPBELL. Well, of course, as Paul would obviously say, you know we would jointly say, you know, I am. But I am not sure that—the issue is not how much water there is on the Moon. The real issue—because all that hydrogen could be combined with the oxygen and form water if you are willing to mine 10,000 tons of lunar regolith to give you one ton of hydrogen, you could then produce more. It is a very expensive way to produce it. What you need is to have sources of water that are in sufficient concentration that it is worthwhile and adequately located—that it is worthwhile to actually make use of them. So, you need reasonable concentrations of water. That seems to occur potentially in the shadows craters—bottoms of these shadows craters at the lunar poles, 1.5 percent, but if that turns out to be a number or potentially higher area. If we have better resolution and can look at smaller areas, we may locate regions with high concentration. Possibly radar systems may locate areas where we have thick deposits that are currently not visible from the—not visible from the Earth or the Clementine radar mission. And, so, what we need to find is, say, is not, you know, how much water, but we need to find water in real usable concentrations. And the other issue, of course, is accessibility, as Dr. Lewis has pointed out, that these are likely to be in the bottoms of large impact craters. And I am talking about large—anything 10 kilometers or larger—accessibility to the bottom of those craters where the temperature is 100 degrees Kelvin or lower, that are extremely—they are deep. We are talking about craters that are 6,000 feet deep or more, and so—and with very steep slopes, and so this is—these are not easy locations to actually look for water, and so we have to be realistic about the accessibility issue.

Chairman ROHRABACHER. Now, what——

Dr. CAMPBELL. Now, hopefully, maybe, we might find it in somewhat more accessible areas, but——

Chairman ROHRABACHER. But over the years, I remember in the beginning the only reason we discovered that there is water on the Moon is the fact that you had a bunch of rebels who were willing to basically not listen to the skeptics and force the issue. I mean, this first—the first missions that we had there were just—were not really the established—the space establishment was actually against this, and then when there was some indication that water existed, then everybody wanted to get on board. Well, Mr. Spudis, do you want to say something?

Dr. SPUDIS. Yeah. First, I would like to comment on the previous question about the disagreement. It is actually what he and I believe is irrelevant. The real issue is we don't know the answer.

Chairman ROHRABACHER. Yes.

Dr. SPUDIS. And what we really need to do is to fly a spacecraft that will get us the answer.

Chairman ROHRABACHER. All right.

Dr. SPUDIS. And in NASA's plan, that is what they are doing.

Chairman ROHRABACHER. But let us resist consensus. If I can say there is a consensus that everybody seems to agree that the most important factor to determine that we need to put very high on our priority list in going back is determining how much water and how accessible it is on the Moon.

Dr. SPUDIS. But also, what condition it is found in. Now, it is in low concentration, but remember, we are looking at low resolution, and in that case, you have a problem. You don't know if a low resolution signal from a big—low signal from a big target, does that mean it is all uniformly distributed throughout that target? In which case, it is very hard to recover it. Or, does it mean that it is lumpy like a chocolate chip cookie where there is ice bits here and there that are in concentrated form. If we have this mission, we can determine that answer. As far as the terrain and accessibility issues go, the Moon is actually—this doesn't seem—this is counterintuitive, but the Moon is actually a very smooth object. Craters that look very steep at low sun angle actually have accessible slopes. The crater at the center right near the south pole, Shackleton, is 23 kilometers across. It looks like the rim is a knife edge, and it looks like it slopes down at a big cliff. In actual fact, the rim—the slope up to the rim is only about five percent and the slope from the rim crest down to the floor is about 15 percent. Both of those are traversable with rover-type equipment, so it is not as hazardous as it looks. And secondly, in space, it is very easy to keep warm when it is cool. It is very energy intensive to keep cool, so I anticipate that operations in the dark will be challenging, but I don't anticipate that they will be impossible. But again, that is another thing that we have to go and actually learn.

Chairman ROHRABACHER. Mr. Lampson.

## ADDITIONAL DATA NEEDED BEFORE A HUMAN RETURN MISSION

Mr. LAMPSON. Given the data acquired by the Apollo lunar landing program and its robotic precursors, as well as the data obtained by the subsequent Clementine and Lunar Prospector spacecraft, what additional information, if any, will be needed by NASA before NASA can send humans back?

Dr. SPUDIS. Well, the missions that I think several of us have outlined in our testimony are the obvious first step, is a reconnaissance from a polar orbit to map the deposits in the environment of the poles. Then, you want to land at those deposits and sample them and make some in situ measurements to see what they are really made of and what their physical state is. And, then, finally, you want to maybe land some demonstration experiments where you might process that stuff to see if it is possible, and those things should precede human return. Now, they don't have to. I mean, you could send people right now with what we know. It would be a bit risky, but we could do that.

### CANCELED APOLLO MISSIONS AS FUTURE EXPEDITIONS

Mr. LAMPSON. Anybody else want to make a comment? If not, the last few Apollo missions which were cancelled by President Nixon in the '70s were intended to explore scientifically interesting locations on the Moon. Would it be appropriate to use the plans for those mission as the basis for the next human expeditions to the Moon?

Dr. SWINDLE. Probably not, in my opinion, because——

Mr. LAMPSON. Why not?

Dr. SWINDLE.—what is important now is to learn about some regions that we weren't able to go to at that time, and so the Apollo missions were rather restricted, and I believe those were also in the same general geographic area, so we would want to go someplace different. And, so, I suspect that those would not be the appropriate mission plans.

Dr. SPUDIS. You can still get valuable science from almost any site you want to go to on the Moon, even returning to an Apollo site, because there are questions we would ask now, going to an Apollo site, that we weren't smart enough to ask 30 years ago. But, I agree with Tim that basically you want to try to sample terrains we haven't been to, like the far side or the limb region, the Orientale Basin, and areas near the poles because we have never been there and we don't know what is there.

### INTERNATIONAL COOPERATION

Mr. LAMPSON. Most of the discussion of the President's program is focused on what NASA will do, but the President did clearly invite participation by other nations. We know that Europe, Japan, China and India have robotic lunar programs—probes planned. To what extent is the lunar—is the robotic exploration of the Moon is being coordinated internationally? What is the mechanism for that coordination? Are we going to share data? What are your thoughts about what we do with that?

Dr. SPUDIS. It is interesting you ask that because I haven't observed any coordination. There is a group called ILEWG, which is the International Lunar Exploration Working Group, and they allegedly coordinate missions between different countries, but if you look at the manifests for these missions that are going to the Moon, a lot of them are carrying the same instruments. So, if that is coordination, they are not doing a very good job. It appears that when it comes to lunar missions, a lot of these countries want to fly their own experiments, and regardless of whether the data set exists or not, they tend to go ahead and fly the same instruments again and again.

Mr. LAMPSON. Dr. Lewis.

Dr. LEWIS. It is a rather interesting, but I might be able to answer your questions two years from now. In the summer next year, I am taking a leave of absence for one year to go to Tsinghua University in Beijing where I will be a visiting professor and teach space science there, the first planetary science course ever taught in China. The reason for going to that particular location is that Tsinghua is the home of most of the engineers who are responsible for the Chinese space program. It is the leading science and technology university in China, and I hope to return, not just older, but considerably wiser after that experience.

Mr. LAMPSON. Good luck with that. That sounds like it would be a fascinating one. Any recommendations that you have to try—any of you, to try and further any kind of coordination? Well, what you are doing is wonderful. Hopefully that will lead to a greater mutual participation. Dr. Campbell, were you going to say something?

Dr. CAMPBELL. I wasn't actually, but——

Mr. LAMPSON. Oh.

Dr. CAMPBELL.—the answer to that is that—while these personal efforts are great, but I think these need to be done on government to government bases and it would be nice if they were to coordinate and to put together other countries.

Mr. LAMPSON. If we develop a plan—should we plan for a comprehensive sized program on the Moon, or maybe break it into specialties somehow or other, specializing in certain activities, and maybe let certain of our—certain cooperatives do one thing and us do another?

Dr. SPUDIS. Do you mean sort of divide the responsibility——

Mr. LAMPSON. Yeah.

Dr. SPUDIS.—for things to do on the Moon among different countries?

Mr. LAMPSON. Yes.

Dr. SPUDIS. That is one model. I don't know if you would have any particular advantage to that. I think, in part, it depends on what the national agenda is of the various countries that go to the Moon. Some are going for differing reasons, and I suspect that, if the past is any guide with our country, we will try to cram as much as we can onto what we can do, and we will try to cover as many disciplines as we can.

Mr. LAMPSON. For me, with the European Smart One probe——

Dr. SPUDIS. Yes?

Mr. LAMPSON. It is supposed to reach the Moon in 2005. It is designed to look for water ice to—and prepare detailed mineral maps. What role does the United States in that? Will we have access to the data that is gleaned from it—from their studies?

Dr. SPUDIS. My understanding is they plan to share the data, but I am not aware of any Americans that are directly involved in the mission. It is strictly a European mission, and—but I—they certainly—I have been talking to scientists involved with that, and they are very anxious to share the data with us.

Mr. LAMPSON. If we learn something that would be helpful, is it possible that we could eliminate some of our own probes or particular missions, perhaps?

Dr. SPUDIS. I don't think so because the instruments they are carrying—and Smart One is a technology mission. It is being—it is electric propulsion. It is going to go in a very elliptical orbit. It is not an ideal mapping orbit. Parts of the Moon will be photographed at high resolution, other parts will be not covered at all, and one of the goals of the missions we have described in our testimony is that we want to systematically map the Moon to assess things like the resource capability and the science issues. And Smart will contribute to that, but it is not a replacement for what we want to do.

Mr. LAMPSON. Okay. Mr. Chairman, by the clock, I am out of time.

Chairman ROHRABACHER. All right. We have Mr. Bartlett.

Mr. BARTLETT. Thank you. I understand that both India and China are planning to go the Moon before we go back. Are we collaborating with them?

Dr. SPUDIS. Well, the Indians have made available a 10-kilogram payload space on their lunar mission Chandrayaan-1.

Mr. BARTLETT. For us?

Dr. SPUDIS. For anyone in the world.

Mr. BARTLETT. Anybody, okay.

Dr. SPUDIS. And they have received a bunch of proposals. In fact, I submitted one myself.

Mr. BARTLETT. Okay. Do they share—plan to share the information they gather with the world, or is it going to be proprietary to their country? Have they told us?

Dr. SPUDIS. The Indians plan to share.

Mr. BARTLETT. They plan to share?

Dr. SPUDIS. Yes.

Mr. BARTLETT. We don't know about the Chinese?

Dr. SPUDIS. We don't know.

Mr. BARTLETT. Okay. I am old enough to have been involved in the space program since its inception. I remember at Pensacola, Florida, I was involved in what I think was the first sub-orbital primate flight, Monkey Able and Monkey Baker. Monkey Able, an Army monkey that they gave a general anesthetic to to take the electrodes out and he died. We didn't do that with Monkey Baker, and she was a little squirrel monkey which lived on for a long time at Pensacola, Florida. And then I went——

Chairman ROHRABACHER. Later elected to Congress, I might add.

Mr. BARTLETT. Yeah. Then I went to the Applied Physics Lab, and that was before we landed on the Moon. And there was a big question about what the lunar surface would be like, and one of the suspicions was that it might be a dust ball and that you stepped off the spacecraft, the spacecraft itself might just sink down over its ears in the lunar dust. So we developed a lunar spacesuit which is really a big sphere about eight feet across that had, on one side of it, a little dome for your head and spacesuit arms and legs so that you could use it like a spacesuit, and the Moon is a very low gravity, so you could easily carry that on your back. And if it was a dust ball, you could simply walk inside of it, like a big ball—as a matter of fact, we demonstrated that it really would do that by walking on water for the first time in 2000 years. The little pond there at APL, if you are familiar with that.

Dr. LEWIS. Very well.

## OUR KNOWLEDGE OF THE LUNAR SURFACE REGARDING VEHICLES ON MARS

Mr. BARTLETT. We walked down the slope and out on the water in this lunar, I guess, it would have worked no matter what the surface of the Moon was like. Fortunately, the powder was packed and we didn't need that. My question is do we know enough about the surface of the Moon and Mars to know if they are sufficiently similar so that experience gained on the Moon will help us in designing vehicles to get around on Mars?

Dr. LEWIS. We know a considerable amount about both surfaces, and they are in many ways quite different from each other. There would be no difficulty at all in designing a rover that can run around on Mars. You just—you know, we run them.

Mr. BARTLETT. And we have—yeah—in one area limited, that is correct.

Dr. LEWIS. Yeah. There is some difficulty involved in having a truly autonomous rover that has good enough sensors and smart enough little brain to know how to avoid obstacles and not kill itself. If you are aware of the recent attempt to race fully automated and autonomous vehicles across the Mojave Desert, you probably will understand that there is—the art is yet imperfect. It would be very valuable to have a man in the loop. If you are running rover around on the Moon, it would be extremely useful to have a—what, a 12-year old with a joystick sitting there in a nearby dome actually monitoring its television transmissions and running it. Human intelligence has many functions in exploration, and that is one of them. But it is not an uncertainty in the nature of the bearing surface, but simply an uncertainty about where the individual sharp rocks are.

Mr. BARTLETT. Both of them have a bearing surface that we can get around on.

Dr. LEWIS. Both of them definitely have a bearing surface.

## PERCENT OF THE MOON THAT HAS CONSTANT LIGHT

Mr. BARTLETT. What percent of the Moon has constant sunlight?

Dr. SPUDIS. An extremely small amount. It is just very tiny little patches that are near the pole. And, in fact, we don't actually know if they are constant sunlight because we have not observed them through a seasonal cycle. But, Clementine observed the North pole in the southern winter and we found three spots that are in sunlight 100 percent of the time. It observed the southern hemisphere through southern summer-or southern winter, and we only found—we found three places that are illuminated for greater than 75 percent of the lunar day. There is no permanent sunlight at the South pole. We don't know if that is true at the North pole.

Mr. BARTLETT. Wouldn't there be big advantages in making your first station there where there was perpetual sunlight?

Dr. SPUDIS. I believe so. In fact, I have advocated that.

Mr. BARTLETT. Even though it is a very small area. Dr. Lewis.

Dr. LEWIS. If you were in such a location, you would be on top of a crater rim on a point of high providence, and the terrain around you would mostly be in darkness, some of it in perpetual darkness. These are areas that are very difficult. Not only are they essentially unmapped from Earth, but they are very difficult to map from orbit because of the darkness problem, so you would be limited in the—there would have to be some other attraction to be there. The energy storage problem on the Moon, as Dr. Spudis mentioned earlier, is a very serious one. It is true that such a location at the poles solves the energy storage problem, but it also introduces the problem that you may not be where you want to be on the Moon for other reasons, and that has to be looked at carefully and synoptically.

Mr. BARTLETT. But mapping the lunar surface would tell us more about this?

Dr. LEWIS. That depends on how you map it because you can't map permanently shadowed crater bottoms optically.

Dr. SPUDIS. Well, you can with imaging radar.

Mr. BARTLETT. Can we not with radar?

Dr. SPUDIS. Yes.

Mr. BARTLETT. Yeah, we have to be able to. Yeah. Not with optical, certainly, but with radar we have to be able to map and know right precisely what is there. Yes. Thank you very much.

Chairman ROHRABACHER. One last question.

Dr. CAMPBELL. I want to make—oh.

Chairman ROHRABACHER. Go right ahead.

Dr. CAMPBELL. Thank you. Can I make a comment that——

Chairman ROHRABACHER. Oh, yes.

Dr. CAMPBELL.—to your walking around inside your plastic balloon, that Professor Thomas Gold at Cornell is a very great and inventive scientist, but this was—he was responsible for the suggestion that the Moon—you may just sink into the Moon if you step on the surface, and over time has caused considerable discussion of that issue at the time of the Apollo landings. And, I guess he is probably happy he is—he is probably sorry that he has put you to that trouble.

Mr. BARTLETT. But this was OART that sponsored this, and Dr. Walt Jones. They would come over—Captain Walter Jones come over from the Navy after his retirement to chair the—or head the OART. Does it still exist, OART?

Dr. SPUDIS. I don't know. It might have been subsumed into another organization.

Mr. BARTLETT. Okay. Thank you very much.

## ROLE OF PRIVATE SECTOR

Chairman ROHRABACHER. One last question, and perhaps what I will do is ask any of you who have a vision of the private sector playing a role on the Moon after, or even during, the initial phases of our return to the Moon, if you could write me a one-pager on it and just give me your thoughts of what the private sector could do, how you could see that, what you could see them doing, and I will make sure that your thoughts and your vision on this are put in as part of this record of this hearing. And with that said, I would like to thank the witnesses.

[The information referred to follows:]

RESPONSE BY PAUL D. SPUDIS

**The role of the private sector in lunar development**

Ultimately, I believe that lunar resources will be almost exclusively developed by the private sector. At the present time, however, there are significant barriers to involvement by the private sector. These barriers fall into three principal categories: fiscal, technological, and legal.

The private sector possesses neither the amounts of capital needed nor the inclination to significantly invest in lunar resource processing or development. This is largely because payoff on investment is quite distant, at least on the order of a decade, and possibly longer. The emplacement of significant capability on the lunar surface requires not only investment in machines and equipment to conduct the processing, but also a significant transportation cost. It takes roughly 15 lbs. in low-Earth orbit to put one pound on the lunar surface; at commercial launch costs exceeding several thousands of dollars per pound, initial investment involves not millions, but hundreds of millions of dollars.

The technical barriers are equally formidable. Although we know a great deal about the polar deposits of the Moon in principle, the specific details of deposit purity, thickness, physical properties, and composition are all completely unknown. Acquiring this knowledge is an important goal of NASA's robotic mission set, but prior to these flights, much about the lunar ice remains conjectural. Even if the properties of these deposits were known, we have no experience extracting and processing such material. The acquisition of such knowledge and experience should be a major programmatic goal of NASA's lunar program.

Finally, legal problems will severely impact any significant private sector involvement for the near future. Specifically, the current legal regime of lunar resources is very unclear. I believe that private property rights on the Moon do exist and are not precluded by the U.N. Outer Space Treaty of 1967 (to which we are signatories), but legal opinions differ. Congress should consider addressing this issue at a very early stage in the initiative; a law guaranteeing private property rights on the Moon (at least as recognized by the United States government) would go a long way towards removing the current ambiguity in the law.

I believe that the best way to encourage private sector investment in lunar development is to phase it in gradually, as the NASA exploration initiative gathers the necessary strategic scientific and engineering information and develops the requisite technology. Early involvement by the private sector could involve government incentive schemes (e.g., tax breaks, prizes) or data purchase (e.g., NASA would pay a set amount for a given piece or set of data and information). As the initiative proceeds, activities that push back the envelope of technology or engineering state-of-the-art can be privatized. Government would likely be an early customer of lunar products, but commercial activities would soon follow, particularly in the production of propellant from lunar resources.

## SPACE EXPLORATION AND NATIONAL SECURITY

Mr. LAMPSON. Well, before you go, could I just ask——

Chairman ROHRABACHER. Mr. Lampson, go right ahead.

Mr. LAMPSON.—one thing that is sort of in passing of Dr. Spudis. You had made some comments in your testimony about protection of national strategic assets. Is this some of the discussion that is going on with the Aldridge Commission? Is there—can you enlighten us?

Dr. SPUDIS. I am not going to discuss any Commission activity. All of my opinions that I presented today are my own.

Mr. LAMPSON. Is—has there been any discussion at any place about that? I am a little interested in knowing if there is going to be a greater involvement in our space exploration effort more from the aspect of defense than from civil science. I am curious about that.

Dr. SPUDIS. There is a lot of discussion going on. I don't know if there are any official discussions going on. There was a talk given here in D.C. a few months ago by James Oberg who has written a book about space power theories, sort of the Mahan of the

21st Century, and he is basically arguing—talking about American space control, the idea of us being able to protect and control our assets in space. I am for pushing it from a slightly different point of view. I am not really looking at the defense angle. I am saying that if you have the capability to routinely travel throughout this volume of space, that has to have implications on everything you do in that volume of space, and that includes national security activities, and it includes all of our commercial space activities as well.

Mr. LAMPSON. Thank you.

Chairman ROHRABACHER. Do you have something to say about that, Dr. Lewis?

Dr. LEWIS. Yes. There is some relevant ancient history here, which is that back in the 1980s, there was a summer study on Defense uses of space resources. It was instigated by, actually, me knocking on Hans Marx's door when he was Secretary of the Air Force, I think, and selling him the idea of the—the study was done, I believe, in the summer of 1983 at the California Space Institute, and the proceedings of that study are still available, certainly not up-to-date, but it shows that Defense Department has thought about these matters.

Chairman ROHRABACHER. Now, let me leave you with one admonishment, Dr. Lewis. You are on the way to China.

Dr. LEWIS. In a year.

Chairman ROHRABACHER. In a year.

Dr. LEWIS. Yes.

Chairman ROHRABACHER. I don't expect a major shift in political structure in China in that year, and one of—I mean, I would think that it would be a catastrophe for us to go to the Moon, and then when we get there, find, you know, chopsticks laying all over the place or something, evidence that our Chinese friends have beat us to it. But I think what is more important here is that I believe in cooperation—space cooperation, but I believe in space cooperation between free people, and I think that the worst thing that happened to us was during the 1990s when our companies went over to China and transferred know-how and technology that has permitted, now, the Chinese to come to this point where they may well be doing some things in space that we are not capable of doing right now, and no matter how far along they are, I would just admonish the scientific community that when we are dealing with countries that are not free countries, it, sometimes, is not beneficial for us to provide them the knowledge and the technology they need to move ahead as fast as the Chinese, for example, have moved ahead.

Dr. LEWIS. I agree completely, and there will be no technology transfer whatsoever. There will simply be an attempt to inspire them in the vision of a cooperative exploration of the solar system.

Chairman ROHRABACHER. And let us hope that some day I don't have to do that, because perhaps someday the Chinese people will have a free country, and I am a great admirer of the people themselves. And their government, of course, is a big problem. But, for example, the Chinese—did you ever hear of the South Pointing Chariot? They call it the South Pointing Chariot. The Chinese developed——

Dr. LEWIS. Are you talking about a magnetic compass or——

Chairman ROHRABACHER. Well, everyone thought it was a magnetic compass. But, I worked in the White House as a speechwriter for President Reagan. President Reagan was going to China, a very famous trip to China, I might add, and one of the issues that I looked at was the South Pointing Chariot, because I was writing some of his speeches, and I wanted him to talk about some of the things the Chinese had accomplished over the centuries. And, just for the record, what I found out is what most historians believe was the development of a compass by the Chinese, because they had a device which they put on top of a wagon which would always point to the South. It was a statue with its arm out like this, so they would not be lost in the Gobi Desert and the far reaches of the desert. And what I found is it was not a compass. And I did research on it, and found out that it instead dealt with the development of a differential gear in the wagon itself, which kept, no matter which way the wagon turned, the statue stayed the same place. There was not a differential gear developed in western societies until about 150 years ago. And, so, while the compass itself would have been quite a discovery, the idea that Chinese engineers, back all those centuries ago, were able to conceive of, and actually implement, a differential gear in a piece of technology is quite astounding.

Dr. LEWIS. There is no shortage of intelligence there.

Chairman ROHRABACHER. That is for sure. Well, thank you all very much. There is no shortage of intelligence in this panel, and we really appreciate all of you witnesses testifying today, and I will look forward to any input that you might have suggestions of what the private sector could possibly do, commercial as well as the foundations, education, business, whatever types of things you would think they could do. Please be advised that Subcommittee Members may request additional information. For the record, I would ask other Members, of course, who are going to submit written questions, to do so within one week of the date of this hearing. And that concludes this hearing, and I now say that we are——

[Whereupon, at 3:27 p.m., the Subcommittee was adjourned.]

# Appendix:

## ANSWERS TO POST-HEARING QUESTIONS

## ANSWERS TO POST-HEARING QUESTIONS

*Responses by Paul D. Spudis, Senior Staff Scientist, Johns Hopkins University Applied Physics Laboratory; Visiting Scientist, Lunar and Planetary Institute, Houston, Texas*

### Questions submitted by Chairman Dana Rohrabacher

*Q1. NASA's Office of Space Science is responsible for the lunar robotic portion of the Space Exploration Initiative. How would you recommend the office reach out to the science community to carry out this program? Is NASA using science advisory panels to select instrument proposals for upcoming missions?*

*A1.* There are two considerations here. First, is a mechanism in place to assure that the correct measurements are being planned and made in the correct priority? Second, how should instruments be selected for the upcoming lunar robotic missions?

In answer to the first question, the measurement requirements are being created through an ad hoc process, whereby a definition team, selected by Code S, sets up a list of measurement requirements that the LRO mission must obtain. This process created a requirements list that more-or-less meets the critical priorities, with the exception that a fairly heavy (~20 kg) radiation experiment received a much higher priority than is actually warranted (the radiation environment of the Moon is already well characterized and such measurements do not significantly impact the design of possible architectures for human lunar missions). There should be a formal process to correct such errors, but I believe in this case, the issue will be resolved correctly.

The process that NASA currently uses to select mission instruments, i.e., the competitive AO process, is as good as any, provided that critical measurement needs are addressed in a timely manner. In this process, NASA will assemble ad hoc panels of interested, but not involved, scientists to judge the merits of proposed investigations. In general, this process works well, except for certain unique or very high-technology instruments or measurement capabilities that may only be available through non-competitive channels. One important consideration is the systems engineering/requirements process used in these robotic missions, since the current Office of Space Science-National Academy of Sciences driven strategy tends to produce "one off' solutions, not spiral development. This problem could be mitigated by having Code T manage the robotic lunar program from the start. Giving requirements to another legacy organization to implement can produce less than optimum results.

*Q2. The Space Exploration Initiative proposes establishing an extended human lunar mission. Based on your knowledge of the Moon's environment and resources, how difficult a task will it be to develop and sustain humans for a two-month period? For a stay of that duration, would it be practical to develop in situ resources to help sustain lunar astronauts? How about a six-month stay?*

*A2.* Lunar stays for periods of two months can be easily accommodated without recourse to the use of local resources. However, since I believe that one of our primary goals in a human return to the Moon is to learn how to live off-planet, I would want to conduct some experiments with resource extraction before and during such a human mission. For example, one can imagine the landing of a small robotic plant designed to process the local regolith and extract both hydrogen and oxygen from the soil. This robot plant could operate continuously for several months, producing and storing this material. The products would then be available for use by the human crew upon their arrival on the Moon.

For lunar stays of six months and more by people, I would want to incorporate local resources into my habitation architecture. At a minimum, I would want to use the local regolith as a radiation shield (because of both continuous cosmic ray exposure and the likelihood of a solar flare in that time period). Also, the production and use of lunar oxygen would both provide the air supply in the habitat and also permit fueling of the return vehicle and hydrogen and oxygen for fuel cell energy storage. I think one of the primary goals of a human return to the Moon is to learn the technical and operational difficulties of living off-planet and use of local resources should be made a primary mission goal. Energy storage will be a key issue. While nuclear energy is feasible for some applications it will be very expensive. If there are well lit areas at the poles, the use of locally produced water as an energy storage medium could greatly expand the capabilities and safety of the lunar operation. Also, nuclear energy is not well suited for mobile applications.

**Questions submitted by Representative Nick Lampson**

*Q1. Given the data acquired by the Apollo lunar landing program and its robotic precursors, as well as data obtained by the subsequent* Clementine *and* Lunar Prospector *spacecraft, what additional information, if any, will be needed before NASA can send humans back to the Moon by 2020?*

*A1.* Primarily, we want to follow up on the *Clementine* and *Lunar Prospector* discoveries that suggest the poles of the Moon are important environments, with key deposits that will enable us to live and work on the Moon for extended periods. Thus, we first need reconnaissance from orbit to map the polar ice deposits, determine their thicknesses, extent, and purity, measure the temperatures, lighting conditions, and topography of the polar areas to determine the setting of the deposits, and improve the geodetic control of the Moon so that we can land precisely on it and navigate across its surface when we return. These knowledge requirements should be met by the proposed Lunar Reconnaissance Orbiter (LRO), currently planned for launch in 2008. Cooperation with an international mission could enable some enhancing measurements not possible with a single spacecraft.

After successful completion of an LRO mission, a lander should be flown that will conduct detailed, surface measurements of the polar ice deposits; a surface rover would likely be required for this mission. We are specifically interested in knowing the composition and physical state of the polar deposits and the nature of the environments of the dark regions. Such a landed mission should be followed by a series of robotic landers that would conduct demonstration experiments, testing the processes and techniques of resource extraction. These small, robotic missions should be completed before return of people to the Moon so as to maximize the capability of the human outposts prior to their establishment.

*Q2. What will it take to definitively answer the question of how much water ice might be on the Moon? How much time is it likely to take to characterize the global availability of water on the lunar surface?*

- *How many remote-sensing missions will be necessary to obtain this complete characterization?*
- *What will it take to map other lunar resources?*

*A2.* The robotic mission series that I outline above should definitively resolve whether there is ice on the Moon, where it occurs and its physical state, the total quantities of ice, and its detailed chemical and isotopic make-up. This information is critical to make informed decisions about the kinds of processing to be undertaken to make the commodities that we need from the lunar surface (mostly water, air, and rocket fuel). Note that all this information is gathered by the first two robotic missions: one orbiter and one lander. We could use additional landers to go to different locations (for example, twin larder/rovers to explore both the north and south polar regions), but our fundamental questions should be answered after the successful flights of these two missions.

Other lunar resources are either already well characterized (e.g., the mineralogical and chemical maps made by *Clementine* and *Lunar Prospector*) or will be mapped at higher resolution and greater precision by future lunar orbiters to be flown by other countries (e.g., Japan's SELENE mission). Depending on the results of our polar mission series, we may decide that it is important to explore robotically new areas in equatorial regions that may contain significant hydrogen and other volatile resources (e.g., regional deposits of volcanic ash, such as near Rima Bode); none of these types of deposits were studied during the Apollo program.

*Q3. Would any of the scientific research you have discussed require astronauts on the Moon as opposed to robotic orbiters, landers, rovers, or research stations? If so, which research and why? Does any of the scientific research or resource extraction you have discussed require a permanent human presence on the Moon? If so, how soon should that permanent human presence be established?*

*A3.* Much scientific research on the Moon is possible with robotic missions, but to truly solve the sophisticated questions we are now asking, we need to have trained human explorers on the Moon and other planetary surfaces. These human explorers should work in tandem with robotic spacecraft to produce the best results. The specific example I cited in my testimony—the impact flux in the Earth-Moon system—can be addressed initially by robotic spacecraft taking grab samples from carefully selected surfaces. But to fully understand the richness and complexity of the lunar impact record, we need human experts in lunar geology, mapping units, making careful observations in the field, and selecting critical samples for laboratory analysis. In short, although we can address scientific questions using only robotic spacecraft, the full details of planetary history and evolution will yield themselves only to a combined campaign using the best capabilities of both machines and people.

Resource extraction from the Moon will likely be done mostly by machines, but these machines will doubtless need constant human supervision, maintenance, and repair. The Apollo program is replete with examples where a swift kick from an astronaut was needed to get some complicated machine to work properly. We will likely require such kicks again and again in this new, difficult endeavor. I envision human presence growing simultaneously with the robotic presence; send machines first to do the initial processing, then send people within a few months to monitor, maintain, and augment the robotic installations. Humans could arrive for increasingly extended periods starting a few months after the initial surface infrastructure is established.

*Q4. Science by itself is not going to sustain the public's support for the long-term program contemplated in the President's plan. After all, the 1960s Apollo lunar landing program had developed some impressive science capabilities, and Apollo 17 carried the first scientist-by-training (geologist Harrison Schmidt) to work on the Moon. Unfortunately, he was also the last. What is different enough about the ideas you are advocating here that will avoid the fate suffered by the Apollo program?*

*A4.* The Apollo program was not about science, but about beating the Soviets to the Moon. After that goal had been accomplished, the political rationale for the program evaporated. Although excellent science was done on Apollo, it was "retro-fitted" onto an operational program and this fit was never completely comfortable. Apollo was a non-optimum tool for lunar exploration, even though superb exploration was done during the course of the missions (a tribute to the Apollo astronauts and scientists for accomplishing as much as they did!).

Our return to the Moon is likewise not about science; it is about creating a new and sustainable capability to journey beyond low-Earth orbit. The key features of the new initiative to return to the Moon—resource extraction, habitation, sustained presence—are all new; none of these activities were part of the Apollo program. If we can create new space-faring capability using lunar resources, we can access routinely all of cislunar space (the volume of space between Earth and Moon), where all of our current space-based assets reside. Such a capability would have enormous implications for our national security and economic health. In contrast to the Apollo program, which required large amounts of funding in short time periods to meet its decadal deadline imposed by the President, the new vision calls for a return to the Moon under existing space funding. We merely need to direct our research and spending toward a focused goal. Thus, the new space vision is both affordable and sustainable, in contrast to the "we're at war—costs be damned!" mentality of Apollo.

## ANSWERS TO POST-HEARING QUESTIONS

*Responses by Daniel F. Lester, Research Scientist, McDonald Observatory, University of Texas, Austin*

### Questions submitted by Chairman Dana Rohrabacher

*Q1. Please provide your views on what roles the private sector, including businesses and educational institutions, can contribute to the successful development and exploitation of lunar resources, and to the provision of services in support of NASA's lunar exploration program.*

- *Based on current capabilities, do you believe the private sector has unique expertise needed by NASA to return to the Moon?*
- *What are the biggest obstacles to private sector participation in lunar exploration and resource exploitation activities?*
- *Once NASA has established a long-term presence on the Moon, are there markets you believe could be exploited by private industry, and if so, what might they be?*

*A1.* The effort to develop and exploit lunar resources, should they be found to be present in quantities that would make such exploitation cost effective, will take a long time. Even in the new Vision for Space Exploration, it may be several decades before such exploitation can be achieved. With this understanding, concern about sustainability of the Vision plan across many Congresses and many Presidential administrations is an important one, and such concern should be applied to the private sector as well. To the extent that our country is dedicated to making lunar development happen, reliance on the private sector to take a leadership role in doing it must be couched in a certain level of long-range business planning that we are not used to seeing. This mismatch of planning time scales is perhaps the biggest obstacle to private sector participation, if not leadership, in space exploration. If resources—in particular water for life support and propulsion—are to be found on the Moon where the low gravity makes supply of exploration missions energetically less costly, the private sector could be called upon by the space agency to bid on such supply efforts. Market forces could then decide whether such supply is better done from the surface of the Earth, where resources are cheap but transportation more costly, or from the Moon, where the reverse may be true. Such a market-based approach is feasible, however, only if the exploration plan is structured with regular short-term opportunities for success and return on investment. Without such short-term opportunities, we should not assume that the private sector will significantly invest in opportunities that are several decades out.

The importance of educational institutions in the success of lunar development can be understood from this same perspective of sustainability. The students we train now are the science and technology leaders of the future. They carry with them into their careers the motivation and rationale for the exploration agenda. The exploration initiative as a whole will be driven by those who can think outside the box, accept risks, and be able to map the excitement about space travel onto national priorities and long-range business success. While students do not have the experience to carry out the detailed efforts required, they are better able to look beyond yearly balance sheets for corporate profits, and make these strategic leaps. Providing schools with mechanisms for a general sense of ownership in space travel is thus a wise national investment. Such mechanisms for ownership could be training partnerships with the space agency and space entrepreneurs, challenges and contests, and drawing clear lines between technology needs of all kinds and space efforts. It is clear to me, from a university environment, that space efforts are exciting to everyone, but those who would enter the workforce developing microprocessors, building bridges, and understanding the molecular processes in cells do not feel as linked to space exploration as those few who design rocket engines and space telescopes. That has to change. For younger students, it is less important to cultivate understanding of space technology and astrophysics than it is to cultivate an appreciation for exploration. We teach social studies and history. Why don't we teach exploration? Curriculum that highlights the achievements of explorers (whether they be scientists, ship captains, or inventors) and teaches exploration as a national priority builds in children the kind of national self-image that the Vision initiative will need several decades hence.

Whether or not the private sector is called upon in this way, it is clear that development of the Moon must be clearly and conspicuously coupled to a real national need, such that we are willing to spend money to underwrite and bring enthusiasm to it. This national need could be driven by resource development (supply of exploration missions with, e.g., water, as above), return to Earth of lunar-unique resources (e.g., $^3$He), or simply national pride and accomplishment. Our lunar program of thirty years ago was clearly based on the latter, and our success was astonishing. We now measure our ability as a nation to do hard things against our national effort to go to the Moon—one of the hardest things ever done by mankind. The can-do spirit that drives our nation has some grounding in this success, I believe.

The importance of a long-term presence on the Moon within the new Vision for Space Exploration has yet to be established. As the plan states, the scope and types of human lunar missions and systems will be determined by their support to furthering science, developing and testing new approaches, and their applicability to supporting sustained human space exploration to Mars and other destinations. Should long-term presence on the Moon become part of the new Vision plan, it can be assumed that it is because such presence brings value to the enterprise and as such offers obvious opportunities for private industry in the market-driven model proposed above. Private industry is much better suited to supply-and-demand roles than the Federal Government. In the same way that private industry is now used routinely by the Federal Government in a cost-conscious manner through competitive procurement to maintain and operate federal investments, whether for science management, resource development, or facility operations, so it can be on the Moon. To the extent that such efforts have to be consistent with a broader operations plan, as it is at military bases and agency centers on Earth, these efforts will likely have overall management by the space agency. Should lunar resource development or manufacturing eventually find markets that are external to federal investments (for example, if $^3$He is mined on the Moon specifically for marketable power production on Earth) this model will need reevaluation.

*Q2. NASA's Office of Space Science is responsible for the lunar robotic portion of the Space Exploration Initiative. How would you recommend the office reach out to the science community to carry out this program? Is NASA using science advisory panels to select instrument proposals for upcoming missions?*

*A2.* It is my understanding that the Office of Space Science is using advisory panels that include a strong scientific background to select instrument proposals for upcoming missions, such as the upcoming Lunar Reconnaissance Orbiter. The needs for the exploration initiative are fairly specific with regard to lunar exploration. They are in part scientific, and in part an assessment of resources available. Thus these panels necessarily include scientific, technological and engineering representation. The resources we find on the Moon may dictate very strongly the way we use the Moon in the future, and the role that it plays in the exploration agenda. As a result, it is of great strategic importance to understand what these resources are, and how easily they may be harvested and utilized. The Office of Space Science has historically done an excellent job in reaching out to the science community to develop missions, and I expect it to do the same for lunar exploration that is part of the Vision initiative.

*Q3. The Space Exploration Initiative proposes establishing an extended human lunar mission. Based on your knowledge of the Moon's environment and resources, how difficult a task will it be to develop and sustain humans for a two-month period? For a stay of that duration, would it be practical to develop in situ resources to help sustain lunar astronauts? How about a six-month stay?*

*A3.* An extended lunar mission, as distinct from the long-term presence discussed above, will be a challenging effort that could bear strongly on our ability to carry out a mission on Mars. It should be clearly understood, however, what such an extended mission offers us beyond the considerable knowledge provided by our long-term human space experience on the International Space Station. Although I do not have background on human life support in space, I will venture to say that efforts to simply extrapolate our Apollo several-day experience to several months will likely involve a lot more than increased masses of consumables. Knowing what we know now about the lunar surface, while relying on in situ resources offers a real challenge, it does not offer a clear path to near-term success. Landing humans on the Moon requires technology that could also land supplies nearby with a separate vehicle, and I would predict that launch costs of a dedicated supply vehicle would be lower than development of reliable low-risk systems to, say, extract oxygen from lunar rocks or ice. Since the extended lunar mission is specifically envisioned as paving the way for Martian efforts, near-term success is a priority. Also, it is by no means clear how exploitation of lunar resources can be used productively to teach us how to survive on Mars, as those two surfaces are considerable different. Efforts to develop lunar resources in this manner could thus be considered a fiscal and managerial distraction from the Martian goal if not approached wisely.

**Question submitted by Representative Nick Lampson**

*Q1. Science by itself is not going to sustain the public's support for the long-term program contemplated in the President's plan. After all, the 1960s Apollo lunar landing program had developed some impressive science capabilities, and Apollo 17 carried the first scientist-by-training (geologist Harrison Schmitt) to work on the Moon. Unfortunately, he was also the last. What is different enough about the ideas you are advocating here that will avoid the fate suffered by the Apollo program?*

*A1.* While I believe that the Moon is an important science target, and quite possibly a useful station for the exploration of the solar system, we should not lose sight of the fact that many opportunities, both science and otherwise, are to be found in free-space, whether in low-Earth orbit or beyond. Our investment in the International Space Station has given us expertise in this regard. Low-Earth orbit has been an enabling destination, giving confidence in microgravity performance, rendezvous skills, and deployment and construction strategies. From a science standpoint, and quite likely from a capabilities standpoint, exploration of the solar system will be more about free-space than about dirt. If resources on the Moon present a low-cost opportunity to develop free-space, then the Moon has great value. If we as a nation decide that survivability as a species requires long-term presence on the Moon, then it also has value. If those resources are not to be found there, or if that survivability decision is not cogent, the Moon is less important to the grand picture. Going to the Moon simply to be on the Moon does not seem a defensible goal, and can only divert attention and resources from a human voyage to Mars, which is the next great challenge that space offers.

The fate of the Apollo program was that we succeeded. We set out a goal that was an enormous challenge to the Nation, and we lived up to it. We proved our stuff to ourselves and to others. After we achieved that goal we were, quite simply, done. The termination of that program was strategic acknowledgment of that fact. The fate of the space program after Apollo was that we were reluctant to commit to new long-range goals, and it is these long-range goals that the new Vision for Exploration addresses. The Vision can succeed if it articulately addresses key national needs, and represents value to the taxpayer.

## ANSWERS TO POST-HEARING QUESTIONS

*Responses by Donald B. Campbell, Professor of Astronomy, Associate Director, National Astronomy and Ionosphere Center (NAIC), Cornell University*

### Questions submitted by Chairman Dana Rohrabacher

*Q1. Please provide your views on what roles the private sector, including businesses and educational institutions, can contribute to the successful development and exploitation of lunar resources, and to the provision of services in support of NASA's lunar exploration program.*

- *Based on current capabilities, do you believe the private sector has unique expertise needed by NASA to return to the Moon?*
- *What are the biggest obstacles to private sector participation in lunar exploration and resource exploitation activities?*
- *Once NASA has established a long-term presence on the Moon, are there markets you believe could be exploited by private industry, and if so, what might they be?*

*A1.* Based on the experience of the Apollo program and the International Space Station, private industry expertise would clearly play a very important role in a return to the Moon with industry participation being contracted by NASA or some other government agency. I am personally pessimistic that there are resources on the Moon that would be commercially exploitable for use on the Earth or in near-Earth orbit in the foreseeable future without substantial direct or indirect government subsidies. Solar power generation has been mentioned. While it may be possible to utilize local resources to fabricate the collectors, beaming the power back to Earth requires relatively sophisticated technology much of which would need to be transported to the Moon. The cost of this, combined with difficulties related to the lunar day/night cycle and the orbital motion of the Moon, would very likely make a lunar based solar power system uncompetitive with one placed in a synchronous orbit above a fixed location on Earth.

*Q2. NASA's Office of Space Science is responsible for the lunar robotic portion of the Space Exploration Initiative. How would you recommend the office reach out to the science community to carry out this program? Is NASA using science advisory panels to select instrument proposals for upcoming missions?*

*A2.* There seems little reason for NASA to change existing practices for organizing and arranging for participation in space missions. An "Objectives and Requirements Definition Team" was established for the Lunar Reconnaissance Orbiter (LRO) mission that laid out the primary objectives of the mission and a possible instrument payload which would enable the objectives to be met to the greatest extent possible. An announcement of opportunity was then issued by NASA soliciting proposals for instruments to be carried on LRO.

*Q3. The Space Exploration Initiative proposes establishing an extended human lunar mission. Based on your knowledge of the Moon's environment and resources, how difficult a task will it be to develop and sustain humans for a two-month period? For a stay of that duration, would it be practical to develop* in situ *resources to help sustain lunar astronauts? How about a six-month stay?*

*A3.* The MIR and International Space Station have shown that it is possible to support humans in space over extended periods. The difficulties in maintaining a human presence on the Moon, however, for even a few months should not be underestimated. Only a determined and sustained preparatory effort would make such an enterprise feasible. Issues such as the radiation environment and power requirements during the long lunar night have been extensively discussed and various solutions proposed including siting a base at the lunar poles where there may be areas that are in near permanent sunlight and where resources such as water ice may be present.

Developing the infrastructure to allow local resources to be utilized will require an extended and sustained effort. An initial two-month stay by astronauts must be preceded by pre-positioning of vital supplies and shelters and, if it seems feasible during the planning stages, the establishment of automated facilities for extraction of lunar resources such as oxygen. There is no point to such a long stay unless it is part of a sustained effort to establish a base that would allow even longer stays (e.g., six months) and the use of local resources to the maximum extent possible.

**Questions submitted by Representative Nick Lampson**

*Q1. Given the data acquired by the Apollo lunar landing program and its robotic precursors, as well as data obtained by the subsequent* Clementine *and* Lunar Prospector *spacecraft, what additional information, if any, will be needed before NASA can send humans back to the Moon by 2020?*

*A1.* The *Clementine* and *Lunar Prospector* orbiters provided maps of the mineralogy and elemental composition of the lunar crust, and Lunar Prospector data suggest the possible presence of water ice in permanently shadowed regions near the lunar poles. What is needed, and could be accomplished by the instrument suite recommended for the Lunar Reconnaissance Orbiter (LRO), is a comprehensive survey of the Moon's polar regions, focused on identifying possible deposits of ice that could be viable resources for even temporary human habitation. The LRO mission and possible follow on missions, will also need to carry out detailed surveys for possible base sites. This involves issues such as landing safety, lighting conditions over the course of a year, suitable terrains for vehicles and proximity to resources.

*Q2. What will it take to answer definitively the question of how much water ice might be on the Moon? How much time is it likely to take to characterize the global availability of water on the lunar surface?*

- *How many remote-sensing missions will be necessary to obtain this complete characterization?*
- *What will it take to map other lunar resources?*

*A2.* While there may be very small quantities of water ice in the general lunar soil due to protons implanted by the solar wind, they are not recoverable. The only likely locations with significant recoverable concentrations of water ice are permanently shadowed terrains at the lunar poles. Only two methods are currently known to remotely sense the presence of water ice; radar and neutron spectrometers. A single mission with these two instruments will provide the best information that we can obtain from orbit. Radar can detect ice in the form of relatively thick sheets, a meter or more in thickness depending on the wavelength of the radar. These sheets can be buried under two meters or more of lunar soil and would still be detectable by radar. Neutron spectrometers detect the presence of hydrogen which may or may not be associated with oxygen in the form of water molecules. Very high concentrations of hydrogen can reasonably be interpreted as indicating the presence of water ice. This ice could be in any form, small crystals or larger sheets, in the upper meter or so of the surface. A survey of the lunar polar regions with these instruments on an orbiter such as the planned Lunar Reconnaissance Orbiter, would take a few months. Verification could be accomplished by *in situ* measurements carried out by landers or penetrators.

Other lunar resources include iron- and titanium-rich lava flows, and possibly isolated deposits of volcanic glasses that may contain useful materials. Most of these deposits have been well-mapped from orbit, and would require little additional information to target initial surface experiments in resource extraction.

*Q3. Would any of the scientific research you have discussed* require *astronauts on the Moon as opposed to robotic orbiters, landers, rovers, or research stations? If so, which research, and why? Does any of the scientific research or resource extraction you have discussed require a* permanent *human presence on the Moon? If so, how soon should that permanent human presence be established?*

*A3.* It has long been suggested that the Moon would be a preferred site for astronomical telescopes operating at wavelengths that are affected by the Earth's atmosphere or, in the case of radio astronomy, to isolate the telescope from the effects of radio frequency interference on the Earth. While there is a debate as to whether, in the long-term, it is preferable for such telescopes to be free-flying space instruments or located on the lunar surface, if they are placed on the Moon then a human presence will probably be needed for the initial installation and, possibly, periodic maintenance. They should be able to run robotically in normal operation.

Unless some commercially viable resource is discovered on the Moon I would think that there is little justification for establishing a permanent human presence on the Moon. However, this comment could have also been made about the Earth's south pole but for geopolitical and, more recently, scientific research considerations, the United States maintains a permanent presence there.

*Q4. Science by itself is not going to sustain the public's support for the long-term program contemplated in the President's plan. After all, the 1960s Apollo lunar landing program had developed some impressive science capabilities, and Apollo 17 carried the first scientist-by-training (geologist Harrison Schmitt) to work on* *the Moon. Unfortunately, he was also the last. What is different enough about the ideas you are advocating here that will avoid the fate suffered by the Apollo program?*

*A4.* The United States has been supporting a human presence in space for over forty years. Withdrawing from space seems unthinkable. Explaining to students that we once had the capability to regularly visit the Moon but have not been back in over 30 years is difficult enough. For the next generation of teachers to explain to students that sending humans into space was once relatively routine but that we decided to withdraw from space would be even more difficult. However, the practical issue of "why do we want to be in space" is a difficult one. It is clear that the International Space Station is not the science platform that its backers long touted and that its major use is the study of the long-term effects on humans of micro-gravity. That leaves the only possible reason for a human presence in space, exploration, the traditional reason that great risks in both lives and money have been taken. Setting up a base on the Moon is little different from the Space Station, just more expensive and accompanied by greater risk. Therefore its only justification has to be in terms of preparations for an expedition to Mars. Sustaining public interest in, and the willingness to continue to expend large sums on this decades long endeavor will be a significant challenge. The Apollo program enthralled the American (and the world's) people despite much of that decade being one of great social turmoil. We need to engender the same enthusiasm for a Mars program.

## ANSWERS TO POST-HEARING QUESTIONS

*Responses by John S. Lewis, Professor of Planetary Sciences, Co-director, Space Engineering Research Center, University of Arizona*

### Questions submitted by Chairman Dana Rohrabacher

*Q1. NASA's Office of Space Science is responsible for the lunar robotic portion of the Space Exploration Initiative. How would you recommend the office reach out to the science community to carry out this program? Is NASA using science advisory panels to select instrument proposals for upcoming missions?*

*A1.* NASA's traditional method of issuing an announcement of opportunity, receiving proposals, peer review, and selection is appropriate for use in future science missions. However, experiments directed toward resource extraction and processing enter new terrain, and there are no acceptable precedents. The one flight experiment on resource extraction selected to date was hand-picked by JSC without peer review and without competition, a poor precedent for the future. Further, the NASA organizational structures responsible for space resource processing have been repeatedly decimated, dissolved, and transplanted. A stable program office with competence in space resource processing is essential for further progress. How NASA will choose to handle this problem is completely unknown.

Changes in the administrative structures for resource-related research over the past 20 years, even when well-intended, have been poorly implemented. The unintentional cancellation of the NASA Universities Space Engineering Research Centers (as described to me privately by Dan Goldin) is a case in point. Another example was the decision to place space resource research under the aegis of the Microgravity Processing research program, which previously, over a period of several years, had insisted that it had no interest in processing extraterrestrial materials. The announcement of this new proposal opportunity by the Microgravity office was sent to their list of prior clients, none of whom had worked on space resource extraction, and the opportunity remained essentially unknown in the space resource community until after the money was awarded. These two fiascoes resulted in the permanent loss of some 90 percent of the research groups that had competence in this area.

The system for resource-related research is broken and must be fixed.

*Q2. The Space Exploration Initiative proposes establishing an extended human lunar mission. Based on your knowledge of the Moon's environment and resources, how difficult a task will it be to develop and sustain humans for a two-month period? For a stay of that duration, would it be practical to develop* in situ *resources to help sustain lunar astronauts? How about a six-month stay?*

*A2.* For sufficiently short mission durations, the advantages of resource utilization vanish. Basically, for short missions the mass of processing equipment may be greater than the mass of products needed, so that it would make more sense to carry the required products from Earth. Whether the break-even point lies at mission durations of one month, or two, or some other number depends in a complex way on the size and nature of the demand, the available power level, and the specific resources available at the site.

Note, however, that the time duration of a manned mission may be completely unrelated to the length of time the processing equipment can function: it would be highly desirable to land an automated processing unit well in advance of the arrival of a manned mission, so that an abundant supply of consumables (air, water, propellant) can be at hand from the moment of the crew's arrival on the Moon. With proper advance planning, any manned mission of any duration could profit from the prior emplacement of unmanned processing equipment.

### Questions submitted by Representative Nick Lampson

*Q1. Given the data acquired by the Apollo lunar landing program and its robotic precursors, as well as data obtained by the subsequent* Clementine *and* Lunar Prospector *spacecraft, what additional information, if any, will be needed before NASA can send humans back to the Moon by 2020?*

*A1.* Strictly speaking, no new data are required before the resumption of manned expeditions to the Moon. If, however, cost containment and operational flexibility are priorities, then resource characterization and small-scale demonstrations of processing schemes should both be accomplished before resumption of manned missions.

*Q2. What will it take to answer definitively the questions of how much water ice might be on the Moon? How much time is it likely to take to characterize the global availability of water on the lunar surface?*

- *How many remote-sensing missions will be necessary to obtain this complete characterization?*
- *What will it take to map other lunar resources?*

*A2.* It is actually more useful to know the concentration of ices, the chemical nature of the ices, and the vertical distribution of ice in the uppermost one or two meters of the regolith than it is to know the total magnitude of the ice deposits. From a practical point of view, it is not necessary to have a global understanding of the abundance and distribution of ice from the outset, only to have assurance that there is at least one locale where the resource constitutes a true ore body, meaning that the location, abundance, purity, extractability, suitability for processing, and proximity to a plausible site of demand combine to make the use of that resource profitable.

A single mission could, with luck, provide such data. With poor luck, dozens of lander missions in the polar regions may not find a single suitable location; indeed, there may not be any suitable locations.

Mapping of other attractive resources, such as ilmenite (a source of oxygen, high-purity iron, and refractory oxides) has already been accomplished to a remarkable degree from Earth and from spacecraft. Rich, wide-spread deposits are well documented. It is not obvious that better mapping would be of any practical significance.

Hydrogen mapping, aside from ice, can be done only very indirectly by remote sensing. Our experience with the Apollo samples shows that hydrogen and helium, both implanted by the solar wind in surface mineral grains in the near-side Mare basins, are strongly enriched in the mineral ilmenite. Therefore existing ilmenite maps are likely to be very good guides to the distribution of hydrogen. However, the concentration of hydrogen in even the most ilmenite-rich regions is generally no higher than 50 to 100 parts per million (50 to 100 grams per tonne).

Should helium-3 emerge as a desirable fusion fuel, the same ilmenite maps would serve as excellent guides to helium-3 “deposits” (recalling that the ceiling on the helium-3 concentration is about 0.01 parts per million).

In general, I remain skeptical of the practical value of polar ice and confident that other oxygen sources can be practically utilized.

*Q3. Would any of the scientific research you have discussed* require *astronauts on the Moon as opposed to robotic orbiters, landers, rovers, or research stations? If so, which research, and why? Does any of the scientific research or resource extraction you have discussed require a* permanent *human presence on the Moon? If so, how soon should that permanent human presence be established?*

*A3.* I shall consider only research oriented toward resource characterization and extraction, since these are the matters touched on in my testimony. The answer is that all such research missions can, and arguably should, be unmanned. The emphasis should be on lowering the cost and enhancing the capabilities of humans, when they eventually arrive, rather than using humans to search out and demonstrate resources.

The only resource whose extraction would clearly require a massive human presence is helium-3, but commercial-scale helium-3 extraction, if it ever becomes possible, is far in the future. A similar consideration applies to construction of lunar solar power stations.

My vision of the future of space travel is that permanent human presence anywhere will follow only if that presence generates benefits that justify the costs. Science exploration is a wonderful benefit, but will not carry us very far by itself. I simply do not see purely scientific endeavors as providing a justification for permanently manned lunar facilities. I regard it as premature and indefensible to arbitrarily set up a goal of having a permanent human presence on the Moon, Mars, or elsewhere in space. However, I regard it as completely plausible that some profitable activity may emerge as the result of acquiring a better understanding of the lunar environment. Such a self-supporting activity may, as others argue, involve utilization of lunar polar ice or helium-3, but I personally think that lunar solar power collection is a more probable economic foundation for permanent human presence.

*Q4. What would it take to be able to extract usable quantities of oxygen and hydrogen from the Moon for use as a rocket fuel? How long would it take to develop such a capability, and how much do you think it would cost? What is the most significant challenge in developing such a capability?*

*A4.* Extraction of oxygen from the lunar surface could in principle be carried out by any of over a dozen different processing schemes. A thorough engineering and cost assessment of all competing schemes has not yet been conducted. Nonetheless, for the sake of concreteness, I will outline one very simple scheme that would be appropriate for use in an early automated lander.

In this scheme, the lander carries a mechanical arm and scoop that can be used to reach and load regolith material. It also carries a tank of compressed hydrogen gas for use in the process. The scoop loads regolith material into a reaction vessel, which is then sealed. Hydrogen gas is admitted into the sealer reaction chamber and the regolith/gas mixture is heated by a parabolic solar collector to a dull red heat. At this temperature, the hydrogen gas reacts with iron oxides in the regolith minerals, principally ilmenite, olivine, and pyroxene, to extract oxygen from the iron oxides and make metallic iron and water vapor. The gas is slowly circulated through a condenser, and water is condensed and removed from the circulating stream of hydrogen gas. The remaining hydrogen is returned to the reaction chamber. The liquid water is tapped off and electrolyzed by a DC electric current, which can be provided by solar cells or a nuclear power supply. The products of electrolysis are hydrogen gas, which is returned to the reaction vessel, and oxygen, which is compressed and cooled to make liquid oxygen. This is our principal product.

Since the ilmenite in the regolith sample contains some hydrogen from the solar wind, the heating process will cause that gas to be released along with water vapor. Any hydrogen lost during the cycle will automatically be replaced or enhanced by the hydrogen released in this manner. The processing of 1000 pounds of regolith with a 20 percent ilmenite content uses up about two pounds of hydrogen and releases 24 pounds of water. Upon electrolysis, this amount of water makes about 22 pounds of oxygen and gives back the two pounds of hydrogen for reuse. The amount of solar wind hydrogen released by heating this amount of regolith is about another 0.1 pounds. With some care, the total supply of hydrogen may be slowly increased over time; however, it is clear that hydrogen extraction can never keep pace with oxygen extraction. The supply of hydrogen in the regolith is simply too small. In other terms, extracting 100 tons of hydrogen from the regolith requires heating one million tons of the most hydrogen-rich regolith and recovering its hydrogen content with perfect efficiency. Extracting 100 tons of oxygen, by contrast, requires processing only four thousand tons of regolith, equivalent to a cube of lunar dirt about 12 meters on a side.

Separating the lunar regolith powder to extract most of the ilmenite in rather pure form would make the chemical processing step far easier, since we would need to heat only 200 pounds of pure ilmenite to make the same 24 pounds of water. However, the separation process, called "beneficiation" in the minerals industry, requires crushing, sieving, and magnetic or electrostatic sorting of the mineral grains, all of which adds considerable complexity to the process. Rock crushing should not be undertaken lightly in the absence of a human crew to diagnose and repair the inevitable equipment breakdowns. Further, the loss of "sticky" ilmenite dust from the process and the difficulty of liberating ilmenite grains from the other minerals in the regolith rock fragments are both essentially unsolved problems. For this reason, I consider such "improvements" as inappropriate for early use on an automated lander.

Adopting the simpler process and processing bulk uncrushed, unsorted regolith appears simple enough so that a 100-pound demonstration experiment suitable for testing on the Moon could be built and made ready for flight in about two years. Building the equipment would be relatively quick and cheap compared to the cost of transporting it to the lunar surface with current rocket hardware. Costs could be reduced more dramatically by changing to competitive launch services than by any plausible changes in the payload itself. To my mind, the most severe technical challenge is making reliably air-tight seals on the processing chamber in the dusty operational environment.

*Q5. Science by itself is not going to sustain the public's support for the long-term program contemplated in the President's plan. After all, the 1960s Apollo lunar landing program had developed some impressive science capabilities, and Apollo 17 carried the first scientist-by-training (geologist Harrison Schmitt) to work on the Moon. Unfortunately, he was also the last. What is different enough about the ideas you are advocating here that will avoid the fate suffered by the Apollo program?*

*A5.* There is one overwhelming difference between the approach of the Apollo program and that which I advocate. The Apollo program was a very dramatic race, little constrained by considerations of cost, to make a political statement of American technical superiority *vis á vis* the Soviet Union. Quite the opposite, I propose and endorse the use of every plausible means to reduce costs, including use of private competitive launch services, the use of non-terrestrial resources to give space missions a high degree of self-sufficiency and autonomy, and the complementary use of manned and unmanned missions. I propose a diligent search, based on the intelligent use of unmanned small probes, for economically self-sufficient future activities on the Moon. I have discussed these issues with Jack Schmitt, and I am pleased to find that he agrees with these principles. We differ on our assessments of the likely profitability of different forms of lunar enterprise, but we differ because the evidence is at present inadequate to assess these competing forms of enterprise. We agree that small and early unmanned missions are required to reduce these uncertainties, and that plans for the longer term must await the results of these studies.

My vision of the future is not a governmental "space program" supported by massive federal infusions of funds. My vision assigns to the Federal Government the responsibility for fundamental scientific research and technology development, and leaves to industry and commerce the task of making a profit in space and paying taxes on their profits. My vision is a space enterprise dominated by organizations that pay tax dollars, not those that spend them. It is a democratic and capitalistic, not a socialist and government-monopolist, vision.

## ANSWERS TO POST-HEARING QUESTIONS

*Responses by Timothy D. Swindle, Professor of Geosciences and Planetary Sciences, University of Arizona*

### Questions submitted by Chairman Dana Rohrabacher

*Q1. Please provide your views on what roles the private sector, including businesses and educational institutions, can contribute to the successful development and exploitation of lunar resources, and to the provision of services in support of NASA's lunar exploration program.*

- *Based on current capabilities, do you believe the private sector has unique expertise needed by NASA to return to the Moon?*
- *What are the biggest obstacles to private sector participation in lunar exploration and resource exploitation activities?*
- *Once NASA has established a long-term presence on the Moon, are there markets you believe could be exploited by private industry, and if so, what might they be?*

*A1.* I won't comment about the obstacles to private sector participation, since that is not something that I have considered in any detail. Whether there are markets that can be exploited by private industry will depend on the scale of the presence on the Moon. As Dr. Lewis said in his testimony, while there are lunar resources that can be very valuable, most of them are valuable only on or near the Moon. The two exceptions that have been suggested most prominently are the use of 3He as a fusion reactor fuel, and the use of lunar solar power "farms" to generate energy to be beamed back to Earth. As I said, I believe that the first, which I have studied, will be a very large and difficult project, though it should not be ruled out. Sending solar power generated on the Moon back to Earth is a concept that certainly deserves more study.

*Q2. NASA's Office of Space Science is responsible for the lunar robotic portion of the Space Exploration Initiative. How would you recommend the office reach out to the science community to carry out this program? Is NASA using science advisory panels to select instrument proposals for upcoming missions?*

*A2.* The Office of Space Science has been pursuing a program for exploration that includes a mixture of missions that are arrived at by some consensus method and missions that are proposed by individual investigators and then chosen by peer review. For example, NASA requested a "decadal survey" of the scientific community. This document, produced under the auspices of the National Research Council and released in 2002, received input from a large fraction of the scientific community, and so far has been used by the Office of Space Sciences. One of the first things the Aldridge Commission did was to seek the input of scientists at the annual Lunar and Planetary Science Conference, which is attended by the vast majority of lunar scientists. Assuming the commission's recommendations reflect that input, and that NASA follows those recommendations, that is an appropriate approach.

*Q3. The Space Exploration Initiative proposes establishing an extended human lunar mission. Based on your knowledge of the Moon's environment and resources, how difficult a task will it be to develop and sustain humans for a two-month period? For a stay of that duration, would it be practical to develop* in situ *resources to help sustain lunar astronauts? How about a six-month stay?*

*A3.* I have not studied the problem of development of lunar bases, so I will not reply.

### Questions submitted by Representative Nick Lampson

*Q1. Given the data acquired by the Apollo lunar landing program and its robotic precursors, as well as data obtained by the subsequent* Clementine *and* Lunar Prospector *spacecraft, what additional information, if any, will be needed before NASA can send humans back to the Moon by 2020?*

*A1.* Given the success of the Apollo program, it is clear that for very short stays at some places on the Moon, we do not need any additional information. For stays at other locations that are not as well-mapped from orbit as the Apollo sites, we would need imagery comparable to that used in the Apollo program. For longer, or permanent, stays, we need to have information on what resource utilization schemes can work. Some of this is laboratory work, simply designing and testing potential equipment, but I would think that we would need missions to at least test those schemes that seem most promising in the lunar environment.

*Q2. What will it take to answer definitively the question of how much water ice might be on the Moon? How much time is it likely to take to characterize the global availability of water on the lunar surface?*

- *How many remote-sensing missions will be necessary to obtain this complete characterization?*

*A2.* I will defer to Drs. Campbell and Spudis, who have far more expertise on this than I do.

*Q3. What will it take to map other lunar resources?*

*A3.* It depends on the resource. For $^3$He, it would require one or two sample returns from specific places (far-side sites with relatively high titanium) as well as one or two missions to the surface to investigate the properties of the lunar "regolith" (soil) in more detail. For most other resources, where the proposals have been simply for extraction of relatively common materials from the lunar regolith, the requirement is again to learn enough about the properties of the regolith to be able to implement extraction schemes. In particular, for many techniques, it is crucial to learn more about how the properties of the regolith change with depth, but a lot of that could be learned with one or two fairly simple missions.

*Q4. Would any of the scientific research you have discussed* require *astronauts on the Moon as opposed to robotic orbiters, landers, rovers, or research stations? If so, which research, and why? Does any of the scientific research or resource extraction you have discussed require a* permanent *human presence on the Moon? If so, how soon should that permanent human presence be established?*

*A4.* Any research that requires the selection of samples will be far more effective with astronauts than without, for the simple fact that a human brain coupled with the human visual system can make selections much more efficiently than any robotic system yet designed. In Antarctic tests, a sophisticated robot designed to search for meteorites was far inferior to non-geologists with a few days of training. Much of the science on the Moon could be done without humans by a brute force technique, simply acquiring many more samples than are really needed, in hopes of finding the right ones. However, humans are remarkably good at finding the "right" sample, as was amply demonstrated by the well-trained Apollo astronauts. Using humans to operate things by telepresence would be an intermediate option, but even that would work far better with the remote presence on the Moon, with virtual no delay between command and response, than on Earth, with the delay caused by the finite speed of light. On the other hand, science that involves measuring global or average properties is far less likely to need human presence. As an extreme case, information that can be determined best from lunar orbit is unlikely to gain much, if any, benefit from the presence of humans.

A large portion of most resource utilization schemes could probably be done robotically. However, the more complex the task and the equipment, the more likely it is that there will be equipment failures of one sort or another. In these cases, a human with a tool kit is far more valuable than any robotic service mission.

Whether any of this requires permanent human presence probably depends on the scale of activities. If only low-level activity is planned, occasional human presence, to go collect a particular set of samples or to service a particular piece of equipment, would be sufficient. The more ambitious the plans, the more valuable continuous human presence would be.

*Q5. Science by itself is not going to sustain the public's support for the long-term program contemplated in the President's plan. After all, the 1960s Apollo lunar landing program had developed some impressive science capabilities, and Apollo 17 carried the first scientist-by-training (geologist Harrison Schmitt) to work on the Moon. Unfortunately, he was also the last. What is different enough about the ideas you are advocating here that will avoid the fate suffered by the Apollo program?*

*A5.* Science was never the primary purpose of the Apollo program, simply getting to the Moon was. Although the astronauts did a wonderful job as scientists, that was only their secondary purpose. Furthermore, the science that they did was not that compelling to the non-scientist, since it was really exploratory, just trying to figure out as much about the Moon as possible.

We now know enough about the Moon to understand that the Moon provides a record of early events, particularly impacts, whose record is lost on Earth. Furthermore, this is intimately tied not only to the impact history of the Earth, but to the origin of life on Earth. Hence, by studying this portion of the Moon's history, we now recognize that we are studying the question of the origin of life itself, one of the most compelling questions in science at the start of this century.

While this science will never be enough to justify the entire Moon-Mars initiative, it is enough to be easily understood as a crucial and worthwhile component.