AN UPDATE ON NASA EXPLORATION SYSTEMS DEVELOPMENT

HEARING

BEFORE THE

SUBCOMMITTEE ON SPACE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

ONE HUNDRED FIFTEENTH CONGRESS

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November 9, 2017

AN UPDATE ON NASA EXPLORATION SYSTEMS DEVELOPMENT

Thursday, November 9, 2017

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

The Subcommittee met, pursuant to call, at 9:37 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Brian Babin [Chairman of the Subcommittee] presiding.

LAMAR S. SMITH, Texas
CHAIRMAN

EDDIE BERNICE JOHNSON, Texas
RANKING MEMBER

Congress of the United States
House of Representatives

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
2321 RAYBURN HOUSE OFFICE BUILDING
WASHINGTON, DC 20515–6301
(202) 225–6371
www.science.house.gov

An Update on NASA Exploration Systems Development

Thursday, November 9, 2017
9:30 a.m.
2318 Rayburn House Office Building

Witnesses

Mr. William Gerstenmaier, Associate Administrator, Human Exploration and Operations Directorate, NASA

Dr. Sandra Magnus, Executive Director, American Institute of Aeronautics and Astronautics (AIAA)

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

Charter

TO:	Members, Committee on Science, Space, and Technology
FROM:	Majority Staff, Committee on Science, Space, and Technology
DATE:	November 9th, 2017
SUBJECT:	Space Subcommittee Hearing: "An Update on NASA Exploration Systems Development"

On Thursday, November 9, 2017 at 9:30 a.m. in Room 2318 of the Rayburn House Office Building, the Committee on Science, Space, and Technology, Subcommittee on Space, will hold a hearing titled, "An Update on NASA Exploration Systems Development."

Hearing Purpose

The purpose of the hearing is to examine the development of the Space Launch System, Orion Crew Vehicle and the associated ground systems.

Witnesses

- **Mr. William Gerstenmaier**, Associate Administrator, Human Exploration and Operations Directorate, NASA
- **Dr. Sandra Magnus**, Executive Director, American Institute of Aeronautics and Astronautics (AIAA)

Staff Contact

For questions related to the hearing, please contact Mr. Tom Hammond, Staff Director, Space Subcommittee, Mr. G. Ryan Faith, Professional Staff Member, Space Subcommittee, or Ms. Sara Ratliff, Policy Assistant, Space Subcommittee, at 202-225-6371.

Chairman BABIN. Good morning. The Subcommittee on Space will come to order.

Without objection, the Chair is authorized to declare recesses of the Subcommittee at any time.

Welcome to today's hearing titled "An Update on NASA Exploration Systems Development."

I now recognize myself five minutes for an opening statement.

Exploration means expanding our reach as humans, as a civilization and as a country. The ability of our nation to explore space is a strategic imperative. Our ability to carry out this critical strategic endeavor will rely on a few key capabilities. We must launch the Space Launch System in order to push beyond low-Earth orbit. We must finish developing the Orion capsule in order to operate in deep space. And we must upgrade our ground infrastructure to support a rejuvenated and an expanded exploration agenda.

NASA's long-term goal, as laid out in the 2017 NASA Transition Authorization Act, is to extend human presence throughout the Solar System. The Space Launch System and Orion are the strategic capabilities that will allow and enable humans and robots to accomplish this goal. SLS and Orion will enable U.S. astronauts to return to the Moon for the first time since Gene Cernan left his daughter's name in the lunar regolith in 1972.

As Vice President Pence said in his inaugural meeting of the reestablished National Space Council, "We will return American astronauts to the Moon, not only to leave behind footprints and flags, but to build the foundation that we need to send Americans to Mars and beyond." SLS and Orion are the tip of the spear that will lead that return. The commercial sector can contribute by supplying necessary services and providing augmenting capabilities, but SLS and Orion are irreplaceable strategic assets that are necessary for missions to the Moon, Mars, and beyond.

One of the first major laws that President Trump signed was the NASA Transition Authorization Act of 2017. The bill, which originated with this Committee, directed NASA to stay the course with SLS and Orion. It also reaffirmed congressional and presidential direction for NASA to utilize a stepping-stone approach to exploration, which allows for a return to the Moon.

I wholeheartedly support the Administration's call to return to the Moon. This Committee has received testimony time and again that the Moon is the appropriate next destination for our space program. Returning to the Moon does not have to mean delaying a mission to Mars. On the contrary, it is a logical step that enables exploration of the red planet and beyond.

And while I'm excited by the promise of how strategic assets like SLS and Orion will enable America to return to the Moon, this committee has a responsibility to conduct oversight to ensure that these programs are successful. All three exploration system elements—SLS, Orion, and Ground systems—have experienced delays and overruns. This year has certainly challenged the program.

Last year, Michoud in Louisiana was hit by a tornado. In August, Texas and Florida were hit by hurricanes. A couple years ago the Michoud's Vertical Assembly Facility foundation was not reinforced, requiring a rebuild. This year, complications with friction stir weld pins at Michoud resulted in poor welds on the core stage.

All of this adds up. It appears as though the new issues with tornados and hurricanes and welding will cost roughly a year of delay. Depending on whether the Europeans deliver the service module on time for integration on Orion, the delay may be greater.

Congress needs to understand where the program is today. What cost, schedule, and performance deliverables can the agency commit to? What is the plan going forward? How will NASA manage future issues to ensure long-term program sustainability? We aren't out of the woods yet on this program, but we can see the edge of the forest. Significant progress has been made. We're bending metal, writing software code, and integrating hardware. Given a program of this magnitude, this is no small feat, particularly given the challenges that the program faced under the last administration.

In order to meet our nation's space exploration goals, it will take focus, discipline, and continuity of efforts going forward. The Administration and Congress must not only provide leadership and direction, but we must also appropriately fund and oversee the program. Similarly, NASA and the contractors have to execute. Failure to do so could have dire consequences for the program, and there will be no one else to blame.

The Administration has demonstrated its renewed support. Congress consistently funds the program at healthy levels. It is time for NASA and the contractors to deliver.

I am thankful that our witnesses are here today to help us better understand where we are with the program and how we plan to move forward, and I look forward to your testimony.

[The prepared statement of Chairman Babin follows:]

COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

For Immediate Release
November 9, 2017

Media Contacts: Thea McDonald, Brandon VerVelde
(202) 225-6371

Statement from Brian Babin (R-Texas)

An Update on NASA Exploration Systems Development

Chairman Babin: Exploration means expanding our reach as humans, as a civilization and as a country. The ability of our nation to explore space is a strategic imperative. Our ability to carry out this critical strategic endeavor will rely on a few key capabilities.

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SLS and Orion are the tip of the spear that will lead that return. The commercial sector can contribute by supplying necessary services and providing augmenting capabilities, but SLS and Orion are irreplaceable strategic assets that are necessary for missions to the moon, Mars and beyond.

One of the first major laws that President Trump signed was the NASA Transition Authorization Act of 2017. The bill, which originated with this committee, directed NASA to stay the course with SLS and Orion. It also reaffirmed congressional and presidential direction for NASA to utilize a "stepping stone approach" to exploration, which allows for a return to the moon. I wholeheartedly support the administration's call to return to the moon. This committee has received testimony time and again that the moon is the appropriate next destination for our space program. Returning to the moon does not have to mean delaying a mission to Mars. On the contrary, it is a logical step that enables exploration of the red planet and beyond.

While I am excited by the promise of how strategic assets like SLS and Orion will enable America to return to the moon, this committee has a responsibility to conduct oversight to ensure these programs are successful.

All three exploration system elements — SLS, Orion and Ground Systems — have experienced delays and overruns. This year has certainly challenged the program. Last spring, Michoud was hit by a tornado. In August, Texas and Florida were hit by hurricanes. A couple years ago the Michoud's Vertical Assembly Facility foundation was not reinforced, requiring a rebuild. This year, complications with friction stir weld pins at Michoud resulted in poor welds on the core stage. All this adds up.

It appears as though the new issues with tornados, hurricanes and welding will cost roughly a year of delay. Depending on whether the Europeans deliver the service module on time for integration on Orion, the delay may be greater.

Congress needs to understand where the program is today. What cost, schedule and performance deliverables can the agency commit to? What is the plan going forward? How will NASA manage future issues to ensure long-term program sustainability?

We aren't out of the woods yet on this program, but we can see the edge of the forest. Significant progress has been made. We are bending metal, writing software code and integrating hardware. Given a program of this magnitude, this is no small feat — particularly given the challenges the program faced under the last administration.

In order to meet our nation's space exploration goals, it will take focus, discipline and continuity of effort going forward. The administration and Congress must not only provide leadership and direction, but we also have to appropriately fund and oversee the program. Similarly, NASA and the contractors have to execute. Failure to do so could have dire consequences for the program, and there will be no one else to blame. The administration has demonstrated its renewed support. Congress consistently funds the program at healthy levels. It is time for NASA and the contractors to deliver.

I am thankful that our witnesses are here today to help us better understand where we are at with the program, and how we plan to move forward. I look forward to your testimony.

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Chairman BABIN. I now recognize the Ranking Member, the gentleman from California, Mr. Bera, for an opening statement.

Mr. BERA. Thank you, Mr. Chairman. And good morning to our distinguished panel.

This is a great hearing and a great time for this hearing to get an update on NASA's exploration systems development activities. NASA continues to progress, but as the Chairman pointed out, there have been some challenges beyond their control in developing key elements needed to move humans beyond low-Earth orbit and eventually send them to Mars.

Construction of the Space Launch System, the Orion crew vehicle, and ground infrastructure at Kennedy Space Center is well underway. Major components for Exploration Mission 1, also known as EM–1, and EM–2, are undergoing fabrication and testing. For example, in August 2017, NASA completed the—welding the liquid oxygen tank that is scheduled for use on the SLS launch vehicle to be flown on EM–1. The Orion spacecraft destined for EM–1 was successfully powered up for the first time in August 2017 and on October 19, 2017, NASA engineers conducted a full duration 500-second test of one of the RS–25 flight engines to be used on EM–2.

NASA and industry partners have not undertaken a rocket development program of this scale for more than three decades. In addition to new hardware and infrastructure, this has also necessitated reestablishing critical capabilities needed for U.S. leadership in deep space exploration. This is not just work NASA and its prime contractors are doing. Over 1,000 suppliers spread across every State are part of this program. However, a program of this size does not happen without challenges, and NASA's human space exploration program is facing several, including having to maintain manufacturing, test, and processing schedules as SLS, Orion, and EGS are integrated; the recovery from tornado damage at the Michoud Assembly Facility that the Chairman mentioned; resolve first-time production issues for SLS elements; and adjust activities in response to unpredictable appropriations funding.

As the Chairman pointed out, independent analysis by GAO and NASA's Office of Inspector General have also identified concerns with NASA's ability to meet projected launch dates. For instance, in an April 2017 report, GAO found that despite SLS, Orion, and EGS activities making progress, "schedule pressure is escalating as technical challenges continue to cause schedule delays." GAO characterized NASA's planned launch date of November 2018 as "precarious."

Part of what I hope to get out of today's hearing is a better understanding of what that clear plan and an updated launch date for EM–1, as well as the opportunity to continue examining other important issues, including the reasons for the latest delay in launching EM–1 and the basis for having confidence in NASA's plan moving forward; indicators and milestones Congress should use for measuring progress being made both by the SLS, Orion, and EGS programs and by NASA in establishing a production capability; and how a return to the Moon, including establishing a human presence, would impact the goal of sending humans to Mars in the 2030s, as directed in the 2017 NASA Transition Authorization Act.

In closing, Mr. Chairman, you've often heard me talk about growing up in the middle of the Space Race, growing up in Downey, California, home of much of the Apollo mission and how that inspired me, along with a generation of kids, to think about the sciences and beyond. What we're talking about in terms of the systems that we're developing today is a reestablishment of American leadership in the space program as we start to think about going back to the Moon and going beyond into deep space. And that does have the ability to inspire another generation of kids and reinvigorate our desire to explore our curiosity about the universe around us.

One of those inspirational figures of the nation's human space program is actually with us today. Dr. Magnus has flown on the shuttle and lived on the International Space Station. We thank you, Dr. Magnus, for your service and appreciate you being a role model for millions of young people.

I look forward to the testimony and I yield back.

[The prepared statement of Mr. Bera follows:]

OPENING STATEMENT
Ranking Member Ami Bera (D-CA)
of the Subcommittee on Space

Committee on Science, Space, and Technology
Subcommittee on Space
"An Update on NASA Exploration Systems Development"
November 9, 2017

Good morning. And welcome to our distinguished panel. Thank you Mr. Chairman for calling this hearing to receive an update on NASA's exploration systems development activities.

NASA continues to progress, under challenging circumstances, in developing key elements needed to move humans beyond low-Earth orbit and eventually send them to Mars. Construction of the Space Launch System, the Orion Crew Vehicle, and ground infrastructure at the Kennedy Space Center is well underway. Major components for Exploration Mission-1, also known as EM-1, and EM-2 are undergoing fabrication and testing. For example:

- In August 2017, NASA completed welding the liquid oxygen tank that is scheduled for use on the SLS launch vehicle to be flown on EM-1;
- The Orion spacecraft destined for EM-1 was successfully powered up for the first time in August 2017; and
- On October 19, 2017, NASA engineers conducted a full-duration, 500-second test of one of the RS-25 flight engines to be used on EM-2.

NASA and industry partners have not undertaken a rocket development program of this scale for more than three decades. In addition to new hardware and infrastructure, this has necessitated re-establishing critical capabilities needed for U.S. leadership in deep space exploration. This is not just the work of NASA and its prime contractors. Over one thousand suppliers spread across every state are part of this program. However, a program of this size does not happen without challenges, and NASA's human space exploration program is facing several, including having to

- maintain manufacturing, test, and processing schedules as SLS, Orion, and EGS are integrated;
- recover from tornado damage at Michoud Assembly Facility suffered last February;
- resolve first time production issues for SLS elements; and
- adjust activities in response to unpredictable appropriations funding

Independent analyses by GAO and NASA's Office of Inspector General have also identified concerns with NASA's ability to meet projected launch dates. For instance, in an April 2017 report, GAO found that despite SLS, Orion, and EGS activities making progress, "*schedule pressure is escalating as technical challenges continue to cause schedule delays*". GAO characterized NASA's planned launch date of November 2018 as "precarious".

I hope that today's hearing will provide us with a clear plan and an updated launch date for EM-1, as well as the opportunity to examine other important issues, including:

- The reasons for the latest delay in launching EM-1 and the basis for having confidence in NASA's plans moving forward;
- Indicators and milestones Congress should use for measuring progress being made both by the SLS, Orion, and EGS programs and by NASA in establishing a production capability; and
- How a return to the Moon, including establishing a human presence, would impact the goal of sending humans to Mars in the 2030s, as directed in the 2017 NASA Transition Authorization Act.

In closing Mr. Chairman, I have frequently shared how the Apollo Program and President Kennedy's vision for space inspired me to become a medical doctor. The systems under development that we are discussing today are an investment. They are an investment in our continued leadership in space exploration, in our ability to one day send humans to Mars, and in the dreams of the next generations of Americans to be part of that journey.

One of the inspirational figures of the Nation's human space program is with us today. Dr. Magnus has flown on the Shuttle and lived on the International Space Station. We thank her for her service and appreciate her being a role model for millions of young people. I look forward to today's testimony and I yield back.

Chairman BABIN. Thank you. I couldn't agree more, Mr. Bera.

I now recognize the Chairman of our full committee, Mr. Smith.

Chairman SMITH. Thank you, Mr. Chairman. And I appreciate your comments and the Ranking Member's comments as well.

Congress has supported NASA's Exploration Systems program for years. We have showed this support in law and with funding, from one Administration to the next. After all these years, after billions of dollars spent, we are facing more delays and cost overruns. Recent hurricanes and tornadoes have damaged some facilities and slowed localized progress, but many of the problems are self-inflicted. It is very disappointing to hear about delays caused by poor execution when the U.S. taxpayer has invested so much in these programs.

For the last eight years, Congress has defended the Space Launch System and Orion crew vehicle from attempts at cancellation and proposed budget cuts. Funding for the Exploration Systems Development now is nearly $4 billion a year.

The Government Accountability Office reported last spring that the first launch of the SLS likely will be delayed a year from late 2018 to late 2019. Delays with the European Service Module also could push this into 2020. If this is the case, the schedule for the first launch with crew is also at risk because the time needed to upgrade the mobile launch platform.

The NASA Inspector General reported this week that the development of Exploration Systems is one of the most significant challenges facing NASA. The IG highlighted problems facing all components of the system: SLS, Orion, and the Ground Systems. NASA and the contractors should not assume future delays and cost overruns will have no consequences. If delays continue, if costs rise, and if foreseeable technical challenges arise, no one should assume the U.S. taxpayers or their representatives will tolerate this forever.

Alternatives to SLS and Orion almost certainly would involve significant taxpayer funding and lead to further delays. But the more setbacks SLS and Orion face, the more support builds for other options. Other space exploration programs at NASA, like the Commercial Crew Program, also are facing significant delays and challenges.

NASA has suffered for decades from program cancelations that have delayed exploration goals. As NASA's exploration systems progress from development to production, operations and maintenance, NASA and its contractors must bring down costs and guarantee that deadlines are met. To this end, I was glad to see NASA issue a request for information last November in order to explore ways to reduce costs. Moving to firm fixed-price contracts for production might be an appropriate path going forward, but only if it benefits the taxpayer.

Congress needs to have confidence in NASA and the Exploration Systems contractors, which I don't believe we have now. That confidence is ebbing. If it slips much further, NASA and its contractors will have a hard time regaining their credibility.

Thank you, Mr. Chairman. I yield back.

[The prepared statement of Chairman Smith follows:]

COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

For Immediate Release
November 9, 2017

Media Contacts: Thea McDonald, Brandon VerVelde
(202) 225-6371

Statement from Lamar Smith (R-Texas)

An Update on NASA Exploration Systems Development

Chairman Smith: Congress has supported NASA's Exploration Systems program for years. We have expressed this support in law and with funding, from one administration to the next.

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NASA has suffered for decades from program cancellations that have delayed exploration goals.

As NASA's exploration systems progress from development to Production, Operations and Maintenance, NASA and its contractors must bring down costs and guarantee deliveries on time.

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###

Chairman BABIN. Thank you, Mr. Chairman.

Now, let me introduce our witnesses. Our first witness today is Mr. Bill Gerstenmaier, Associate Administrator of the Human Exploration and Operations Mission Directorate at NASA. Mr. Gerstenmaier began his NASA career in 1977 performing aeronautical research, and he has managed NASA's human spaceflight portfolio since 2011.

He received a bachelor's of science in aeronautical engineering from Purdue University and a master's of science in mechanical engineering from the University of Toledo.

Our second witness today is Dr. Sandra Magnus, Executive Director at the American Institute of Aeronautics and Astronautics, AIAA. In addition to her role at AIAA, Dr. Magnus is a former NASA astronaut and, prior to that, worked as a practicing engineer in the aerospace industry.

Dr. Magnus received a degree in physics, as well as a master's degree in electrical engineering, both from Missouri University of Science and Technology. She also earned a Ph.D. from the School of Material Science and Engineering at Georgia Tech.

And I now recognize Mr. Gerstenmaier for five minutes to present his testimony.

TESTIMONY OF MR. WILLIAM GERSTENMAIER, ASSOCIATE ADMINISTRATOR, HUMAN EXPLORATION AND OPERATIONS DIRECTORATE, NASA

Mr. GERSTENMAIER. Thank you.

We're living in an amazing time in human spaceflight. NASA and our international partners have had crewmembers living onboard the International Space Station for more than 17 consecutive years. Most high school students today have only known a time when humans were living and working in space.

We are using the space station to expose a broader community beyond the current space industry the benefits of using microgravity as an environment to develop new systems and techniques for use on the Earth. These new companies and researchers have never seen the benefits of space to their products and processes. The space station is becoming a place for business to expand, grow, and gain competitive advantage over companies not doing research in space. Just as having crews in space is now accepted, business operating in space will become normal and accepted.

NASA has bought services for cargo delivery from two companies and is adding a third. The agency is in the process of acquiring services and certifying two new systems to transport crews to the ISS. These companies are busy manufacturing and certifying their systems. Our partners in low-Earth orbit are helping build a strong commercial space industry and this allows us to focus our efforts on deep space exploration, which brings us to the subject of today's hearing: exploration systems development.

NASA's Space Launch System rocket, the Orion deep space capsule with the European Service Module, and Ground System programs are undergoing manufacturing and certification in preparation for their first integrated flight. Just think about it. There is more human spaceflight hardware in production today than at any time in the United States since Apollo.

As a nation, we are building three different crew vehicles: Orion, Starliner, and Dragon, one for deep space and two for low-Earth orbit. Getting to this point was not easy, and there are still challenges ahead. However, we all need to pause and reflect on this amazing time.

As we pursue human exploration further into the solar system, our exploration teams are building more than a rocket and a spacecraft for a single flight. Rather, we are building a flexible, sustainable system that will be used for decades to come. With this approach, we can incrementally upgrade and enhance our exploration systems to accomplish a variety of missions, crewed and un-crewed in deep space.

We are also building a system designed with modern manufacturing technique for lower production costs than previous designs. The work performed in support of SLS and Orion has applications to other programs in aerospace. For example, hundreds of requests for information have been transferred from Orion to the commercial spacecraft in development for low-Earth orbit. The work on self-reacting—reaction friction stir welding developed for SLS will have application beyond SLS to other launch vehicles in development.

It is the proper role of government to develop capabilities for use by all. Hardware to support the multiple flights has been built. Three Orion crew modules, one structural test article, one flown during Exploration Flight Test 1, and the current flight article have all been built for Orion. Four major test stands are complete at Marshall. The engine section structural testing is fully complete at Marshall. The vertical assembly building at KSC is complete. The launch pad is nearing completion. All RS–25 engines and controllers are ready for flight.

Seventeen parachute development tests are complete. Four qualification parachute tests are complete with four more open. The data from these parachute tests are helping our commercial crew partners with their tests also.

The amount of work completed today for the deep space exploration system is large, and it is documented in my written testimony. Further, this government investment in SLS and Orion is benefiting all. We need to be careful and not focus on a single launch date projection but rather take time to examine the quality, quantity, and future benefit of the work completed. This deeper examination will reveal the value of the work completed to the nation.

NASA has carefully reviewed the work remaining to the launch, including certification, and while this review shows EM–1 launch date of June 2020 is possible, the agency has chosen to manage to a December 2019 launch. This earlier launch date is reasonable and challenges the teams to stay focused on tasks without creating undue pressure. Furthermore, NASA's taking additional steps to reduce schedule risk for both known and unknown issues and protect for the earliest possible launch date. The cost for EM–1, even with the June date, remain within the 15 percent limit for SLS and are slightly above for Ground Systems operations. Exploration Mission 2, Orion costs, and schedule are not adversely impacted by the EM–1 schedule, and, as discussed earlier, the work completed by SLS, Orion, and GSDO shows outstanding progress.

I welcome your questions and thank you for this opportunity to discuss the amazing work accomplished by the men and women of NASA and their contractor partner teams. Thank you.

[The prepared statement of Mr. Gerstenmaier follows:]

HOLD FOR RELEASE
UNTIL PRESENTED
BY WITNESS
Nov. 9, 2017

Statement of
William H. Gerstenmaier
Associate Administrator for Human Exploration and Operations
National Aeronautics and Space Administration

before the

Subcommittee on Space
Committee on Science, Space, and Technology
U. S. House of Representatives

Mr. Chairman and Members of the Subcommittee, thank you for the opportunity to appear before you today to discuss NASA's progress on our Exploration Systems Development (ESD) programs: the Space Launch System (SLS) heavy-lift launch vehicle, the Orion deep space crew vehicle, and the Exploration Ground Systems (EGS) that provide critical integration and launch infrastructure for these vehicles. The ESD programs are creating a new space transportation capability, the first components of an architecture for human exploration beyond low-Earth orbit (LEO) and into cislunar space. It is in cislunar space where NASA intends to conduct deep space missions to test systems and concepts, paving the way for long-duration human space exploration including missions to the Moon and Mars.

NASA is now in the fabrication and assembly phase of developing SLS, Orion, and EGS, and is focused on bringing these capabilities together to conduct the first Exploration Missions. Exploration Mission-1 (EM-1) is the first integrated test of these new transportation systems. Launching atop SLS, an uncrewed Orion spacecraft will travel into space for up to a 25-day journey beyond the Moon and back to Earth. EM-1 is a test flight, but will also include a payload of several CubeSats that will be deployed to perform a variety of scientific investigations, such as to analyze the presence of water and ice on the Moon, visit and examine a near-Earth asteroid, and detect and measure radiation levels. The data that we gather from these CubeSats will be used to better understand our solar system and, in particular, cislunar space. Production is also underway on flight hardware for the first crewed mission, EM-2, which is planned to launch no later than 2023.

Space Launch System

SLS is planned as a national capability and designed as a heavy-lift launch vehicle for transporting humans and cargo to space. It can also be used as a cargo delivery rocket to enable science missions to reach remote destinations faster, though there are tradeoffs that should be considered when comparing to commercially available vehicles, such as cost and performance. SLS is intended to launch astronauts in the Orion spacecraft on missions to cislunar space. In future updates, it will have the highest-ever payload mass and volume capability, and enough energy to dramatically reduce travel times to deep space destinations. This will enable larger payloads beyond LEO.

SLS capabilities are planned to evolve using a block upgrade approach. SLS Block 1 will have the capability to carry over 70 metric tons to LEO and nearly 30 metric tons toward the Moon, which for the first flight will be used to launch the Orion capsule. The next evolution of the SLS, Block 1B, incorporates a new upper stage, the Exploration Upper Stage (EUS), now under development, along with updates to associated adaptors. With these planned updates, Block 1B will improve vehicle lift performance to over 105 metric tons to LEO and 40 metric tons to cislunar space, and enable an increase in payload diameter from 5 meters to 7.5 meters and total payload volume from 255 cubic meters to over 900 cubic meters, all of which are capabilities that could help enable deep space exploration.

SLS leverages over a half-century of experience with launch vehicles, including Saturn and Space Shuttle, along with advancements in technology since that time, including model-based engineering, additive manufacturing, high-fidelity computational fluid dynamics capabilities, new composite materials and production techniques, and large-scale self-reaction friction stir welding. Additionally, initial flight units use components already owned from the Space Shuttle, such as RS-25 engines and boosters. More efficient methods are under development for manufacturing these components, including new NASA investment in expendable RS-25 engines for the SLS Core Stage with the goal of achieving a lower per-unit cost than the original reusable RS-25s used as the Space Shuttle Main Engines. The Agency continues to identify affordability strategies for missions beyond EM-2. Reducing overall costs of the systems will be critical to achieving a successful and sustainable exploration capability.

In FY 2017, SLS continued to progress towards EM-1, and concurrently, develop the Block 1B vehicle. The Program completed the Orion Stage Adapter (OSA)/Interim Cryogenic Propulsion Stage (ICPS)/Launch Vehicle Stage Adapter (LVSA) integrated structural test qualification phase ahead of schedule. The ICPS has been delivered to the Kennedy Space Center in Florida and is now in storage at the Space Station Processing Facility. In February 2017, an F-3 tornado caused significant damage on the site of the Michoud Assembly Facility (MAF) in Louisiana where the Core Stage is manufactured. Thanks to the extraordinary work of personnel at MAF and the swift passage of an emergency supplemental bill that will support damage repairs, production at MAF was quickly restored, enabling the Program to complete a major milestone with the completion of major welding of the five large Core Stage sections (forward section, liquid oxygen tank, intertank, liquid hydrogen tank, and engine section) in the Vertical Assembly Center (VAC). The VAC is the largest of the six new large welding tools at MAF; together, these tools represent a major advance in manufacturing technology that reduces the number of tools and touch labor by 50 percent compared to Space Shuttle External Tank production.

The SLS program also completed the Core Stage Pathfinder build. The Pathfinder, a full-sized 212 foot long, 228,000 pound replica of the SLS Core Stage, will be used to test shipping and handling equipment and procedures at the Stennis Space Center (SSC) in Mississippi (where the Core Stage will be test fired on the B-2 test stand) and Kennedy Space Center (KSC). For Core Stage engines, NASA engineers closed a summer of successful hot fire testing for flight controllers on the RS-25 engines that will help power the SLS. The 500-second hot fire of a RS-25 engine flight controller unit on the A-1 Test Stand at SSC marks the completion of the engine adaptation testing to certify the former Space Shuttle engines for use in the more challenging SLS environment. The test series also certified the new engine controllers and new control software for EM-1. All EM-1 Core Stage engines have now completed their single-engine test sequences and are being packaged for delivery to MAF for integration into the Core Stage in FY 2018.

Finally, the SLS Program began manufacturing on a number of components for the EM-2 mission, including completing major welding of the EM-2 core stage engine section in FY 2017 and completion of the EUS Preliminary Design Review (PDR), which validates progress to critical design and fabrication.

In FY 2018, Core Stage integration and outfitting (including installation of the four RS-25 engines) will continue at MAF, though challenges remain to completing production of the Core Stage and delivery to the Stennis Space Center in Mississippi in December 2018 for the Green Run test sequence. FY 2018 will also see a series of EM-1 flight hardware deliveries to EGS at KSC, starting this month with the hand-over of the ICPS, followed by the OSA and LVSA. The EM-1 Booster segments will arrive at KSC beginning final assembly with the aft and forward skirts. SLS will prepare for the EM-1 Design Certification Review planned for early 2019, conduct the EM-2 Critical Design Review (CDR), and begin fabrication of components for EM-3 and beyond.

Orion

NASA's Orion spacecraft builds upon more than 50 years of spaceflight research and development. Its design is meant to be able to carry crew to space, provide emergency abort capability, sustain crew during space travel, and provide safe reentry at the high-return velocities typically needed for deep space missions. Orion is designed to support human exploration missions to deep space with a crew of four for periods of 21 days. However, with modifications and the support of other new deep space elements, most of the Orion capsule systems could be capable of operations in deep space for periods of time up to 1,000 days. Additionally, the Orion systems are designed to operate in a contingency mode to augment life support systems in other space transport systems.

Orion's crew module (CM), spacecraft adapter, and launch abort system (LAS) incorporate numerous technology advancements and innovations. Orion's LAS can activate within milliseconds to carry the crew from harm's way and position the module for a safe landing. The spacecraft's propulsion, thermal protection, avionics, and life support systems will enable extended duration missions beyond Earth orbit and into deep space. Its modular design will be capable of integrating additional new technical innovations as they become available.

The European Space Agency (ESA) is providing the European Service Module (ESM) for Orion, including structural and propulsion qualification test articles and the flight articles for EM-1 and the crewed EM-2 flight. ESA is providing this ESM hardware in lieu of other contributions, as part of their barter agreement with NASA for ESA utilization of the International Space Station (ISS). ESM qualification and structural hardware is currently undergoing testing at the White Sands Test Facility in New Mexico and Colorado, while the EM-1 flight article is in production today at the Airbus Space and Defense facility in Bremen, Germany, for scheduled delivery in 2018.

Orion's design, development, and testing (including flight tests) schedule is intended to have the spacecraft ready to carry crew to the area around the Moon no later than 2023. Any future flights of SLS and the Orion spacecraft into cislunar space will be intended to extend NASA's capability for human deep space exploration operations, and demonstrate an evolving set of capabilities in cislunar space to reduce the overall risk of longer duration missions.

In FY 2017, Orion Program structural testing made significant progress, including the delivery of the ESM Structural Test Article (STA) from NASA's Plum Brook Station in Sandusky, Ohio to KSC, then to Denver, Colorado, to support integrated Crew Module (CM), LAS, and ESM STA testing in FY 2018. The Program completed a successful hot fire test of the LAS attitude control motor (HT-11) in April 2017 and a successful test of the LAS abort qualification motor 1 in June 2017. ESA's ESM Propulsion Qualification Module was installed at NASA's White Sands Test Facility in February, and the first hot fire test of the Reaction Control System thrusters for Orion's ESM was conducted. The Program has conducted 17 full-scale development airdrop tests on the Orion parachutes at the U.S. Army Proving Ground in Yuma, Arizona, and is half way through the qualification program of 8 tests. Engineers at the Space Power Facility at Plum Brook station in Sandusky, Ohio, conducted acoustic testing on the ogive panels. The ogive panels protect Orion's crew module from harsh acoustic conditions at launch and in case of an abort. The EM-1 CM and Crew Module Adapter (CMA) production at the KSC Neil Armstrong Operations and Checkout Building has made significant progress; both the CM and the CMA have completed initial power on. During the initial power-on tests, engineers and technicians connected the vehicle management computers to Orion's power and data units to ensure the systems communicated precisely with one another to accurately route power and functional commands throughout the spacecraft for the duration of a deep space exploration mission. Steady progress is also being made on the EM-1 ESM being manufactured in Bremen, Germany. NASA and a Department of Defense team tested Orion exit procedures in a variety of scenarios in July in the waters off the coast of Galveston, Texas.

In addition, the Orion Program began manufacturing of components for the EM-2 mission, including the crew module forward and aft bulkheads, the crew module cone panel, solar cells, and EM-2 motors.

In FY 2018, Orion will continue qualification testing of Orion systems for the first crewed flight. As part of this qualification work, NASA is planning to accelerate the ascent abort-2 test (AA-2) into 2019, ahead of an updated EM-1 launch date. Structural work is already underway on Orion EM-2 flight hardware production, and this will continue in FY 2018. For EM-1, the ESM is scheduled to be delivered to the Operations and Checkout Building at KSC for integration with the CM in April 2018 and the start of integrated thermal vacuum testing in November 2018, though challenges remain to this schedule, including timely delivery of necessary components to support the ESA hardware integration schedule and shipment to KSC.

Exploration Ground Systems

The objective of EGS is to prepare KSC to process and launch the SLS and Orion. To achieve this transformation, NASA is developing new ground systems while refurbishing and upgrading infrastructure and facilities to meet tomorrow's demands. This modernization effort is designed to maintain maximum flexibility in order to also accommodate a multitude of other potential Government and commercial customers. Drawing on five decades of excellence in processing and launch, KSC continues to work toward serving as a multi-user spaceport as was envisioned post Space Shuttle retirement.

The EGS program enables integration, processing, and launch of SLS and Orion, and the program is making the required facility and ground support equipment modifications at KSC to enable assembly, test, launch, and recovery of the SLS and Orion flight elements. EGS is also modernizing communication and control systems to support these activities. Upon completion, the KSC launch site will be able to provide a more flexible, affordable, and responsive launch capability for SLS and Orion when compared to approaches used for the Space Shuttle.

In FY 2017, EGS completed Vehicle Assembly Building (VAB) platform installation and outfitting. EGS' renovation of Launch Pad 39B is progressing well and includes upgrades and modifications to the flame trench, environmental control system, and a new flame deflector. EGS successfully tested Crawler-Transporter 2 (CT-2) upgrades; CT-2 upgrades included new generators, gear assemblies, jacking, equalizing and leveling hydraulic cylinders, roller bearings and brakes. The Program is progressing with Multi-Payload Processing Facility (MPPF) Verification and Validation; this facility will be used for offline processing and fueling of the Orion spacecraft and service module stack before launch. As of September 2017, the EGS Program had completed the installation of five sets of umbilicals/attach points on the Mobile Launcher (Orion Service Module Umbilical, Core Stage Intertank Umbilical, Core Stage Forward Skirt Umbilical, Vehicle Support Posts, Aft Skirt Electrical and Pneumatic Umbilicals), completing more than 70 percent of the umbilical and launch accessory deliveries to the Mobile Launcher from the Launch Equipment Test Facility. The first major integrated operation at Launch Pad 39B at KSC began in September 2017 with the initial test filling of the Liquid Oxygen (LO2) storage tank, a giant sphere that can hold about 900,000 gallons of LO2 and maintain the propellant at cryogenic temperatures of -297 degrees Fahrenheit. Hardware delivered to EGS this year included left-hand forward skirt for SLS solid rocket boosters, service platforms for SLS booster engines, and the ICPS. Damage to EGS systems during Hurricane Irma was minimal (limited to some minor damage to the MPPF and some water intrusion on the Mobile Launcher, none of which will significantly impact EM-1 preparations), thanks to the diligence of EGS personnel to "safe" systems ahead of the storm.

In FY 2018, once the program has completed the system verification and validation phase, it will begin the operations and integration phase in preparation for Multi-Element verification and validation for the Mobile Launcher, Pad, and VAB. Spacecraft offline processing will begin in the fourth quarter of 2018.

Exploration Mission-1

The preponderance of SLS, Orion, and EGS development and production content is making sustained progress toward EM-1, and work is underway to prepare for the first flight of crew on EM-2 and subsequent exploration missions. While progress on these programs has been substantial, NASA, its contractors, and international partners have faced challenges with first-time design and assembly. This has adversely affected the schedule for the EM-1 test flight, and as a result, the Agency has rescheduled program planning of EM-1 to reflect completion of work required to prepare for flight. While NASA's review shows an EM-1 launch date of June 2020 is possible, the Agency is managing to December 2019. NASA is taking additional steps to reduce schedule risks known and unknown, and protect for the earlier launch date. NASA's ability to meet the Agency's Baseline Commitment for EM-1 cost, which includes SLS and ground systems, currently remains within original targets. Orion is included in NASA's EM-2 Agency Baseline Commitment.

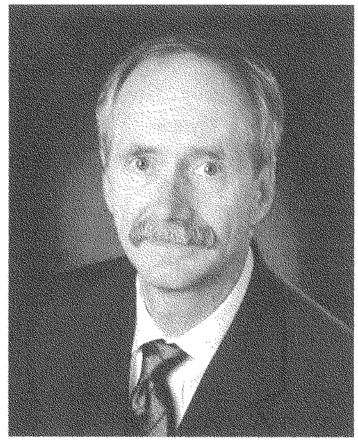
NASA has made significant progress in addressing some of these development issues. For instance, the SLS program has resolved the VAC weld strength issues and all VAC assembly welding for EM-1 is now complete. Additionally, NASA continues to make progress on key elements. All EM-1 booster separation motors are cast and finalized, and the engine controller qualification testing has been completed. The EM-1 CM and CMA production at the Operations and Checkout Building is making good progress; both the CM and the CMA have completed initial power on. ESM coordination on assembly, integration, and testing is improving, and NASA has increased involvement in resolving domestic and international vendor technical and schedule performance issues. The Interim Cryogenic Propulsion Stage has been delivered to EGS. At the Kennedy Space Center, VAB platform installation is complete. Pad 39B development is progressing well, and five sets of umbilicals/attach points have been installed on the Mobile Launcher as of September 2017. Finally, NASA is making progress with ongoing issues associated with spacecraft command and control software.

Conclusion

The Agency has developed an approach to expand the distance and duration of human space exploration, building off the exploration happening today on the ISS. The SLS, Orion, and EGS programs are developing systems intended to provide transportation capabilities for human space exploration beyond low-earth orbit.

While NASA continues to shape this exploration architecture, the objective is to extend human presence deeper into the solar system through a sustainable human and robotic spaceflight program. On October 5, 2017, the National Space Council finalized a recommendation to the President to alter existing policy for NASA's human exploration program to focus on "an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system" and that such a program would "lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations." NASA is working with the Executive Office of the President on further policy and budgets to support this directive.

Mr. Chairman, I would be happy to respond to any questions you or the other Members of the Subcommittee may have.



WILLIAM H. GERSTENMAIER
ASSOCIATE ADMINISTRATOR FOR
HUMAN EXPLORATION AND OPERATIONS

William H. Gerstenmaier is the associate administrator for the Human Exploration and Operations Mission Directorate at NASA Headquarters in Washington, DC. In this position, Mr. Gerstenmaier provides strategic direction for all aspects of NASA's human exploration of space and cross-agency space support functions of space communications and space launch vehicles. He provides programmatic direction for the continued operation and utilization of the International Space Station, development of the Space Launch System and Orion spacecraft, and is providing strategic guidance and direction for the commercial crew and cargo programs that will provide logistics and crew transportation for the International Space Station.

Mr. Gerstenmaier began his NASA career in 1977 at the then Lewis Research Center in Cleveland, Ohio, performing aeronautical research. He was involved with the wind tunnel tests that were used to develop the calibration curves for the air data probes used during entry on the Space Shuttle.

Beginning in 1988, Mr. Gerstenmaier headed the Orbital Maneuvering Vehicle (OMV) Operations Office, Systems Division at the Johnson Space Center. He was responsible for all aspects of OMV operations at Johnson, including development of a ground control center and training facility for OMV, operations support to vehicle development, and personnel and procedures development to support OMV operations. Subsequently he headed the Space Shuttle/Space Station Freedom Assembly Operations Office, Operations Division. He was responsible for resolving technical assembly issues and developing assembly strategies.

Mr. Gerstenmaier also served as Shuttle/Mir Program operations manager. In this role, he was the primary interface to the Russian Space Agency for operational issues, negotiating all protocols used in support of operations during the Shuttle/Mir missions. In addition, he supported NASA 2 operations in Russia, from January through September 1996 including responsibility for daily activities, as well as the health and safety of the NASA crewmember on space station Mir. He scheduled science activities, public affairs activities, monitored Mir systems, and communicated with the NASA astronaut on Mir.

In 1998, Mr. Gerstenmaier was named manager, Space Shuttle Program Integration, responsible for the overall management, integration, and operations of the Space Shuttle Program. This included development and operations of all Space Shuttle elements, including the orbiter, external tank, solid rocket boosters, and Space Shuttle main engines, as well as the facilities required to support ground processing and flight operations.

In December 2000, Mr. Gerstenmaier was named deputy manager, International Space Station Program and two years later became manager. He was responsible for the day-to-day management, development, integration, and operation of the International Space Station. This included the design, manufacture, testing, and delivery of complex space flight hardware and software, and for its integration with the elements from the International Partners into a fully functional and operating International Space Station.

Named associate administrator for the Space Operations Mission Directorate in 2005, Mr. Gerstenmaier directed the safe completion of the last 21 Space Shuttle missions that witnessed assembly complete of the International Space Station. During this time, he provided programmatic direction for the integration and operation of the International Space Station, space communications, and space launch vehicles.

In 2011, Mr. Gerstenmaier was named to his current position as associate administrator for the Human Exploration and Operations Mission Directorate.

Mr. Gerstenmaier received a bachelor of science in aeronautical engineering from Purdue University in 1977 and a master of science degree in mechanical engineering from the University of Toledo in 1981. In 1992 and 1993, he completed course work for a doctorate in dynamics and control with emphasis in propulsion at Purdue University.

Mr. Gerstenmaier is the recipient of numerous awards, including three NASA Certificates of Commendation, two NASA Exceptional Service Medals, a Senior NASA Outstanding Leadership Medal, the Meritorious Executive Presidential Rank Award, and Distinguished Executive Presidential Rank Award. He also was honored with an Outstanding Aerospace Engineer Award from Purdue University. Additionally, he was twice honored by Aviation Week and Space Technology for outstanding achievement in the field of space. His other awards include: the AIAA International Cooperation Award; the National Space Club Astronautics Engineer Award; National Space Club Von Braun Award; the Federation of Galaxy Explorers Space Leadership Award; AIAA International Award; the AIAA Fellow; Purdue University Distinguished Alumni Award; and honored at Purdue as an Old Master in the Old Masters Program; recipient of the Rotary National Award for Space Achievement's National Space Trophy; Space Transportation Leadership Award; the AIAA von Braun Award for Excellence in Space Program Management; and the AIAA von Karman Lectureship in Astronautics.

He is married to the former Marsha Ann Johnson. They have two children.

October 2015

Chairman BABIN. Thank you, Mr. Gerstenmaier.

And now, I recognize Dr. Magnus for five minutes for her testimony.

TESTIMONY OF DR. SANDRA MAGNUS, EXECUTIVE DIRECTOR, AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS (AIAA)

Dr. MAGNUS. Chairman Babin, Ranking Member Bera, and distinguished Members of the Subcommittee, thank you for the opportunity to address you today.

The development system of the Space Launch System and the Orion crew vehicle are major milestones for our nation's space program, and I would not understate their importance. However, I would like to address the larger view related to the current state of our human spaceflight program and comment on its progress and direction.

The idea of what is possible in space has been in transition over the last decade. When talking with the public, I use a model to describe the ecosystem that is today's human spaceflight program. I refer you to the figure on the TV monitors and have you imagine a bubble or a balloon centered on the Earth slowly expanding. That expanding surface represents the outward expansion of human activity. Since the Apollo era for the last 40 years, the surface of that bubble has expanded only to low-Earth orbit in that initial phase, and it's remained there. During this period, the government was the driving force behind the expansion of human activity in space, and this had led to an accumulation of experience, technology, and management operations in this environment.

Now, private industry has become interested in engaging more proactively and independently in this open space, in that development phase as on the figure. As commercial activities mature, it creates stability and a foundation upon which the surface of the bubble, the initial phase, can expand yet further beyond low-Earth orbit.

For the foreseeable future, expansion beyond will continue to be driven primarily by government-derived goals and investments. Because of the increased engagement by industry in LEO, in low-Earth orbit, NASA and the government are now free to develop beyond into cislunar space and beyond that.

But at the core of implementing this model are two key questions. What are the technologies, knowledge, and experience that the government wants to have available for broad dissemination to industry 50 years from now? And two, what are the capabilities and services that are—that the government and private industry, each driven by their own motives, are interested in developing that can potential sustain viable space-based businesses after leveraging initial government investment?

A core concept inherent in the model and underscored by these questions is the fact that there is a need for government investment and activity at the leading edge of exploration during that initial phase and the fact that industry will sooner or later reap the benefit of that government investment to create and establish new capabilities and business ventures in the development phase.

And I might comment the normalization phase we're not ready for yet in human spaceflight but you see that happening over the last decades in the satellite industry where there are independent economic spheres active and the government is a customer. However, the government still does its own thing for its own purposes. So if you can add that sort of with a twist to human spaceflight, we're just simply not ready for that phase yet. And this is the dynamic that's unfolding in human spaceflight, as I mentioned.

The model I have discussed is a powerful one, and if it's employed strategically—if employed strategically—and that brings me to the important point, and this is one that you've heard many, many times and I don't think that you disagree, and so the United States needs a comprehensive national space strategy. It is imperative that we commit as a nation with a constancy of purpose for the long term. It is the nature of the space business that it takes time, patience, and constant purpose to make advancements. The establishment of the National Space Council provides an opportunity to create this integrated approach.

A committed long-term strategy is necessary but it's not enough to ensure the success of the U.S. space program. To be effective, sufficient resources need to be allocated to implement the plan. This is something that has challenged NASA in the past and continues today. When I joined the agency in 1996, NASA received approximately 7/10 of a penny for every tax dollar. Today, the agency receives approximately 5/10 of a penny for every tax dollar, this despite the fact that the number, breadth, and complexity of programs has increased.

Fundamentally, NASA is constrained by limited control on the expense side of its budget as well and has limited freedom to adjust overhead, either facilities or civil workforce, whether size or skillset, and in some cases the management of task assignments around the agency. To execute a long-term strategic U.S. space program in a constrained budget environment effectively and successively, NASA must be given the ability to make decisions and take actions in these areas.

Equally important to the adequate resources is the stability insurance of those resources. Developing space hardware is complex and challenging, as you've heard today. A program with a multiyear phase budget can absorb more initially expensive engineering decisions knowing that the result will be lower operational costs and hence overall net savings over the life of the program. The current budgeting process and lack of a stable budgetary environment prohibits this kind of comprehensive approach to be used.

The transition that is occurring in how humans engage in space has been a goal for decades. Our nation was built upon exploration, expansion, and economic development. From the arrival of the first immigrants and settlers to the westward expansion across the continent, we have faced the challenges, forged new paths, and overcome all obstacles. As we expand into space, the next frontier, I am confident we can tap into the same spirit and energy.

Again, thank you for the opportunity to address this body, and thank you for your continued support of our nation's space program. I look forward to answering any questions you may have.

[The prepared statement of Dr. Magnus follows:]

Shaping the Future of Aerospace

Written Statement of

Dr. Sandra Magnus
Executive Director
American Institute of Aeronautics and Astronautics

Subcommittee on Space
Committee on Science, Space, and Technology
United States House of Representatives

"An Update on NASA Exploration Systems Development"

November 9, 2017

Chairman Babin, Ranking Member Bera, and distinguished members of the Subcommittee, I want to thank you for the opportunity to address you today concerning our nation's space program and its trajectory. My last testimony before the full committee was in February 2014, and many of the points I made then I will reiterate today. I will also highlight changes and/or progress that have been made and the potential that is unfolding before us.

EM-1 and its attendant schedule are major milestones for our nation's space program, and I would not understate its importance. However, I would posit that the larger purpose of today's hearing is to examine the current state of our human spaceflight program and comment on its progress and direction. I believe that we are on the brink of an exciting new phase in human spaceflight. For the last decade or so numerous companies, including those working with and directly supported by NASA, such as Boeing, SpaceX, Lockheed Martin, Sierra Nevada, and Orbital ATK, as well as those privately funded, such as Virgin Galactic and Blue Origin, have been working very hard to develop and operate the next generation of vehicles to send cargo and humans from U.S. soil into space. The different vehicles will have the ability to launch humans and cargo into suborbital trajectories, to low Earth orbit, and beyond low Earth orbit to the moon and to Mars. Each and every program has had its technical and management challenges and its setbacks. Each and every company has risen to these challenges, tackled problems, created solutions, and thus, incrementally, step by step, made progress toward their respective first flights. Some of the cargo vehicles are already operational. The next two to three years will be very exciting as the crewed vehicles will start flying. To the public it will seem as if suddenly, overnight, a whole new phase of the U.S. space program will have been initiated. But as those of us in the industry and in this room know, our space program has been steadily, determinedly working on the tools and capabilities to achieve these goals.

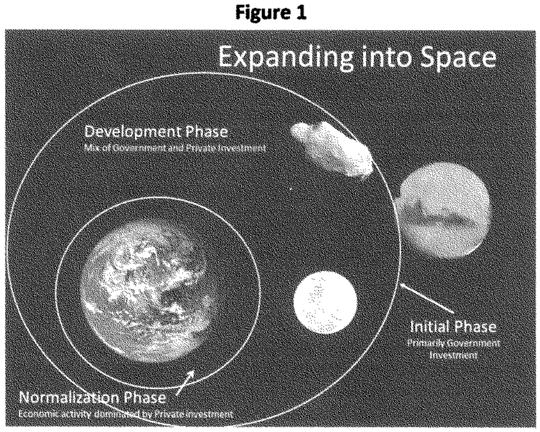
Indeed for those of us here today and the many who work diligently across our country in the space industry, we know the hard work, planning, dedication, and commitment required to execute a successful human spaceflight program. We know that sending humans into space is hard. That despite numerous decades of experience in this endeavor the exercise of launching humans out of the Earth's gravity well into the challenging environment of space continues to be anything but straightforward. Progress in human spaceflight is measured not in days or weeks, but in months and years. Every human spaceflight program in development or operation today, whether it is driven by governmental or private motivations, is advancing steadily, but they will still encounter technical, management, and operational challenges. I make these statements not to imply that the industry is at risk, but, alternatively, to highlight the steady, committed, and talented community that is determined to succeed and will succeed in keeping America engaged and at the forefront of what is possible in space.

The idea of "what is possible in space" has been in transition over the last decade or so. As I have mentioned in my previous testimony and in other venues, after 60 years of government investment and activities in space we have reached the point where the private sector is able to leverage the accumulated technological developments, operational experience, and management knowledge to create and execute plans for engagement in and economic development of space. In concert with and because of this expanded private interest, NASA has been able to extend its ambitions beyond low Earth orbit and outward toward the moon and Mars.

Times of transition and change are chaotic: norms are challenged, creative energy and new ideas enter the paradigm, and what has been a well-understood landscape seems to be constantly shifting. During such a dynamic phase I find it useful to take a step back and examine the situation from some distance to better understand possible trajectories, motivations, and outcomes. There is a model that I like to use to describe the ecosystem that is today's U.S. human spaceflight program.

I would like to refer to Figure 1. As illustrated in the figure, imagine a bubble or balloon, centered on the Earth, slowly expanding outward. The expanding surface represents the outward expansion of human activity. Putting aside our trips to the moon in the Apollo era, for the last forty years the surface of the bubble has expanded to low Earth orbit and has remained there. During this period government-directed investment and government-led missions, which were the driving force behind the expansion of human activity to low Earth orbit, led to an accumulation of experience, technology, and knowledge about operating in this environment.

Figure 1



Outward Expansion of Human Space Activity

Now many decades later we are at the point where private industry has become interested in engaging more proactively in the open space—between the Earth's surface and the surface of the bubble. As these activities initiate and mature, it creates stability and a foundation upon which the surface of the bubble of human activity can expand yet further, for example, beyond low Earth orbit. Similar to the initial expansion into low Earth orbit, further expansion beyond it will be driven by government-derived goals and investments. Because of the increasing engagement by industry in the open space created by the expansion's surface, currently stationed at low Earth orbit, NASA can now begin to disengage as the main investor in low Earth orbit. In doing so, government can take advantage of the options that are created due to the maturation of the private sector and evolution in the industrial base. So, in summary, human activity is moving outward from the Earth with government leading the outermost expansion and private enterprise evolving to provide stability and sustainability in government's wake. While this is a simplistic model, it helps create a framework for us to establish a strategic approach to human spaceflight. I might note that this model is applicable to civil space and commercial development but not national security-related activity in space, which will remain the purview of government.

This is a model that, in some form or another, many in the industry espouse even if it is not described as an expanding bubble as I have illustrated in Figure 1. Indeed I believe NASA is attempting to create a framework based on this model, but I would argue that it is difficult for it to achieve this vision comprehensively as a single agency, outside of a larger, more nationally comprehensive view of what the United States is and should be doing in space.

Before I expand on this further, I would like to address why the government, with its goals and investments, is and should be (for the time being) the driver for the expansion of human engagement in space. I think it is important to note that true exploration is occurring at the leading edge of the bubble. As we expand human reach further into the solar system away from Earth, new technologies require development, new operational paradigms require testing, and potentially even new program management techniques will need to be established. Any one of these areas alone can be high risk and all require investment, and there is no clear understanding of how much investment will be necessary to be successful. In addition, the return on that investment is unknown or highly uncertain at best. The government is the natural investor and developer in such a scenario—it is not driven by profit motives, but has other concerns. I would add that it is quite possible that in the future companies may be driven to conduct exploration missions outside of a government framework and government investment; I would argue, though, that based on where we are today the business case and profit motive for such activity is still solidifying.

Even though, for the reasons I just articulated, the government has an important role in driving human expansion into space, by no means does that mean that it does so alone and absent partnership with industry. How the government defines and executes those partnerships is the critical strategic question that we struggle with today. Answering this question clearly and thoughtfully is vital. With a truly long-term and integrated strategic plan, government investment can be leveraged to meet its goals in ways that address the maturation of U.S. industry's capabilities in space as well as the development of a non-government-based economic sphere off of the planet. The identification of an effective strategy requires that two key questions must be addressed:

1. What are the technologies, knowledge, and experience base that the government wants to have available for broad dissemination to industry fifty years from now?

2. What are the capabilities and services that the government, for a myriad of reasons, and private industry, driven by their own motives, are interested in developing that can potentially sustain viable space-based businesses after leveraging initial government investment?

With regard to the first question about broad dissemination in the future it is worth noting that Elon Musk has talked about the importance of several publications on rocketry and rocket propulsion, knowledge funded by government investment during the Apollo era, that were the genesis of SpaceX. That is just one example of how the innovations occurring today in the space sector were incubated by decades of government-sponsored research and development (R&D). So, consequently, we have to think about the investments that the government is making in R&D today and project into the future how the results of that investment will enable the next wave of innovation. I believe it is necessary to address this question on a national level from the viewpoint of not only what technologies the U.S. space industry can benefit from, but also from the lens of identifying what technologies are critical for the United States to maintain or take a lead in globally. The answer to this question will help guide R&D investment and spending, as well as shape partnerships.

Regarding the second question about private industry developing capabilities and services that the government can leverage, I would like to illustrate the success of the commercial cargo program. Because the contracted companies were able to apply decades of NASA technology and know-how, they demonstrated the ability to develop and operate a reliable cargo delivery service, freeing NASA from the need to focus on this effort. While only the U.S. government still primarily uses these systems, the companies have the ability to provide these services in the future to other customers. Going forward NASA has to decide where it is appropriate to develop similar partnerships. The question should be addressed from both an economic viewpoint as well as an industrial base/national security lens; the government has many different goals driving decisions. The approach taken in addressing this question will help guide mission architectures, partnerships, acquisition strategies, and, to a certain extent, the types of international collaborations in which we might engage. Done correctly, this second question should begin to be addressed by the NASA Human Exploration Roadmap due to Congress in December 2017.

Through the National Space Council we, as a nation, have an opportunity to address these questions and others. The Council, as it is structured, has the ability to work across government to create and integrate a comprehensive national space strategy and then to implement it effectively. I can imagine four main pillars that might inform a national strategy: continuing exploration beyond low Earth orbit, creating an economic sphere in low Earth orbit, national security, and driving and influencing the "norms" for engagement in space for humanity. A government-wide effort is required. The Council touched on this at its first meeting, for example, when discussing the topics of rules, regulations, policies, and enabling laws that might influence space activities. All of these issues encompass the supporting infrastructure that is vital for the success of a framework based on the model I have described. The Council strategically answering these key questions will allow several decisions related to NASA to come into focus—decisions about where NASA (and other government agencies) should invest in technology and capability, decisions about how to help industry establish an independent economic base in space while simultaneously pursuing NASA's mission to expand human presence outward, and decisions about NASA's role in leading or establishing international collaborations for exploration.

Given such clarity there is no reason why a framework cannot be crafted that can send us to the moon, Mars, and beyond, while supporting and nurturing private economic activity in space. From the framework, missions can then be designed in the context of the broader strategy that advance humans into the solar system while developing the capabilities and experience-base of U.S. industry.

I would like to pause here to emphasize an important point; one that many of us in the space industry have emphasized time and time again. The United States needs a comprehensive national space strategy accompanied by a continuous long-term commitment for its execution. It should be crafted such that it allows us to leverage our resources for the maximum benefit of achieving all goals identified. I repeat, because this is critical, to be successful in our space endeavors it is imperative that we commit, as a nation, with a constancy of purpose for the long term—it is the nature of the space business that it takes time, patience, and constant purpose to make advancements.

Crafting such a strategy, while complex, is possible. It is complex because any strategy has to take into account the constraints of our governance structures, general politics, and our tendency as human beings toward short-term thinking.

A committed long-term strategy is necessary but not, by itself, enough to ensure the success of the U.S. space program. To be effective and produce the desired results, sufficient resources need to be allocated to implement the plan. This is something that NASA has been challenged by in the past and continues to be challenged by today. When I joined the agency in 1996, NASA received approximately 7/10ths of a penny for every tax dollar paid. Today, in 2017, the agency receives approximately 5/10ths of a penny for every tax dollar paid. This is despite the fact that the number, breadth, and complexity of programs has increased in that same time frame. I applaud NASA for working diligently to cut costs, streamline processes, and identify new ways of doing things that has allowed it to manage to this point in time.

However, fundamentally, NASA faces constraints on how efficient and streamlined it can become as its budget shrinks; it has limited control on the expense side of its budget. The politics of the situation give it no freedom to adjust overhead, either facilities or civil workforce, whether in size or skill set, as well as in some cases, the management of task assignments around the agency. To execute a long-term strategic U.S. space program in a constrained budget environment effectively and successfully, NASA must be given the ability to make decisions and take action in these areas. Without that freedom, an increasing portion of NASA's shrinking budgets will go to maintaining the agency as an institution and not to successfully executing its programs. The model I described earlier depends on both a healthy government effort and a strategically husbanded and growing industrial base. With a budget allocation of only 5/10ths of a penny per tax dollar, ignoring this dynamic and expecting lofty achievements cripples our collective (both government and industry) efforts to succeed now and in the future.

I would also like to take a moment to address one other critical aspect of resource allocation. Clearly having adequate resources is imperative, but equally vital is the phasing and consistency of the flow of those resources. Developing space hardware is complex and technologically challenging. As stated earlier, every program in existence today, regardless of whether it is primarily government funded or completely privately funded, and regardless of acquisition approach, has had to face, and likely will face again, technical, manufacturing, and operational challenges. What we do is hard. Period. Uncertain and improperly phased budgets as a result of lack of clarity in funding timelines add extra management challenges that drive inefficiencies, ultimately affect schedules, and drive decisions that trade off engineering design versus operational complexity. I saw this dynamic at work in the early days of the International Space Station program. Flatline budgeting—an approach that did not take into account the changing funding needs during different phases of development programs—and uncertainty in funding levels—affected engineering decisions that resulted in driving operational costs higher in the long term. A program with an optimized multiyear and appropriately phased budget can absorb more initially expensive engineering designs knowing that the result will provide lower operational costs and hence overall net savings over the life of the program. The current budgeting process, including the regular usage of continuing resolutions, threat of government shutdowns, and lack of a stable budgetary environment, prohibits this kind of comprehensive trade space to be used. With a budget allocation of only 5/10th of a penny per tax dollar, introducing flexibility and constancy into the budgeting process is another lever that will allow NASA to optimize program execution, regardless of the acquisition methodology being employed.

We are living in a time of transition as we redefine how humans engage in space. Many decades of government investment and experience have produced a dynamic in private industry that is driving a new approach to human spaceflight. We have to consider carefully how we manage and drive change while continuing to explore and expand our technology and knowledge. Now, more than ever, the nation must commit to a bold strategy that provides multiyear stability and that is adequately resourced.

This transition started about ten years ago, and I suspect that it will continue for another ten years or so as we figure out what the next "small step for mankind" looks like. It is a grand experiment, and we are forging the path and writing the rules as we go. We have a unique opportunity at the moment, but to take full advantage of that opportunity it is imperative that we establish a strategy that will guide our efforts. The strategy cannot be so constrained that it will stifle the energy and innovation, but must have enough structure to ensure coherency in direction. We still have a lot to learn; some of our lessons are going to be difficult and painful. We have to be prepared to meet those challenges and promise ourselves that we will persevere. Above all, we must remain committed, strategic, and flexible. And we must also provide sufficient resources to progress along our journey.

The transition that is occurring as we evolve to the next phase of how humans engage in space is a goal that we have been pursuing for many decades. How we choose to guide, nurture, and define our expanding human presence and outward exploration of space will determine our country's role in the next century. The roots of our nation lie in exploration, expansion, and economic development; from the arrival of the first immigrants and settlers at the founding of our nation to the westward expansion across the continent, we have faced the challenges, forged new paths, and overcome all obstacles. As we expand into space, the next frontier, I am confident we can tap into that same spirit and energy. I know the passion and dedication of the people in our industry, and I know their ingenuity and determination to succeed. I know that our national leaders, no matter which branch of government or party affiliation, understand the importance of space for the future of our country. I do not know how we can fail if we apply our minds and energies toward success.

Again, thank you for the opportunity to address this body and thank you for your continued support of our nation's space program. I look forward to answering any questions you may have for me in this regard.

Dr. Sandra H. Magnus

Executive Director

American Institute of Aeronautics and Astronautics

Dr. Sandra H. "Sandy" Magnus is the Executive Director of the American Institute of Aeronautics and Astronautics (AIAA), the world's largest technical society dedicated to the global aerospace profession.

Born and raised in Belleville, Ill., Dr. Magnus attended the Missouri University of Science and Technology, graduating in 1986 with a degree in physics and in 1990 with a master's degree in electrical engineering. She received a Ph.D. from the School of Materials Science and Engineering at Georgia Tech in 1996.

Selected to the NASA Astronaut Corps in April, 1996, Dr. Magnus flew in space on the STS-112 shuttle mission in 2002, and on the final shuttle flight, STS-135, in 2011. In addition, she flew to the International Space Station on STS-126 in November 2008, served as flight engineer and science officer on Expedition 18, and returned home on STS-119 after four and a half months on board. Following her assignment on Station, she served at NASA Headquarters in the Exploration Systems Mission Directorate. Her last duty at NASA, after STS-135, was as the deputy chief of the Astronaut Office.

While at NASA, Dr. Magnus worked extensively with the international community, including the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA), as well as with Brazil on facility-type payloads. She also spent time in Russia developing and integrating operational products and procedures for the International Space Station.

Before joining NASA, Dr. Magnus worked for McDonnell Douglas Aircraft Company from 1986 to 1991, as a stealth engineer. While at McDonnell Douglas, she worked on internal research and development and on the Navy's A-12 Attack Aircraft program, studying the effectiveness of radar signature reduction techniques.

Dr. Magnus has received numerous awards, including the NASA Space Flight Medal, the NASA Distinguished Service Medal, the NASA Exceptional Service Medal, and the 40 at 40 Award (given to former collegiate women athletes to recognize the impact of Title IX).

Chairman BABIN. Thank you very much, Dr. Magnus.

I appreciate the witnesses' testimony. The Chair recognizes himself for five minutes for questions.

And I want to thank you both. I was running a little bit late this morning, didn't have a chance to see you before the hearing started, so anyway, great to have you here. We appreciate you.

One of the primary purposes of the NASA Transition Authorization Act of 2017 was continuity of purpose and expressing the importance of staying the course on program development so as not to delay American space exploration any longer. Can each of you discuss the importance of continuity of purpose and how you balance that against good program management and discipline? And we'll start with you, Mr. Gerstenmaier.

Mr. GERSTENMAIER. Again, I think it's really important we have a common vision of what we're doing as we move forward so we can build the hardware and systems that can support that vision. And we've done that with SLS and Orion. We've built a system that allows us to move human presence into the solar system. So the Orion capsule has applications for around the Moon, can support activities on the Moon and lunar activities. It can also support development beyond the Earth-moon system, the same with SLS. The rocket is designed to really be a heavy-lift launch capability. It can support the human missions around the Moon, it is also absolutely critical and needed for Mars-class missions, and it also can serve a very strong role for the science activities such as the Europa mission to go out to the outer planets. It can reduce the transit time by 50 percent to the outer planets.

So we have tried to build pieces of key infrastructure that enables this vision and allows us to fit within this architecture and framework we've been given, but keeping a constancy of purpose or a general direction when we're moving forward is extremely important to us. Starting and stopping is very difficult in our industry.

Chairman BABIN. Okay. Dr. Magnus?

Dr. MAGNUS. Yes, I'd—excuse me. Yes, I'd like to echo that. Starting and stopping in our industry is really not healthy.

Chairman BABIN. Right.

Dr. MAGNUS. We saw that with the end of the shuttle program, and we lost a lot of our corporate knowledge, and we're going to see some of that when we start launching again. We'll have to relearn some lessons that we've already learned.

But the continuity piece is important. You know, as a nation, we have a little bit sometimes of a short attention span, and we end up hurting ourselves. It was already mentioned earlier there were a lot of programs that we've seen NASA have to cancel over the years.

If you look back in the Apollo era, you think of the dedication and the commitment they had over a decade and longer to commit and execute that program. That's really what you need in the space—human spaceflight. You need a ten-year, 15-year, a 20-year program, and you need to be able to stick to it.

I think it's really exciting that the Committee's interested in this topic. I think the oversight's important to sort of keep people focused. I think that's an important key as well, so it takes the whole community. But you have to be able to stick to the——

Chairman BABIN. Right.

Dr. MAGNUS. —program, and you have to be able to fund it appropriately so that the intelligent decisions can be made to do the tradeoffs with the expenses.

Chairman BABIN. Excellent. Thank you very much. How will a delay in the first launch of an uncrewed Space Launch System until no earlier than December of 2019 impact the scheduled launch date of a crewed launch of SLS? NASA has an internal date it's managing to, as well as a date is has formally committed to. Do either of these dates now change?

Mr. GERSTENMAIER. Yes, again, in terms of our Exploration Mission 2, our first crewed mission, so far the schedule delays, even if the Exploration Mission 1 went all the way to June, it doesn't really impact where we are with EM–2. There's a constraint that the mobile launch platform in Florida—that's the facility that the rocket launches off of—it needs to be modified between the first flight and the second flight to allow for the exploration upper stage. And there's a 33-month amount of time needed between—for that upgrade of that mobile launcher. So that's what keeps EM–1 and EM–2 tied together, but right now, the slips that we've seen with EM–1 don't impact where we can launch the first——

Chairman BABIN. Okay.

Mr. GERSTENMAIER. —crewed flight at this point. But again, we need to be very careful of that, we need to watch for that, and we need to potentially discuss whether it's advantageous to us to have another mobile launcher available to avoid that tie between EM–1 and EM–2, but that's the current tie.

Chairman BABIN. Okay. Thank you. Dr. Magnus, do you have anything to add to that? Okay.

How will a slip in the first launch of the un-crewed Space Launch System impact the cost of the program?

Mr. GERSTENMAIER. Again, it's surprising to some that the overall cost hasn't really changed that much because what we've—especially for EM–1 because what we've done is we're really building much more than just one single flight. So as work is completed on the first launch and the first flight, when that work is completed, that work can be set off to the side and the teams can go off and start working on the next element. So in fact——

Chairman BABIN. Okay.

Mr. GERSTENMAIER. —we have today multiple pieces of hardware in flow for the multiple missions across the sequence.

Chairman BABIN. Okay. I have got six seconds. How will a delay in the first un-crewed launch of the Space Launch System impact a potential launch of SLS for the Europa mission?

Mr. GERSTENMAIER. Again, there's really no impact there. We can support——

Chairman BABIN. Okay.

Mr. GERSTENMAIER. —pretty much whatever the Science Mission Directorate needs for that mission, and we'll figure out whether it occurs after the first flight or after the second flight to meet their needs.

Chairman BABIN. Okay. I have several more questions, but we're going to go on to the gentleman from California, Mr. Bera.

Mr. BERA. Thank you, Mr. Chairman.

Dr. Magnus, in your opening statement you talked about the importance of having a strategic vision over the long period, and we saw that when President Kennedy challenged us in the 1960s to put man on the Moon in this decade. My colleague from Colorado probably does have a sticker that says "Mars by 2033," so we ought to commit to putting a woman on Mars by 2033. It does give the public a sense of what we're working towards, and in that perspective as we're thinking about SLS and Orion, the lunar mission, et cetera, it gives us the chance to think about it in a context of, okay, if we're going to the Moon, how does that help us then think about how we're going to go and take that next step.

So in that context, as we're thinking about EM–1 in the context of going to deeper space, I'm sensing that as we do the EM–1 mission we're learning a lot. We're reestablishing supply chains. We're reestablishing a workforce and a talent base that will make EM–2 easier, is that correct?

Mr. GERSTENMAIER. Yes, definitely. As we—the first EM–1 flight is to test the vehicles and the systems and the hardware to make sure they're really operating to the levels that they need to be when we put crew onboard. And I think as you see this movement outward, we go to the Moon where we can return if something goes wrong in several days, five days. On station today, we can be back in about an hour, hour-and-a-half from station. When we go to Mars, we're now committed for multiple months, so I think you see that natural progression in taking more risk, learning to operate in a more challenging environment, and as you operate in that more challenging environment, you need systems that can support operating in that environment. So it's kind of a natural stepping stone and movement as we use the Moon as a proving ground, a training ground, a development area where we can build concepts, processes, procedures, and hardware that will eventually allow us to go to the Mars-class missions in the future.

Mr. BERA. And as we move on to EM–2 and send a crew up, are we also now conceptually thinking about EM–3?

Mr. GERSTENMAIER. Yes. If we're really building continually to challenge what we can do, the big advantage of the Space Launch System is we can not only carry crew, but we can carry a substantial cargo with us, with the crew, so we can carry potentially a habitation piece with us on EM–3, and when the crew will be there, they can go into that habitation module and begin a crew-tended presence around the Moon, which is, again, starting to break that tie back to the home planet and getting us ready to move into deep space. So you can see that natural progression of where each mission builds on the past mission, and we take stronger challenges, we push the team more, we gain the experience. And what we learn from those earlier missions, it feeds directly into the next mission, so each mission builds on each other.

Mr. BERA. Dr. Magnus, in the slide that you presented, you also showed the private commercial sector following behind, so could you describe how you see the private and international community kind of falling behind as the government starts to push further and further, how the private sector and international community can continue to support that?

Dr. MAGNUS. Yes, so that goes back to the idea of a national comprehensive strategy because, ideally, what you would want to do from a national viewpoint is figure out what are the technologies and capabilities that you want to invest in from a government viewpoint so that those knowledge and those pieces of technology are available for everybody. And then what is—what are the things that are a little bit more mature that you could encourage companies or companies might be interested in developing.

And then from a national viewpoint as well when you think about the international piece, what are those technologies and capabilities that as a country we want to take the lead in? Do we want to be the transport experts? If you look at Canada, they've decided to focus on robotics, for example.

And then understanding the concept of those priorities, you can then establish how do you want to bring the international partners in and how do you want to help the companies establish, you know, the leverage that they need to build into their businesses. So you have to kind of start with that big-picture view that has to be a little bit more governmentwide and nationally focused.

Mr. BERA. In prior committee hearings—let me make sure I'm thinking about this correctly, when we've thought about a return to the Moon, I can visualize a day where NASA is focused on the science mission. They may look at the various launch vehicles that are available in the commercial market as opposed to having to build their own launch vehicles, say, okay, we'll contract with company X to be the launch vehicle. They'll look at various lunar landing commercial vehicles, say, okay, we're going to contract with this lunar landing vehicle. That will take our science project. Is that the right way to think about this potentially?

Dr. MAGNUS. Yes. If I may, if you think about—you know, you have a toolbox to build a house. You don't have just one tool in a toolbox, and you find the right tool for the job. And so, again, in using the satellite business as a model, there are economic activities going on that—where the government purchases services, and there are government activities as well, so you need a mix, and it has to be driven by what are the—what is the strategic view for the country and what kind of capabilities do you want to create and make sure that you have going forward, so you have to think about it from that big picture. There's a place for all of it in the right strategy.

Mr. BERA. Right. Thank you. I'm out of time. I yield back.

Chairman BABIN. Okay. Thank you.

Now, I'd like to recognize the gentleman from Alabama, Mr. Brooks.

Mr. BROOKS. Thank you, Mr. Chairman.

The production of the core stage element is currently driving the Space Launch System program schedule. The program is combining welding techniques and materials—specifically, the thickness of the metal—that have not been used before. While establishing new production techniques is laudable, the program has faced numerous setbacks as it is developing these processes and correcting defects.

How confident is the program that it and its contractors will have gained enough knowledge to avoid these setbacks and delays for future flight hardware?

Mr. GERSTENMAIER. We've met the challenges of self-reacting friction stir welding of the thicker materials. We understand now how to do that. We'll still probably continue to refine the welding technique as we go into future pieces, but the basic understanding is in place now and we know how to do the welding.

And as I said in my opening remarks, that's also important to the industry as a whole. NASA paved the way by now allowing others to use those same techniques in the larger thickness of materials.

Mr. BROOKS. If you could, what steps does the program and contractor have in place to avoid mistakes such as welding tool changes that shut down production?

Mr. GERSTENMAIER. We're again carefully monitoring all that activity. We're looking at ways we can do inspection. We knew fairly soon and immediately that there was a problem with our welding when it occurred, so the good news was we had tools and techniques in place to find the defects to prevent that from extending into the flight hardware. That was good.

The bad thing we didn't know is we fully didn't understand—we had done smaller samples. We had done smaller welding tests, but we had not done of—any of the magnitude or the scale of which we're trying to do with the full vehicle. So I think we just need to be prepared as we build schedules going forward to know that these first-time things that we have never done before of a magnitude that has never been done before may need a little bit of extra time that first time through and not be overly optimistic in our schedule. So we'll build in some time to go ahead and do those kind of things to make sure we don't have that same kind of problem moving forward. And we've identified those areas in the future where we see these first-time items. We will put in place processes and procedures to prevent what's—what occurred in the past.

Mr. BROOKS. The core stage element, again, which is currently driving the SLS program schedule, still has to complete a major integrated test fire, which is called the green test run. The green test run will have the core stage integrated with its four main engines. The tanks will be filled with cryogenic fuel for the first time, and the core stage will be fired for about 500 seconds. The engines have been tested individually but not all together, which creates a different heat, acoustic, and vibration environment, and this will be the first for the core stage. What areas cause the most concern during this test, cryogenic fuel piping, leaks, material stresses, et cetera?

Mr. GERSTENMAIER. The teams are really analyzing that test in all its detail to make sure that we are really prepared for that test. And one thing we learned out of this last schedule problem is that we're going to have a dedicated person and a team that actually will look at that test to make sure we have accommodated and taken into account everything that might occurred during that test. The concerns are when you—when the rocket is designed to come off the launchpad and typically fly, it's not designed to stay in one location for the entire firing, so there could be some heat that builds back into the systems. We've been analyzing that in wind tunnels. We've been looking to make sure we're prepared for that. We've done extensive work on a test stand to look at modeling and testing of how we do the fluid flows. We've looked at procedures so we bring in tankers to bring in the liquid hydrogen and oxygen during the test in the most efficient manner. We've protected for slips in schedules.

But we see that test coming up after the core stage gets delivered to Stennis as one of the key tests and one of the key risks. We and the teams, we'll be fully prepared for that test when it occurs.

Mr. BROOKS. What potential damage are you testing for that might occur during a nominal test of this nature such as insulation damage, internal harnesses, boxes coming loose? Just what are you looking for?

Mr. GERSTENMAIER. All those things you describe. I think probably our biggest concern is probably thermal and potential thermal damage to the bottom of the vehicle and what needs to be repaired. We'll have procedures in place to go do those repairs. We'll have alternate techniques to fix things if they occur during that testing. So we're actively working that area, and we will have detailed test plans and detailed mitigations for anything that can arise.

Mr. BROOKS. Thank you, Mr. Gerstenmaier. And, Mr. Chairman, I yield back.

Chairman BABIN. Yes, sir. Thank you.

Next, the gentleman from Virginia, Mr. Beyer.

Mr. BEYER. Thank you, Mr. Chairman, very much. And thank you for being with us today.

If I can be parochial for just a minute, in two days, Orbital ATK's Antares rocket is going to launch from the mid-Atlantic Regional Spaceport at NASA's Wallops Flight Facility up to the International Space Station with important supplies for astronauts living and working in space. And two of my wonderful staff members are going in to watch the launch. So I'm really proud of the role that Virginia plays in supporting NASA and the ISS from Wallops because, aside from Cape Canaveral, it's the only launch site in the United States that supports the station, and it's supported national security missions, including a recently announced NRO mission next year. And just last month, an emerging small launch startup Vector Space announced that its three initial launches will occur at Wallops next year. We had an accident here a couple of years ago, and Virginia has put nearly $200 million of taxpayers' money into the spaceport. It's been a really unique, successful public-private partnership between NASA, Virginia, and Orbital ATK.

So, Mr. Gerstenmaier, as we look at our future space operations, can you discuss how Wallops can contribute to NASA's planning and operations?

Mr. GERSTENMAIER. Again, we see Wallops playing a key role for cargo delivery to the space station. I think it's already interesting to see how the Orbital ATK team is using that cargo vehicle in creative ways. As you see, it completes its cargo delivery mission. Then, that vehicle can come off the space station and then do another mission for its own uses afterwards. We've looked at full-scale combustion experiments on board space station or on board the Cygnus vehicle where we actually set a large fire inside Cygnus prior to reentry to understand what fire detection should be like and what fire suppression should be.

So it's pretty exciting to see the Orbital ATK team look at creative ways of using their vehicles with a post-mission after the cargo mission is done in creative ways and bringing other folks in. So I think we'll continue to see a large number of launches out of Virginia supporting that activity and growing in that area.

Mr. BEYER. Great.

Mr. GERSTENMAIER. You also notice the control center's been upgraded. You'll notice some of the other things that we've done in the times between the flight, so you'll see NASA's investment in the launch site, as well as what the State of Virginia has done.

Mr. BEYER. Thank you very much.

And, Dr. Magnus, in your testimony, you said and you wrote, and I quote, "The United States needs a comprehensive national space strategy accompanied by a continuous, long-term commitment for its execution." Do we not have that already? And where are the holes in that?

Dr. MAGNUS. Yes, I think some of it—some of the holes came out during the National Space Council meeting. You know, we have—NASA has a comprehensive strategy for how they want to continue doing exploration, you know, that initial phase of the bubble, and they've been working with the private sector and the development stage, sort of that middle stage, but there's a lot of work the FAA is still working on with respect to the licensing. There's discussion about the on-orbit piece, there's discussion about laws, there's tax incentives, there's—so there's all kinds of the other pieces when you think about what you have to do to develop a healthy economy or a stable economy or help one get off the ground. It's not just about the rockets and the habitats. There's legal frameworks, there's regulations, things like this.

So—and then you also have to fold in the piece of what do we want from our international cooperation? What do we want to encourage in our private industry? How do we want to help the innovation succeed? How do we want to make sure that the government has its mission and stays focused on its mission? So there's all these pieces that I think they're out there, but it's not clear to me they have all been brought together comprehensively.

Mr. BEYER. So connected to that, Mr. Gerstenmaier, as you know, one of the ongoing debates that we hear on our Space Subcommittee is should—do we go directly to Mars or do we go to the Moon first and use that as the launching part for Mars? I noticed in your testimony you talked about how such a program would, quote, "lead the return of humans to the Moon," the long-term exploration. So is it already decided that we go to the Moon first?

Mr. GERSTENMAIER. Again, I think, as we—I described earlier, this stepping-stone approach where we use the Moon as a training ground to move further out is a good approach, and I think that's consistent with the authorization language that we've received and the direction from Congress and the Administration. So it's a stepping-stone approach of where we use the Moon to learn the things, learn skills, learn things that we need to help us advance, but ultimately, we're moving human presence into the solar system with the ultimate goal towards Mars.

Mr. BEYER. Thank you. Dr. Magnus, I just want to quote from your written testimony. "The current budgeting process, including the regular use of continuing resolutions, threat of government shutdowns, lack of a stable budgetary environment prohibits this kind of trade space to be used." I just want to say amen. Thank you for putting that in writing. The entire federal workforce, the government contracting community, the military, everyone agrees with you.

Mr. Chairman, I yield back.

Chairman BABIN. Yes, sir. Thank you.

Now, I recognize the gentleman from Florida, Mr. Posey.

Mr. POSEY. Thank you, Mr. Chairman. And thank you for calling this informative meeting. And I want to thank the witnesses, both of you. It's always a pleasure to hear from you and gain your insight.

Mr. Gerstenmaier, would you say that reaching Mars is the top priority of NASA right now?

Mr. GERSTENMAIER. Again, I—the way I describe it is moving human presence in the solar system, but it's one of the stepping-stone approaches as we move human presence into the solar system.

Mr. POSEY. I mean—but, I mean, as a priority basis, how would you prioritize things?

Mr. GERSTENMAIER. Again, I think we need to be careful, and I don't pick destinations. I talk more about kind of building a capability or the expanding bubble that Sandy described where we kind of move out into the solar system and we bring the commercial sector, the economy with us as we move. So I'm looking for a much longer strategic vision than a particular single destination. And I see this as a continuum of gaining the skills that we need to have as we move further into the solar system.

Mr. POSEY. Well, I really appreciated hearing you use the words stepping-stone in reference to the Moon just a few moments ago in answer to that question, and I think that Congress has kind of expressed they'd like pretty much everything you do in space to be a stepping-stone to Mars, that that ought to be a goal. And you know and I know that if everything's a priority, nothing's a priority, and so I'd really like to hear it acknowledged that reaching Mars is a top priority, and everything that we do is in fact a stepping-stone to reaching that goal for a number of reasons.

You're familiar with Buzz Aldrin's Cycler program. He's my constituent, and I hear about that plan frequently. Would you just take a moment to share with me why the plan that you're pursing is superior to the plan that he suggests with his cyclers?

Mr. GERSTENMAIER. Again, I think in our world we often like to contrast things and show how they're different and we try to pick one or the other. If you look at the approach that we've laid out where we have potentially some kind of crew-tended platform around the vicinity of the Moon and we use that as a staging ground to go to Mars, that's very—that has very similar aspects to many of the cycler concepts that Mr. Aldrin talks about. It doesn't continually cycle, but we're using the Moon potentially and the high elliptical orbit around the Moon as a staging position to go to Mars rather than returning directly back to the Earth.

So it's a—there's pieces of what he describes in our plan. It may be not as much as he would like. He would like to have the pure plan the way he describes it with a large cycler in place, but I think we look—and we look to the community to get good ideas from everyone. We look to academia. We look from our Apollo astronauts. We look from commercial industry. We want to take all those great ideas and put them together and then build the strategic plan that was—we've been describing here to keep us moving forward.

So I don't see it as one or the other. I'm not going to say our plan is superior to his or his is superior to ours. There's advantages and disadvantages of both, but possibly a hybrid between those two might be the actual best solution for all of us.

Mr. POSEY. That's a pretty good answer, and I assume funding approvals play a big part in that.

Mr. GERSTENMAIER. Definitely. If we're constrained by the financial environment. You know, we're given the adequate resources to do what we need to go do, but we need to reflect that in our planning, that we don't try to build a program that requires more funding then is reasonably available, and that's a consideration and a concern as we do the planning.

Mr. POSEY. Dr. Magnus, do you care to weigh in on this?

Dr. MAGNUS. Yes. I would just like to comment that we have to quit talking about either the Moon or Mars because, as Bill mentioned, it's an "and." And if you think about the model that I presented, if we're—and—if we're really thinking carefully about how we're, you know, moving that initial phase——

Mr. POSEY. I think everyone here in this room understands we want to go Mars for a number of reasons, as a launching area, the potential of fuel there. I mean, at one time there was quite a bit of opposition to it, and people who were opposed to it that said been there, done that have pretty much acknowledged that to go further, that's the smartest way to do it.

Dr. MAGNUS. Right. And we can do it to—in a way that, as we bring industry behind us, they can, you know, expand that development phase out to the Moon. The government continues to go to Mars and leaving that charge if you will, so there's a smart way to do this where you pass through the Moon, you do the things that you need to do there to continue to build your operational capability to go to Mars. The government keeps expanding to Mars, and you bring that economic system behind you so that it's stable and provides the additional capability to continue that outward thrust. There's a way to do this.

Mr. POSEY. Thank you, Doctor.

Mr. Chairman, I see my time is up. Thank you.

Chairman BABIN. Yes, sir. Thank you.

Yes, the gentleman from Colorado, Mr. Perlmutter.

Mr. PERLMUTTER. Thanks, Dr. Babin. And I'll just put up my prop for one second.

And to be parochial, in three days or four days from Vandenberg Air Force Base we will launch the JPSS, which that satellite was built in Colorado up on the United Launch Alliance rocket, which was also built in Colorado. So each of us from an economic point of view but also just from a point of view of pride has a stake in our space program, period. And all of us up here are pretty much on the same page when it comes to getting us to Mars.

I don't care how we get there; just get there by 2033, if not a lot earlier. And so my job, whether it's a stepping stone to the Moon or we use a hyperloop or we—you know, somehow somebody comes up with beaming us over to Mars, I just want our astronauts on Mars. Orion and SLS are the main vehicle we have to do this now.

And, Mr. Gerstenmaier, you've heard me talk about this, and obviously, our job up here is to get you the funding so you can have that constancy of purpose on a 16-year project. And we don't have that yet, and it's our responsibility to do that. But for me, I'm a results-oriented guy, okay? I don't know what the best engineering and the best science and, you know, exactly how to do that. That's your responsibility, Dr. Magnus. That's your responsibility, Mr. Gerstenmaier. Me, I got to try to find you the resources so that you can do that.

But others up here are more sort of accountant types and, you know, want to make sure we hit our benchmarks and the milestones, as do you, your engineers. I mean, that's how you guys operate. So the anxiety that some feel that we're already missing kind of a milestone early in this 16-year journey is something I think we all have to take seriously. But our responsibility as Members of Congress are to provide you the resources to get this done and for you—let me just ask a couple just basic questions.

In sort of developing this program, how do you see us adding international partners? Has there been any discussions with other countries about partnering with us in a major project like this, Mr. Gerstenmaier?

Mr. GERSTENMAIER. There's been quite a bit of work discussed with an overall framework. There's a Global Exploration Roadmap that'll be published next January, and that kind of provides a framework of moving forward and of which is consistent with everything we're building. They see SLS, they see Orion, they see what we're doing with space station as part of that overarching framework.

The activities around the Moon where we talk about potentially a crew-tended activity in the vicinity of the Moon, the international partners are extremely interested in that, as well as commercial industry, so we're working with both commercial industry and international partners.

As was described earlier, I think this is really a team activity where NASA does a piece. We have the Space Launch System that can take 45 metric tons to the vicinity of the Moon, but then we can use commercial launch vehicles to take 5 or 10 metric tons of cargo routinely to the vicinity of the Moon, so SLS doesn't have to be every flight to the Moon. The rockets you talked about from Colorado, the United Launch Alliance Stuff, what's being done by Falcon, what's being done with Blue Origin, those can all be used as part of this architecture so——

Mr. PERLMUTTER. And we better not forget Sierra Nevada and the Dream Chaser——

Mr. GERSTENMAIER. And Sierra Nevada, who has——

Mr. PERLMUTTER. —or I'll be in real trouble.

Mr. GERSTENMAIER. And they have a drop test on the 14th of this month to look at their vehicle coming back. All that fits together as part of this interactive framework, and I've seen tremendous interest from all partners in seeing how they can participate, how they can be part of this endeavor.

Mr. PERLMUTTER. Dr. Magnus, in your position with the association, what are you seeing in terms of the willingness by the private sector, as well as when you're doing outreach to other countries? How do you see us building the team that will help us, you know, get to Mars?

Dr. MAGNUS. There's a huge amount of interest in the private sector in the United States to participate in this project in any way, shape, or form. There are a lot of small companies that are engaging in space that never existed before. There are established companies who are taking innovative approaches to how they want to engage in space. There's a lot of energy out there. There's a lot of great ideas out there. I have no doubt that we can do it.

Internationally, I think they look to us, our international partners look to us to provide the vision and the energy and the drive, not necessarily to be the dictators and direct everybody what to do, but Bill mentioned the roadmap. There's a lot of enthusiasm to have the United States—"You guys, you know, this is great. You've got this vision. We all want to take a part of it. Let's figure out how we can do that." So we can do it if we just keep constancy of purpose and funded.

Mr. PERLMUTTER. And at the bottom of it, it says, "We can do this."

Dr. MAGNUS. Right. There you go.

Mr. PERLMUTTER. All right. Thank you. I yield back.

Chairman BABIN. Thank you, Mr. Perlmutter.

I now recognize the gentleman from Florida, Mr.—Dr. Dunn.

Mr. DUNN. Thank you very much, Mr. Chairman. It's always a lot of fun to come here and listen to the interesting and intelligent people that you bring to these hearings. I have a thousand questions and 5 minutes, so I'm going to jump right in.

We spoke earlier. You know my background as a surgeon, so I'm going to ask a lot of questions about life sciences if I can. So what are the special risks or are there special risks in deep space missions that differ from long-duration, low-Earth orbit missions?

Mr. GERSTENMAIER. Probably the biggest risk that occurs is the risk to radiation and radiation exposure to take humans in deep space. Around the Earth, we're shielded somewhat from some of the radiation by the magnetosphere. In deep space, that shielding is gone, so we're going to have to go look at techniques to shield the crews and look at the—if there's any other techniques we could even do in terms of medication and other things to help with radiation during their journey. It's not an insurmountable problem, but it's a problem that we need to address that we can't look at as easily around the Earth as we would like.

Mr. DUNN. So you're already opening up new avenues of research in life sciences for the extended deep space missions. That's exciting.

Mr. GERSTENMAIER. Yes.

Mr. DUNN. Can—and of course some of that can obviously translate to Earth, too? So what interesting things have we learned from the Kelly astronaut twin experiments? And you don't have to go too long. I mean, I know how about the telomeres and all that.

Mr. GERSTENMAIER. Yes, I think that's the exciting thing is looking at how the genome changes just exposed to microgravity. And we believe that it's a microgravity change that is causing changes to the——

Mr. DUNN. Microgravity, not radiation?

Mr. GERSTENMAIER. Yes. And they can differentiate between radiation and microgravity changes and why certain genes upregulate some way. They downregulate when exposed to microgravity. That's a fascinating research subject. I would have to bring some of the researchers here that are much better versed than myself, but they can explain to you what they're seeing. And it's really opened up a whole new line of questioning. And this is how I think science and medicine really advance, that new questioning, something you never thought about and now you're exposed to it, it puts into—calls into question your basic theory. Then, that basic theory changes, and now, you're going to develop a brand-new way to go solve some problem or to do something in the future. So this is a very exciting phase of research.

Mr. DUNN. Yes, we look forward to hearing from that side of your shop as well. How does this affect it? There some interesting design modifications for deep space missions then that vary from our low-Earth orbit. What are you doing with that Orion capsule to make that more habitable?

Mr. GERSTENMAIER. Yes, one big thing is the radiation environment, again, we look at some potential shielding. When we took Orion on the exploration flight test, we flew radiation sensors on it. When we take it on Exploration Mission 1, it will also fly radiation sensors. We'll also fly a mockup of a human torso inside the capsule, and embedded in the human torso will be radiation monitors to simulate the various organs inside the human. And then we'll look at a radiation protection vest on the outside of the human on Exploration Mission 1 to gain insight to see if that provides some protection for our crews. But I think there will be some type of storm shelter or radiation shelter design into our future deep space vehicle.

Mr. DUNN. Well, we talked about changes in DNA in long-duration microgravity and radiation. Are we going to put animal experiments on the——

Mr. GERSTENMAIER. We presently——

Mr. DUNN. —unmanned Mars missions?

Mr. GERSTENMAIER. We presently don't have any—I don't believe we have any animal missions on the Exploration Mission 1, the first mission. We just have the instrumentation and the hardware, but we——

Mr. DUNN. It'd be interesting.

Mr. GERSTENMAIER. —could look at that. We don't have the life support system there, so we'd have to put some kind of life support system on that first test flight to accommodate some animals, but we're doing significant animal research on board space station. We have all the basic animal models, which you're familiar with——

Mr. DUNN. Or tissue cultures even, something with——

Mr. GERSTENMAIER. And tissue cultures——

Mr. DUNN. —DNA in it. Right.

Mr. GERSTENMAIER. Yes.

Mr. DUNN. So, Dr. Magnus, you have kind of a personal relationship with radiation in space, so can you comment on this?

Dr. MAGNUS. No, I found—you know, I was on space station for 4–1/2 months, and I felt like the exercise protocols that we had were sufficient. I came back with no bone mass or muscle loss——

Mr. DUNN. No loss of bone density?

Dr. MAGNUS. No. So I think we've got that licked, and it's—I think Bill's right; the radiation is the key issue, and we still are learning a lot about what can happen in a radiation environment. I think the ability to do some work around the Moon will inform us a little bit more about what we don't know and, as Bill mentioned, give us new lines of inquiry to make sure we've got our bases covered before we go to Mars.

Mr. DUNN. Well, you have an excited and engaged, interested committee here, so keep us in your thoughts and keep us informed. Thank you very much.

I yield back, Mr. Chairman.

Chairman BABIN. Yes, sir. Thank you for those good questions.

And now, I recognize the gentleman from California, Mr. Rohrabacher.

Mr. ROHRABACHER. Thank you very much, Mr. Chairman, and I apologize for having—you know, you have to jump between various events that you're committed to, and so I will go back and look at the testimony we've had so far.

I am on the Foreign Affairs Committee, as well as the Science Committee, and I am very interested now what our next major step into space as to what we see it as an international goal and not just an American goal meaning when we're talking about going to the Moon and establishing a long-term presence on the Moon, we—in the space station we have people from other countries and other countries have partnered with us. Are we planning anything like that for our moon presence?

Mr. GERSTENMAIER. Yes, we are, and in fact, as we discussed earlier, the service module that provides the propulsion and life support gases for the Orion capsule come from the European Space Agency, and that's being manufactured by them. And this is their contribution in the real way to the first steps in exploration.

Mr. ROHRABACHER. And does the Administration have any plans on this? Do we—that we need to know about?

Mr. GERSTENMAIER. I don't know that we've—you know, we've got some—we had the 45-day report action that came out of the Space Council. We continue to work on that and see and refine details, but I think there's been a general agreement that international support is a good thing for deep space, and we'll continue to build off of what we've done with the space station and look for ways that we can continue that same partnership as we move out towards the Moon and out towards Mars.

Mr. ROHRABACHER. I would hope so. You know, I—when I first got here, we've both been around a long time, and I remember that my vote was actually very instrumental in the space station. And if I had switched my vote, it would—the station would not have moved forward. I'm actually very pleased with how that turned out and how my vote actually made a positive difference.

I would hope that we actually have a plan that is a little bit more detailed in terms of the Moon and what we're planning to do there now that we've made that decision because up until now, we've had a great deal of debate as to whether we're going to go right on to Mars and how—you know—and now, I think we've reached a consensus that the Moon is the step to Mars and—but I need to—I would hope that we get a little bit more details exactly what we're planning to have on the Moon, what type of cooperation—if it's an international effort, what type of cooperation we can expect and how much money of course it will cost us to accomplish the specific goals that we have in our Mars mission next but in a Moon mission now.

Mr. GERSTENMAIER. We have an exploration report that's due to Congress in December, and in that report, we'll start to show you some of the specifics of the kind of questions and agreements and how we'll do some of these things internationally in that report when you see it in December.

Mr. ROHRABACHER. Okay. Well, thank you very much, Mr. Chairman.

Chairman BABIN. Yes, sir. Thank you, Mr. Rohrabacher.

Now, I'd like to recognize the gentleman from Louisiana, Mr. Higgins.

Mr. HIGGINS. Thank you, Mr. Chairman.

I very much appreciate your appearance before this Committee today. We're all united in our enthusiasm for moving this program forward, and we all have many questions and very little time.

I represent Louisiana. The Michoud facility in New Orleans has developed a friction stir welding process. Mr. Gerstenmaier, could you explain that, please, for the Committee?

Mr. GERSTENMAIER. The—there's a large facility, the largest in the world that essentially welds our large—the tanks, the hydrogen tank and the oxygen tank for the Space Launch System. The way reaction friction stir welds are, the two plates of aluminum are together; then, there's a spinning rod and then self-reacting—instead of having a tool behind it that holds the two plates together, there—the pin itself goes through and it actually spins at high RPM and actually melts and fuses the two pieces of aluminum sheet together. It's different than fusion welding when you use like an arc or a tool to weld and the fact that there's no heat distortion, it actually just molds and puts those two pieces of structure together.

Mr. HIGGINS. And this is the latest welding technique on the planet, am I correct, and provides a very, very strong weld and allows you to use new, thinner layers of steel that allows them to be sufficient and strong, stronger than in the past and yet lighter, is that correct?

Mr. GERSTENMAIER. Yes, it provides a superior weld performance and the fact that the defects are typically less, and the fact that there's no heat distortion allows for the components to be joined together and put together in a much stronger manner than they could through another process.

Mr. HIGGINS. All right. Thank you. And let me jump forward to manned presence on the Moon, as we have discussed earlier, as a stepping-stone to Mars. Have landing sites, lunar landing sites been discussed and determined?

Mr. GERSTENMAIER. From a robotics standpoint, I think what we're interested in now is if you look at the Apollo missions, they—most of those missions were equatorial, around the equator of the Moon. We see potential water or at least water in the north and south pole of the Moon. That could be very, very important to us as we think about moving forward. If we don't have to carry all our resources with us as we move into the solar system, if we can get water from the Moon, that would be very interesting to us. So we see some permanently shadowed regions in the north and south pole of the Moon that we would like to investigate maybe first robotically and then potentially if it makes sense with humans in those areas. But as soon as we can understand how that water's potentially held in the lunar regolith, that can be really important to a market and how we use that and how we move presence into the solar system.

Mr. HIGGINS. Yes, sir. Regarding shelter for human presence on the Moon for extended exploration and extended periods of time on the Moon's surface, one of the major challenges is developing habitant, you know, protected areas where the astronauts could stay. Last month, the Japan Aerospace Exploration Agency discovered a large and stable lava tube beneath the surface approximately 300 feet deep, 300 feet wide, accessible through what they refer to as skylights, areas where the ceiling or the roof of the tube had collapsed. Does this change the paradigm of what you and your team might be considering regarding human habitation?

Mr. GERSTENMAIER. I think it's definitely something to be considered because if you can take advantage of the radiation shielding provided by the lunar regolith and you can have a structure or a location to actually go into for storm shelters, that could be interesting. So I think that's something that we need to continue to keep looking at and see how that fits into——

Mr. HIGGINS. And this could be explored robotically. Am I correct?

Mr. GERSTENMAIER. Yes. You could definitely do it robotically. We've talked sometimes about having an orbiting crew-tended capability around the Moon. You could do that, and then you could use astronauts on board this gateway concept that we've talked about to actually command rovers to drive into these potential lava tubes, explore them, understand what's available prior to committing humans to go to——

Mr. HIGGINS. Yes, sir. And one more thing regarding these underground caverns and tubes. As opposed to on Earth because of the low gravity of the Moon, it's been stated by reputable scientists that these tubes could be as large as two or three miles in diameter. Do your studies concur with that?

Mr. GERSTENMAIER. I'm not familiar with those studies, and I'd have to go research that or ask someone.

Mr. HIGGINS. Thank you for your response. Could you—if that information becomes available during the course of your studies, sir—and thank you for your continued research—could you possibly provide that to this Committee?

Mr. GERSTENMAIER. Yes, we will.

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

Chairman BABIN. Yes, sir. Thank you, Mr. Higgins.

They've called votes, so I'm—there's several of us that had questions, and we're going to take a minute apiece, one minute apiece.

I'm going to go quickly. The recent slip in the un-crewed launch of the Space Launch System seems to be the result of many factors, which we've mentioned today, hurricanes, tornadoes, the core stage welding issues. What impact will a delay in delivery of the Orion service module by the Europeans have on the December 2019 date? And what tools does NASA have to ensure that the European Service Module does not lead to further delays? If you can answer that, please, Mr. Gerstenmaier?

Mr. GERSTENMAIER. We're working extensively with the European Space Agency. They've committed some extra funding to make sure that they can do it from a schedule standpoint, be prepared. We know there's some high-pressure helium valves that are actually manufactured in the United States for the Europeans. We know those valves are having trouble being manufactured. We've sent some of our people to the plant to actually help with that activity, to help mitigate that concern. We actually have a NASA design for a valve, which we may manufacture and provide for that application. Lockheed Martin has also gotten State Department approval to send some of their technicians to Europe to actually assist with some of the manufacturing of the European Service Module.

So I think we're doing everything we can. I think the current service module delivery date is supposed to be April of next year. I think we're very likely to see that schedule slip a little bit maybe to May or June, and then we're looking at what we can do to help with that downstream. So we might do a simulator on top of the SLS when it goes to Florida to do a modal testing instead of having the actual Orion and European——

Chairman BABIN. Okay.

Mr. GERSTENMAIER. —Service Module on top, but we're well aware of that. That is probably one of our key risk areas.

Chairman BABIN. Yes.

Mr. GERSTENMAIER. We're doing everything we can, but it's really just this first-time manufacturing that's causing us the problems that we're seeing.

Chairman BABIN. It is a great concern. Thank you very much.

Now, the gentleman from California, Dr. Bera.

Mr. BERA. Thank you.

Quick question. One of the exciting parts of this is I'm looking at newer propulsion systems as well, and one that we certainly have talked about is solar electric propulsion as part of SLS and Orion. Could either one of you talk about the importance of why solar electric propulsion's important, particularly as we want to go into deeper space and——

Mr. GERSTENMAIER. Sure. I can start and Sandy can help. I think that the big advantage is that in terms of efficiency and the amount of propellant that needs to be there to actually go move things, it's very, very efficient to move large masses throughout the solar system. And so you can move—if we have this crew-tended facility around the Moon, it can be in one orbit. Then, we can use electric propulsion to move it to a totally different orbit. So we can be in an equatorial; we can go to polar. It takes a long time to do that. It may take up to a month, but if the crew's not on orbit or with the vehicle, it can move. So I think the big advantage is it allows us to move large masses, although slowly, throughout the solar system, and that's the advantage to us in the architecture.

Dr. MAGNUS. Yes, I would just add, you know, in the context of our discussions that were more strategic, because NASA's developing this system, it'll be technology that's available for everyone to use, and so it's one of those feeders if you will that will allow our economy to advance and other companies to take advantage of that kind of capability.

Mr. GERSTENMAIER. And I might add we just recently awarded some study contracts to typical communication satellite manufacturers to see if they would have interest in using the next generation of electric propulsion thrusters in a higher-powered propulsion bus. So we might actually be enabling the commercial communication satellite industry to get a jump over other foreign competitors by advancing the state-of-the-art in electric propulsion and power generation beyond where they are today. And we—so we gain—they gain directly from what we're trying to do, and then we get a capability we can use around the Moon for our needs, so this is kind of a win-win between industry and us.

Chairman BABIN. Yes, sir. Now, I think Mr. Rohrabacher has—from California has one question.

Mr. ROHRABACHER. Well, you just mentioned commercial activities and I had asked before what we thought about international cooperation. Is there anything part of the plans for this extended moon presence that we're talking about now that would include the private sector? And we know now—you know, 20 or 30 years ago we didn't have these private companies like SpaceX and all the others making their contribution. Do we expect there to be private involvement and commercial involvement in a way that will help bring down the cost as well?

Mr. GERSTENMAIER. Yes, we currently have the NextSTEP Broad Agency Announcements where we're working with five companies to go look at habitation capability around the Moon, and we're actively engaged with them. They're very interested in what they can do with us, and then they may have application for that in low-Earth orbit as maybe a follow-on to the International Space Station. So we're actively very much involved with them.

Mr. ROHRABACHER. Right.

Mr. GERSTENMAIER. As I described earlier, SLS meets a unique niche. It can carry large mass to the vicinity of the Moon along with crew, but we will definitely use expendable launch vehicles, new vehicles that are coming online, the Falcon 9, Falcon 9 Heavy, New Glenn, all those capabilities, United Launch Alliances, they build their rockets. All those will be used. So I think what's interesting as we look to this whole suite of launch capabilities and commercial capabilities and how do we build a plan that involves all of them? So just like you described, we do the best of international, the best of commercial. We put it together in a plan to allow us collectively as a nation to move forward.

Mr. ROHRABACHER. That's terrific. Thank you for that answer. And I hope maybe Bigelow might have a little play in that as well.

Mr. GERSTENMAIER. He's one of the Broad Agency Announcements——

Mr. ROHRABACHER. Okay.

Mr. GERSTENMAIER. —participants in the habitation activity.

Mr. ROHRABACHER. Great. Thank you.

Chairman BABIN. All right, sir. Thank you, Mr. Rohrabacher.

I want to thank the witnesses for this very, very interesting hearing and your valuable testimony, and I want to thank all the members for their questions.

The record will remain open for two weeks for additional comments and written questions from the members.

So with this, the hearing is adjourned.

[Whereupon, at 10:56 a.m., the Subcommittee was adjourned.]

Appendix I

Answers to Post-Hearing Questions

ANSWERS TO POST-HEARING QUESTIONS

Responses by Mr. William Gerstenmaier

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"An Update on NASA Exploration Systems Development"

Mr. William Gerstenmaier, Associate Administrator, Human Exploration and Operations Directorate, NASA

Questions submitted by Ranking Member Ami Bera, House Committee on Science, Space, and Technology

1. In your prepared statement you state that "*While NASA's review shows an EM-1 launch date of June 2020 is possible, the Agency is managing to December 2019.*"

   a. Are NASA and contractor management and personnel all working to the December 2019 launch date, meaning that all schedules and tests must be completed within timeframes predicated on making that December 2019 date? How is NASA ensuring that its efforts to meet the manage-to-date not be perceived by its workforce as causing unhealthy schedule pressure?

      Answer: NASA and its contractor partners are working to the December 2019 launch date for Exploration Mission-1 (EM-1). The majority of work on NASA's new deep space exploration systems is on track. To address schedule risks identified in the review, NASA established new production performance milestones for the SLS Core Stage to increase confidence for future hardware builds. NASA and its contractors are supporting the European Space Agency's (ESA) efforts to optimize build plans for schedule flexibility if sub-contractor deliveries for the European Service Module (ESM) are late. The 2019 launch date target is intended to keep the teams focused and moving forward with a sense of urgency. However, NASA also recognizes that the Programs are carrying four to six months of schedule risk associated with first-time production and operations. NASA will continue to assess progress against the December 2019 planning date.

   b. What assumptions did NASA use to establish the December 2019 date? What would be the impact on meeting the December 2019 date should those assumptions need adjustment in the future?

      Answer: Among the key assumptions behind the December 2019 launch date are those that affect the enterprise "critical paths" that are the schedule drivers pacing other exploration activities relating to the first-time production of elements for the Space Launch System (SLS), Orion crew vehicle, and Exploration Ground Systems (EGS) and the integration of those elements. Key assumptions for these critical paths include:

- Delivery of the Orion ESM to the Operations and Checkout facility at the Kennedy Space Center (KSC) in late spring / early summer of 2018 for integration with the Orion Crew Module and the start of integrated testing;
- Delivery of the SLS Core Stage to the Stennis Space Center in December 2018 for the start of green run testing, followed by delivery to KSC in June 2019 for stacking;
- Completion of spaceport command and control software testing and checkout in February 2019.

Potential challenges that impact one or more of the elements might delay this integration and testing plan.

c. What remaining technical, production, and integration issues have the potential to negatively impact NASA's latest EM-1 launch date estimate? What are some ways by which you plan on addressing them?

Answer: While most hardware development and activities for these systems are on track with multiple months of margin, the Agency's technical management team remains focused on the "critical paths" of ESM delivery, the SLS Core Stage development, and spaceport command and control software development. The ESM and Core Stage issues largely involve challenges related to first-time design and assembly.

NASA is working closely with ESA to ensure delivery of the ESM in late spring/early summer 2018. This cooperation is focused on quickly solving technical issues as they arise, reducing schedule dependencies, and generally finding efficiencies through the integrated schedule. For example, NASA is working with U.S. vendors supplying hardware to Airbus (prime contractor for the ESM) to resolve technical issues seen in component-level testing; providing additional technician support to accelerate wire harness building, installation, and testing; and assessing the overall Orion integration schedule to provide opportunities for integrating ESM components after the ESM is delivered to KSC.

NASA and Boeing have implemented a number of changes already having a positive impact on core stage production. For example, senior Boeing management is very engaged in monitoring program progress and quickly addressing challenges as soon as they occur. Boeing has increased on-site production labor working three shifts during the week and two shifts on weekends. Boeing has also set up a dedicated core stage production operations center with integration managers coordinating daily operations, as well as a dedicated green run manager to ready the first core stage for testing at the Stennis Space Center in Mississippi starting approximately one year prior to launch.

NASA has moved additional engineering staff to Michoud Assembly Facility to reduce the cycle time for solving manufacturing problems in real time. Overall, NASA and Boeing are working methodically through issues that are not unexpected during the first-time production of such a large and complex piece of aerospace hardware.

2. Regarding NASA's establishment of the December 2019 manage-to-date:

    a. Is that the date to which Congress should hold NASA accountable? How will NASA communicate both (1) the status of risks as it moves towards the manage-to-launch date of December 2019 and (2) the ongoing impacts that resolution of those risks are having on the achievability of the December 2019 date?

    Answer: NASA is managing to the December 2019 EM-1 date, which is aggressive – with up to six months of additional schedule risk – but achievable. It is important to understand that in developing and integrating the Orion crew spacecraft, SLS heavy-lift launch vehicle, and extensive ground-based systems to support them, we are laying the foundation for a sustainable infrastructure for human deep space exploration for decades to come – one that will support missions to a variety of destinations, including the Moon and Mars. Thus, while EM-1 itself is important, it also represents the first in an ongoing continuum of Exploration Missions.

    NASA will provide formal notification to Congress under Section 103 of the NASA Authorization Act of 2005 (P.L. 109-155).

    b. More generally, what indicators and milestones should Congress use to measure progress on the SLS, Orion, and EGS programs?

    Answer: As noted in the response to Question #1b and #1c, above, NASA is particularly focused on ESM delivery, the SLS Core Stage development, and spaceport command and control software development.

3. In a recently released report, the NASA Inspector General said "the biggest challenge facing Orion for EM-1 is delivery of the European Service Module." Do you agree with that assessment? Can you describe the challenges that have caused delays to the delivery of the European Service Module? Have the difficulties experienced in designing and developing European Service Module informed NASA on how future international and commercial partner participation in human space exploration programs should be

structured? What, if any, changes have been made to ensure that the Service Module for EM-2 does not encounter similar challenges?

Answer: The critical path items at this point for EM-1 include the projected delivery of Orion's ESM, SLS Core Stage development, spaceport command and control software development. Challenges with the ESM delivery for EM-1 are largely related to issues involving first time design and assembly. Coordination with ESA on ESM assembly, integration, and testing is improving, and NASA has increased involvement in resolving domestic and international vendor technical and schedule performance issues.

NASA is planning on ESA supplying the service module for Orion on future deep space missions. The relationship we have built with ESA working on EM-1 will serve to strengthen our joint efforts moving forward on EM-2. Furthermore, we are working with both domestic and international partners to solve the great challenges of deep space exploration, including studying lunar activity. We will build on the partnerships we have established with both industry and international space agencies in low-Earth orbit as we move humans farther into the solar system.

4. Regarding the Vice President's recent direction to conduct human lunar exploration:

    a. How would a return to the Moon, including potentially establishing a human presence there, impact the goal of sending humans to Mars in the 2030s, as directed in the 2017 NASA Transition Act?

        Answer: A NASA return to the Moon for long-term exploration and utilization will enable building and testing systems needed for other challenging missions to deep space destinations, including Mars. The details of NASA's lunar missions are currently being developed and will be reflected in future budget requests.

    b. When will NASA inform Congress of (1) the total budgetary impact of adding lunar surface activities the agency's exploration program and (2) how much funding will need to be added to the HEO budget on an annual basis to pursue both the Moon and humans to Mars?

        Answer: Please see response to Question #4a, above.

5. While many people may naturally tend to focus on the EM-1 launch date, I understand that the factors surrounding that launch date involve establishing a development, production, and launch capability for NASA's human exploration missions for decades to come.

    a. What key challenges is NASA facing during the development of systems like SLS/Orion/EGS in establishing production processes for the first time and what will it take to achieve a production capacity capable of conducting a sustained human space exploration program? When do you anticipate NASA will have that capability in place and what do you estimate the average annual launch rate will be at that juncture?

Answer: The SLS and Orion programs have made extensive investments in advanced manufacturing techniques like reaction friction stir welding and additive manufacturing, investments to help achieve a production capacity capable of conducting a sustained human space exploration program.

One example of a key challenge NASA has overcome during EM-1 has been the development of friction stir welding techniques and equipment used in the manufacture of SLS. NASA and Boeing have done extensive work to develop weld parameters and processes for making the first-of-their-kind large propellant tanks, and engineers working on the rocket have learned a great deal from meeting challenges ranging from the precise alignment of weld machines to addressing the fact that tiny threads on welding pins affect weld strength. Producing the SLS' propellant tanks has pushed the state-of-the-art for self-reacting friction stir welding of thicker materials. This is the first time robotic self-reacting friction stir weld technology has built such large rocket parts with thicker joints. NASA and Boeing have learned a great deal by working through processes to get weld parameters for the large fuel tanks adjusted to produce high-quality welds that can withstand the extreme forces of launch and spaceflight.

SLS, Orion, and exploration ground systems are being designed to be capable of supporting a long-term flight rate of one per year with a surge capability of three per year. The actual cadence of missions beyond EM-2 will be defined based on mission needs, available resources, and operational costs. Reducing production and operations costs will be critical for enabling an ambitious exploration program.

b. What have NASA and its SLS and Orion contractors done to incorporate efficiencies into production processes?

Answer: NASA has assessed the results from a recent affordability Request for Information and will work with industry to reduce overall costs once SLS and ground systems enter the production and operations phase.

As one option, NASA will assess whether some elements may be reused and if reuse will lead to reduced costs. For example, NASA is assessing the potential reuse of avionics boxes on the Orion Crew Module (and possibly even the pressure vessel of the Crew Module itself). That assessment will take into account the demonstrated condition of that hardware on EM-1 and subsequent flights, after the hardware has been through long-duration missions in the hostile environment of deep space.

SLS leverages over a half-century of experience with launch vehicles, including Saturn and Space Shuttle, along with advancements in technology since that time, including model-based engineering, additive manufacturing, high-fidelity computational fluid dynamics capabilities, new composite materials and production techniques, and large-scale self-reaction friction stir welding. Additionally, initial flight units use components already owned from the Space Shuttle, such as RS-25 engines and boosters. More efficient methods are under development for manufacturing these components, including new NASA investment in expendable RS-25 engines for the SLS Core Stage with the goal of achieving a lower per-unit cost than the original reusable RS-25s used as the Space Shuttle Main Engines. The Agency continues to identify affordability strategies for missions beyond EM-2. Reducing overall costs of the systems will be critical to achieving a successful and sustainable exploration capability.

For ground systems, the launch and flight support infrastructure at KSC will be able to provide a more flexible, affordable, and responsive national launch capability compared to prior approaches.

c. To what extent will establishing a development, production, and launch capability have benefits for other stakeholders, including commercial and international partners? If so, will they share the costs?

Answer: As noted in the response to Question #5a, above, the SLS and Orion programs have made extensive investments in advanced manufacturing techniques like reaction friction stir welding and additive manufacturing, investments which have helped to position the nation and U.S. companies as world leaders in this critical technological area. The specifics of potential benefits to commercial and international partners, as well as any cost-sharing plans, would depend on the details of partner proposals.

d. How is NASA applying lessons learned on fabricating EM-1 to its work on EM-2? To what extent have these lessons affected the EM-2 production process?

Answer: Please see response to Question #5a, above, regarding friction stir welding as an example of work on EM-1 that is being refined as NASA moves forward to EM-2. As NASA and its contractor teams overcome first-time production and operations issues and gain experience with new manufacturing processes, the Agency expects further refinements that will benefit future production.

6. How important is the role of component and system suppliers in meeting SLS, Orion, and ground system production milestones? What has been your experience with suppliers in preparing for EM-1? What, if any, changes are needed to ensure that the supply chain is working smoothly toward making maximum progress on exploration development systems?

   Answer: Component and system suppliers are critical to the development of NASA's exploration systems, and the Agency's experience with such subcontractors has demonstrated their dedication to the mission. As the U.S. aerospace industrial base has evolved in recent decades, the overall number of suppliers of certain highly specialized items used in the SLS and Orion systems have been reduced, and certain areas of expertise have been de-emphasized. NASA is working with its industry partners to ensure that the supply chain will work smoothly to provide long-term production support, and the teams are gaining important experience as they support EM-1 and beyond.

7. Both the NASA Inspector General and the GAO have expressed concern about the limited amount of cost reserves available to address issues as they arise in exploration systems development. The IG states, "*according to guidance developed at Marshall Space Flight Center (Marshall), the standard monetary reserve for a program such as the SLS should be between 10 and 30 percent during development.*"

   a. How much cost reserve do the SLS, Orion, and EGS programs currently have as a percentage of the development budget? How do you see this changing in the future?

      Answer: While NASA is not managing based upon percentages of reserves, the three programs do have reserves spread across their life cycles. Through the budget horizon through 2023, the following are being bookkept as reserves within the respective program offices:

      - SLS: approximately 3 percent from FY 2018 through FY 2023
      - Orion: approximately 6 percent from FY 2018 through FY 2023
      - EGS: approximately 6 percent from FY 2018 through FY 2023

      These reserves (along with the updates NASA has made to its approach to managing systems engineering and integration, and an increased emphasis on production performance for the Orion ESM, SLS Core Stage, and spaceport command and control software development) give NASA confidence to deliver EM-1 and to continue evolving the overall enterprise capability.

b. Is maintaining a 10 to 30 percent cost reserve a best practice NASA should follow in the development of systems like SLS, Orion, and EGS? If not, what is the optimal level of reserves?

Answer: While some NASA Centers emphasize the use of a percentage of total life cycle costs as reserves, this best practice was developed for one-off missions such as the development of a science satellite or planetary mission. However, SLS, Orion, and EGS are not one-off missions. NASA manages the SLS, Orion, and EGS programs as an evolving and multi-mission capability with workforce and costs being divided among several different missions and objectives. As a result, there are many tools (in addition to holding cost reserves) which can be utilized to meet program goals, such as manifest and schedule management (including phasing the sequence of missions); evolution and upgrade management (including phasing of when new system capabilities are needed); contract management (including the phasing of contract awards); workforce management; and management of cost reserves. NASA has decades of experience (including most recently with Space Shuttle and the International Space Station) balancing the unknowns of an ongoing spaceflight capability within an annual topline budget using such a combination of tools.

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"An Update on NASA Exploration Systems Development"

Mr. William Gerstenmaier, Associate Administrator, Human Exploration and Operations Directorate, NASA

Questions submitted by Representative Mo Brooks, House Committee on Science, Space, and Technology

1. Nuclear Thermal Propulsion is one of the more promising areas that NASA is working on to help speed transit time and limit radiation exposure for astronauts lengthy deep space missions. What is the current timeline for the development of technology and when can we expect it to become operational for deep space missions?

   Answer: In FY 2016, the NASA's Space Technology Mission Directorate (STMD) initiated development of foundational technologies and began studies to advance nuclear thermal propulsion systems that face numerous challenges to develop, but could ultimately provide a rapid and architecturally robust in-space transportation capability. This three-year project is taking the initial key steps to explore how to enable more efficient spaceflight by developing and testing low-enriched-uranium fuel elements to support a potential future nuclear thermal propulsion system.

   The overarching goal for this three-year plan is to assess the technical feasibility and affordability of nuclear thermal propulsion for faster and more flexible transport on deep space exploration missions. The resulting analysis will close the gaps in our current knowledge of low-enriched-uranium based systems, and allow NASA to make informed decisions on Mars exploration architectures with credible cost estimates and a higher level of schedule confidence.

   However, high cost, long development times, and a lack of utility for US commercial providers are preventing nuclear propulsion from being considered in NASA's near-term exploration plans.

2. The Marshall Space Flight Center in my district has been doing some exciting work on Nuclear Thermal Propulsion technology over the years. Can you elaborate a little on if you support the plan to complete a ground demonstration project in the next few years?

   Answer: NASA has made initial investments through a three year project funded within Space Technology's Game Changing Development Program. As noted, this project is led by NASA's Marshall Space Flight Center (MSFC) with contracts to Dynetics, Aerojet Rocketdyne, BWX Technologies, Analytical Mechanics Associates, and with NASA's Stennis Space Center (SSC), NASA's Glenn Research Center (GRC), and the

Department of Energy (DOE) as collaborating partners. At the conclusion of this three-year activity, a determination will be made whether to continue to pursue development of the nuclear thermal propulsion technology.

Dependent on the outcome of the initial three year effort, subsequent steps might include completing the design and building the reactor and engine, culminating in a full-scale, full-power engine test. During the course of these efforts, a ground test approach for capturing the exhaust would need to be developed and implemented. Additionally, long-term space storage of liquid hydrogen would need to be demonstrated, utilizing cryogenic fluid management (CFM) technologies that are currently being developed through Space Technology's eCryo project. The last major step would be to design and build the space propulsion stage that would utilize the NTP system and the CFM technologies.

The Agency is working to reduce technology barriers for potential future applications. However, the total cost of the full scale, full power engine test along with the development of an operational NTP system, would be significant barrier in considering NTP for future human exploration missions.

3. How can NASA lay the groundwork for this potentially innovative technology with greater foresight and ambition toward deep space exploration?

Answer: NASA's near term objective is to find an affordable approach for the development of NTP systems using Low Enriched Uranium, enabling the participation of industry and/or academia by lessening the burden of security requirements on the system and avoiding building new government infrastructure. NASA hopes to leverage commercial manufacturing techniques, infrastructure and business base to defray costs. The Agency faces several key technology challenges in developing nuclear thermal propulsion, including:

- Fabricating high-temperature fuel elements that minimize erosion and accompanying fission product release and which use lower quantities of enriched uranium than those developed for past programs;
- Testing and qualification of the fuel elements;
- Devising a safe and affordable engine ground test and qualification approach; and,
- Maturing reactor and engine system designs.

As noted above, STMD initiated a technology assessment and maturation project in FY 2016 to determine whether a design based on low enriched uranium (LEU) fuel elements could enable an affordable nuclear thermal propulsion system. Major tasks for the three-year effort include:

- Design, fabrication, and testing of ceramic-metallic composite (cermet) fuel elements;
- Performing feasibility analysis and detailed cost analysis of an LEU-based engine;
- Developing a safe and affordable nuclear thermal engine ground testing approach; and
- Performing a detailed cost analysis for the full development effort leading to the first flight system.

In addition, the research efforts mentioned above on long-term storage of cryogenic hydrogen propellant is an essential part of the nuclear thermal propulsion research activities. Cryogenic fluid management (CFM) technologies are currently being developed and tested on the ground, including Space Technology's eCryo project. eCryo is conducting a large-scale ground demonstration of liquid hydrogen storage with very low boil off of the propellant.

These activities are the essential first step in determining the applicability for future exploration.

4. Is it true that nuclear thermal propulsion technology can dramatically increase the safety for astronauts on a future trip to Mars?

   Answer: Nuclear thermal propulsion systems face numerous challenges to develop, but could ultimately provide a rapid and architecturally robust in-space transportation capability. The extremely high energy density of nuclear reactions makes them attractive conceptually as an energy source for propulsion systems. With hydrogen as the propellant, exhaust velocities for nuclear thermal propulsion can be more than a factor of two greater than the highest performing chemical propulsion systems. By comparing that increase with the high thrust values associated with chemical rocket engines, it is estimated that a nuclear thermal propulsion system could reduce the round-trip transit time to Mars by 25 percent or more, and also provide increased flexibility in Earth departure and return trip scheduling. However, as a new and complex technology, it will take substantial analysis, ground facilities testing, and on-orbit performance to fully match the safety reliability of existing chemical propulsion systems.

5. As we march forward making the Space Launch System and Orion the system that will send humans into deep space, commercial companies are working to provide human access to low earth orbit. Safety must remain the number one priority in all these programs. Do you have any concerns with the Falcon 9 platform given the recent failure of a Merlin D engine?

   Answer: SpaceX continues to make good progress towards launching crew to the International Space Station (ISS) in 2018, and incorporates lessons learned from test failures. SpaceX notified NASA of the recent Merlin engine failure. The company is investigating internally and keeping NASA fully informed of the team's progress. NASA's insight into the SpaceX and Boeing Commercial Crew efforts is helping to ensure that our astronauts will have safe, reliable, domestic transportation to ISS in the years ahead.

6. Does NASA plan to provide an incident report for all recent failures to Congress?

   Answer: NASA briefed its findings on the SpaceX-7 launch failure to Congressional staff in January 2016. The Agency is in the process of producing a Public Summary Report for the NASA Launch Services Program (LSP)-led Independent Review Team investigation of the SpaceX-7 launch failure. This report is currently going through the appropriate reviews to ensure that International Traffic in Arms Regulations (ITAR)/Export Controlled, and Proprietary information is not included.

   NASA is still active with its independent review of the SpaceX Pad Anomaly that occurred on Sept. 1, 2016. The independent review's findings will be captured in a briefing to the Agency's Flight Planning Board. NASA is happy to brief the interested Congressional Members and/or staff on our findings once the investigation is complete. This failure is being used as the basis for analysis and design of the composite overwrap pressure vessel planned for use on the Falcon 9 Block 5 launch vehicle planned for commercial crew flights. Procedural changes are being implemented by SpaceX to prevent problems similar to this anomaly for commercial cargo flights. No formal written report or public summary is planned. For further details on the event and specific lessons learned, NASA recommends contacting SpaceX.

7. What are the indemnification coverage steps that NASA has in place with regards to commercial companies?

   Answer: The procedure for a contractor to request indemnification for third-party liability and the process for NASA to consider and analyze such a request is set forth in Part 50 of the Federal Acquisition Regulation (FAR) and Part 1850 of the NASA FAR Supplement (NFS). This process is the same for any contractor, regardless of the type of contract or whether a company is "commercial". However, this process for requesting and granting indemnification is applicable only if NASA has specific statutory authority to indemnify the contractor under the particular circumstances of the request. Among several factual bases required for NASA or any Federal agency to indemnify a contractor is that the work required to be performed under the contract must involve unusually hazardous risk for which commercial insurance is unavailable. Such legal authorities are narrowly construed because the Government's indemnification of a contractor for third-party liabilities represents an extraordinary contractual re-allocation of risk and responsibility among the parties to a contract.

   Government contract law and regulations ordinarily require that contractors will be responsible for the risks resulting from their own work, and accordingly, contractors protect themselves from resulting liability with a financial protection program that includes commercial insurance. In a few extraordinary circumstances, Congress has recognized that certain work performed by a contractor entails unusually hazardous risks for which commercial insurance is not available and as such Congress has authorized, through a few very specific legal authorities such as Public Law 85-804 and the Price Anderson Act Amendments, some agencies to relieve the contractor with respect to assuming liability resulting from the contractor's performance of that work. Specifically with respect to "commercial" launch services providers, under the **Commercial Space Launch Act (CSLA)**, the Federal Aviation Administration (FAA) handles indemnification for launches conducted under a FAA-issued commercial license.

8. Is NASA able to offer indemnification to Nuclear Thermal Propulsion technology? If not, why not?

   Answer: NASA is currently exploring options for indemnification that would not require additional Congressional authority. Should new or modified authority be necessary, the Agency will notify the appropriate Congressional Committees.

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"An Update on NASA Exploration Systems Development"

Mr. William Gerstenmaier, Associate Administrator, Human Exploration and Operations Directorate, NASA

Questions submitted by Representative Bill Posey, House Committee on Science, Space, and Technology

1. When it comes to space, the unimaginable has often become the imaginable and the achievable, especially when we commit to long-term research, development and strategies. As we hone in on making manned mission to Mars a reality and other lengthy missions — manned or unmanned — I am intrigued by the potential for resources available in space to be used as fuel in space. If realized, this potential will lighten payloads and extend the range and duration of our missions. As such, would you comment on NASA's strategic view or long-term architecture for in-space refueling? Moreover, in NASA's exploration plan will NASA evaluate the value and potential for utilizing in-space resources like those found on asteroids?

   Answer: The farther humans go into deep space, the more important it will be to produce propellants and life support system consumables with in-situ resource utilization (ISRU). Some of the most promising space-based commodities that could enable substantial reductions in the mass, cost, and risk of human space exploration include oxygen, water, and methane. These products are critical for sustaining crew and for space propulsion and power systems. They may be derived from space resources such as the carbon dioxide-rich Mars atmosphere and water deposits based in lunar, Mars, and asteroid soil (also called regolith). Deposits of water and other useful volatiles, which are substances that evaporate easily at moderate temperatures, are not yet fully characterized, and work remains to understand their accessibility. Accordingly, NASA's priorities for advancing ISRU include exploring volatile deposits at destinations of interest so resource potential can be determined, and extraction and utilization equipment can be properly designed.

   In FY 2018, NASA is pursuing several activities that will advance ISRU technology. NASA is developing the Mars Oxygen ISRU Experiment (MOXIE) for the Mars 2020 rover that will demonstrate the production of oxygen from the Mars atmosphere. In December 2017, NASA issued a Broad Agency Announcement (BAA) to solicit proposals for public-private partnerships to develop and test component technologies and subsystems for ISRU.

   For further information on the BAA, please see:

   https://www.nasa.gov/feature/nasa-seeks-commercial-solutions-to-harvest-space-resources

For further information on ISRU, please see:

https://www.nasa.gov/isru

The Space Technology Mission Directorate (STMD) is developing capabilities for in-space propulsion, including cryogenic propellant storage, power generation and energy storage, and on-orbit refueling. For example, cryogenic fluid management technologies are currently being developed and tested on the ground, through Space Technology's eCryo project. eCryo is conducting a large-scale ground demonstration of liquid hydrogen storage with very low boil off of the propellant. Managing cryogenic fluids and minimizing boil-off of cryogenic propellants on long duration missions is a critical capability needed to enable high-performance in-space propulsion stages, as well as on orbit refueling.

For information about Space Technology, please see:

https://www.nasa.gov/directorates/spacetech/home/index.html

2. In September, this Subcommittee held a hearing with Mr. Jason Crusan on your staff about NASA's work with robotic lunar lander companies, like on the Lunar CATALYST program, which I understand NASA just extended for an additional two years.

   During the hearing, Mr. Crusan said:

   "The agency is currently assessing possible robotic mission concepts, acquisition approaches, and associated payloads for a potential series of lunar cargo missions to the surface of the Moon starting as early as 2018," and "the agency is interested in assessing the availability of commercial delivery services from earth to the lunar surface as early as next fiscal year."

   As you know, Chairman Culberson and the Commerce-Justice-Science Appropriations Subcommittee included $30 million for Lunar Lander demonstration missions in the FY2018 Appropriations bill. Based on Mr. Crusan's testimony and the Appropriations Subcommittee support, how does NASA plan to leverage robotic lunar lander missions starting in FY2018, especially as the Administration is focusing on Lunar exploration opportunities?

   Answer: NASA is supporting the development of commercial lunar exploration. In 2014, NASA introduced Lunar CATALYST (Lunar Cargo Transportation and Landing by Soft Touchdown) and entered into competitively awarded partnerships with three U.S. firms (Astrobotic Technologies, Masten Space Systems, and Moon Express) to provide in-kind support to develop commercial lunar robotic landing capabilities. NASA is providing engineering expertise, hardware and software, and test facilities to these companies. The purpose of the initiative is to encourage the development of U.S. private-sector robotic lunar landers capable of successfully delivering payloads to the lunar surface using U.S. commercial launch capabilities. Initial flights of commercial lunar landers may begin as early as 2018, and as a result one or more of these companies will be able to market lunar payload delivery services for small instruments and technology demonstrations. Commercial lunar transportation capabilities could support science and exploration objectives such as sample returns, geophysical network deployment, resource utilization, and technology advancements.

The details of NASA's lunar missions are currently being developed and will be reflected in future budget requests.

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"An Update on NASA Exploration Systems Development"

Mr. William Gerstenmaier, Associate Administrator, Human Exploration and Operations Directorate, NASA

Questions submitted by Representative Bill Foster, House Committee on Science, Space, and Technology

1. The Apollo lunar landing program cost $24 billion in 1960s dollars over 10 years. That means NASA set aside nearly 4 percent of U.S. GDP to get to the moon. Today, 50 years later, NASA's budget is about $19 billion per year which is less than one tenth of one percent of GDP.

   In order to begin our political and fiscal planning for a mission to Mars, it is imperative to have an estimate of what it would cost to meet this goal. Mr. Gerstenmaier, do you have what you believe is a realistic upper and lower limit to the cost for getting to Mars? If so, please share that estimate with this Subcommittee.

   Answer: Between 1960 and 1973, the Apollo Program accounted for approximately 0.9 percent of total Federal outlays (peaking at approximately 2.2 percent of Federal outlays in 1966) and approximately 0.1 percent of the U.S. gross domestic product. As NASA learns from initial missions using SLS and Orion and develops new technologies to make exploration more affordable, the Agency will formulate cost and schedule details of future goals and hardware, and this analysis will be reflected in future budget requests. NASA is planning toward roughly today's budget levels.

Material requested for the record by Representative Higgins during the November 9, 2017 hearing at which Mr. William Gerstenmaier testified.

Provide information about the large lava tubes on the Moon.

Answer:

NASA's Lunar Reconnaissance Orbiter (LRO) and Gravity Recovery and Interior Laboratory (GRAIL) data supported the attached analysis, "The Structural Stability of Lunar Lava Tubes," by D.M. Blair, et al., from the journal *Icarus*, published by Elsevier, Inc.; the attached article provides the requested information on lava tubes on the Moon.

Icarus 282 (2017) 47–55

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Icarus

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The structural stability of lunar lava tubes

David M. Blair[a,1,*], Loic Chappaz[b], Rohan Sood[b], Colleen Milbury[a], Antonio Bobet[c], H. Jay Melosh[a,d], Kathleen C. Howell[b], Andrew M. Freed[a]

[a] Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Stadium Mall Dr., West Lafayette, IN 47907, USA
[b] School of Aeronautics and Astronautics, Purdue University, 701 W. Stadium Ave., West Lafayette, IN 47907, USA
[c] Lyles School of Civil Engineering, Purdue University, 550 Stadium Mall Dr., West Lafayette, IN, 47907, USA
[d] Department of Physics and Astronomy, Purdue University, 525 Northwestern Ave., West Lafayette, IN 47907, USA

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GRAIL

ABSTRACT

Mounting evidence from the SELENE, LRO, and GRAIL spacecraft suggests the presence of vacant lava tubes under the surface of the Moon. GRAIL evidence, in particular, suggests that some may be more than a kilometer in width. Such large sublunarean structures would be of great benefit to future human exploration of the Moon, providing shelter from the harsh environment at the surface—but could empty lava tubes of this size be stable under lunar conditions? And what is the largest size at which they could remain structurally sound? We address these questions by creating elasto-plastic finite element models of lava tubes using the Abaqus modeling software and examining where there is local material failure in the tube's roof. We assess the strength of the rock body using the Geological Strength Index method with values appropriate to the Moon, assign it a basaltic density derived from a modern re-analysis of lunar samples, and assume a 3:1 width-to-height ratio for the lava tube. Our results show that the stability of a lava tube depends on its width, its roof thickness, and whether the rock comprising the structure begins in a lithostatic or Poisson stress state. With a roof 2 m thick, lava tubes a kilometer or more in width can remain stable, supporting inferences from GRAIL observations. The theoretical maximum size of a lunar lava tube depends on a variety of factors, but given sufficient burial depth (500 m) and an initial lithostatic stress state, our results show that lava tubes up to 5 km wide may be able to remain structurally stable.

1. Introduction

Lunar lava tubes present an enticing target for future human lunar exploration. A vacant lava tube could provide astronauts shelter against small meteorite impacts, cosmic radiation, and the extreme temperature variations at the lunar surface (Hörz, 1985; Haruyama et al., 2012). Because lava tubes are by their nature found in the vicinity of volcanic vents, there may also be good local availability of volatile chemical species such as sulfur, iron, and oxygen, as well as pyroclastic debris which could be useful as a construction material (Coombs and Hawke, 1992). Their enclosed nature and limited exposure to the space environment may also make them possible storage locations for water and other ice deposits, useful sites for studying the stratigraphy of the lunar regolith and dust environment, and suitable sites for finding comparatively pristine examples of mantle-derived rocks near the surface (Haruyama et al., 2012). Locating and characterizing potential lunar lava tubes has therefore been a priority in the lunar science community for some time.

Lava tubes form when a channelized lava flow forms a roof either through the development of levees or the formation of a surficial crust, while the molten material underneath flows away and leaves a partially or completely vacant conduit (e.g. Cruikshank and Wood, 1971). Such features occur in numerous locations on Earth, and it has long been posited that they may also exist—or have existed—on the Moon. Through interpretation of images returned by Lunar Orbiter V, Oberbeck et al. (1969) were among the first to suggest that sinuous rilles such as those observed in northern Oceanus Procellarum and elsewhere may be the collapsed remains of lava tubes which formed during the emplacement of the maria. Numerous other studies during the Lunar Orbiter and Apollo mission eras supported this idea, and showed examples of similar processes occurring in Hawai'i (e.g. Cruikshank and Wood, 1971; Greeley, 1971; Oberbeck et al., 1972).

It is only recently that we have obtained direct evidence for the existence of uncollapsed voids beneath the lunar surface. In 2009, Haruyama et al. published their discovery of a 65 m-diameter

* Corresponding author.
E-mail address: david_blair@brown.edu (D.M. Blair).
[1] Present address: Department of Earth, Environmental, and Planetary Sciences, Brown University, Box 1846, 324 Brook St., Providence, RI 02912, USA.

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vertical-walled hole in the Marius Hills region of the Moon, using data from the Terrain Camera and Multi-band Imager aboard the SElenological and ENgineering Explorer (SELENE) spacecraft. The following year, two additional pits were identified in SELENE data, in Mare Tranquilitatis and Mare Ingenii (Haruyama et al., 2010). Subsequent high-resolution imagery returned by the Lunar Reconnaissance Orbiter Camera (LRO/LROC) (Robinson et al., 2010) was then used not only to provide more detailed views of the pits discovered by Haruyama et al. (2009, 2010), but also to identify 150 additional pits at the lunar surface (Robinson et al., 2012). Overall, these openings are found to have widths ranging from 49 to 106 m, which represents a minimum size for the underlying void, and oblique views of the pits do show that the underlying cavern is wider than the hole in the surface in at least several cases (Ashley et al., 2011; Wagner and Robinson, 2014). Voids may also exist in areas such as the Al-Tusi impact melt pond near King Crater on the lunar far side, where skylights and sinuous fracture patterns have been found in high-resolution LROC images (Ashley et al., 2012), suggesting a lava tube collapse. Unfortunately, the size and shape of a void cannot be determined by the use of imagery alone (e.g. Robinson et al., 2012).

Gravity data, however, is particularly suited to the identification and characterization of subsurface density variations such as vacant lava tubes. Work by Chappaz et al. (2014a,b, 2016) and Sood et al. (2016a,b) has shown that lava tubes, buried craters, and other density anomalies can be located and characterized in the high-resolution datasets returned by NASA's Gravity Recovery And Interior Laboratory (GRAIL) mission (e.g. Zuber et al., 2013; Lemoine et al., 2014). Using a combination of techniques such as gravity anomaly Eigenvalue mapping, cross-correlation between observed gravity signals and those of hypothetical features, and forward modeling of the gravity anomalies caused by lava tubes, Chappaz et al. (2014a,b, 2016) have found possible sublunarean extensions of surface sinuous rilles at both Vallis Schröteri and Rima Sharp. In both cases, GRAIL observations were found to positively correlate with a buried tube 1–2 km in width. The depth and shape of these putative lava tubes cannot be explicitly determined from gravity data, however, as a tube even several hundred meters under the surface would produce a nearly identical GRAIL-observable gravity signature to one sitting centimeters under the surface since in both cases the spacecraft's altitude would be much greater than the feature's depth. While a collection of smaller lava tubes could also produce a gravity signature that would match GRAIL observations, the general pattern of volcanic flows on the Moon is one characterized by a relatively small number of high-volume flows. The interpretation favored here and in Chappaz et al. (2014a,b, 2016) and Sood et al. (2016a), therefore, is that these gravity anomalies are each caused by a single, large vacant lava tube buried at some non-zero distance under the surface.

The size of the lava tubes inferred by Chappaz et al. (2014a,b, 2016) is much larger than any known terrestrial examples, which reach a maximum of ~30 m in width (e.g. Greeley, 1971). Oberbeck et al. (1969) addressed the question of how large a lava tube could be on the Moon and remain structurally stable by modeling the roof of a lava tube as an elastic beam. Doing so, they found that a lava tube with a roof 65 m thick could remain stable at a width of ≲ 385 m, given a lunar basalt density of 2500 kg m^{-3}. They also suggest that lava tubes up to 500 m wide may be possible under lunar conditions, a number which has been frequently cited since that work was published; that calculation, however, uses a hypothetical vesicular basalt density of 1500 kg m^{-3}, well below the 3010–3270 kg m^{-3} density of that material which is now known from modern re-analysis of Apollo mare samples (Kiefer et al., 2012). Furthermore, while Oberbeck et al. (1969) mention that an arched roof would allow a larger stable tube or a thinner possible roof at a given tube width than the beam model used in their study, they do not quantify that effect.

In this study, we aim to constrain the maximum size at which vacant lava tubes could remain structurally stable under lunar gravity. More specifically, we seek to determine whether the large lava tubes inferred from analysis of GRAIL data by Chappaz et al. (2014a,b, 2016) are mechanically plausible, leaving aside the mechanisms for forming tubes of that scale. Our methods incorporate numerical modeling techniques of a scale not available to investigations of similar questions performed during the Apollo era, as well as modern knowledge about the densities of lunar rocks and the behavior and failure mechanisms of large rock bodies in general.

2. Modeling techniques

We approach the question of lava tube stability through the use of finite element models built in the *Abaqus* software suite (version 6.12; http://www.simulia.com/solutions). Our models assume plane-strain conditions and are symmetric about the tube's longitudinal axis for the sake of computational simplicity. Models were verified against analytic results for simple cases (e.g. gravitational self-compression of a block) and were found to be accurate to within 1%. Zero-motion boundary conditions are set at the far lateral and bottom edges of the model, which are placed sufficiently far away (20 tube widths) so as not to influence our model results. In every model, we ensure that there are 20 elements through the thickness of the lava tube's roof, and then adjust other mesh parameters to ensure suitable element aspect ratios (< 10:1). Our general model setup and an example mesh are shown in Fig. 1. We do not model the formation of the lava tube itself, but instead investigate the stability of the completed structure under various potential lunar conditions.

The primary variables in this study are the width of the lava tube, the thickness of the lava tube's roof, and the pre-existing stress state of the material. The shape of the tubes is held at a constant 3:1 width-to-height ratio, mimicking the general non-circular arched shape of terrestrial lava tubes while remaining somewhat close to the circular cross-section used in Chappaz et al. (2014a,b, 2016) such that our models do not grossly over-predict the width of the tube responsible for a particular gravity deficit. The fixed aspect ratio also means that we are varying the tube's volume linearly by adjusting only the width, which is useful for comparison with analyses of GRAIL data since these scales with the volume of the void space. While this single aspect ratio cannot represent the various lava tube shapes on the Moon or elsewhere, focusing on a single shape also enables efficient exploration of parameter space in terms of width, roof thickness, and initial stress state (see next paragraph). Because these structures are buried, the roof thickness is in one sense equivalent to the depth to which a lava tube has been buried by one or more flows after its initial formation. It can also be considered as the thickness of the thinnest layer within the lava tube's roof, however, by analogy to terrestrial caves in bedded rock which tend to collapse when individual beds start to fail (e.g. Ford and Williams, 1994; Palmer, 2007). We therefore test a range of roof thickness values from 1 to 500 m that includes both the range of layer thicknesses seen in the walls of lunar skylights (~1–12 m) (Robinson et al., 2012) and a thickness comparable to the larger flows in Oceanus Procellarum (~600 m) (Wieder et al., 2010). Our modeled lava tube widths range from 250 m to 10 km, representing a size slightly smaller than the maximum size calculated by Oberbeck et al. (1969) and the approximate present-day width of the widest part of Vallis Schröteri, respectively. With our assumed width-to-height ratio, this range also includes lava tubes with heights similar to the ~100–150 m depths of observed skylights.

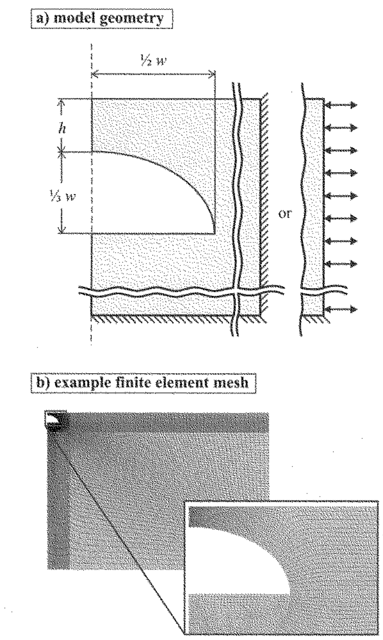

Fig. 1. (a) Diagram of our model configuration showing our geometric variables: the lava tube's width, w, and the thickness of its roof, h. The height of the lava tube is set at ⅓ of its total width. Our model is symmetric about a plane bisecting the lava tube lengthwise (dashed line), and extends infinitely into and out of the page due to our assumption of plane-strain conditions. The right and bottom edges of the model are 20 w away from the plane of symmetry and the surface of the model, respectively, and the bottom of the model is fixed. The right edge of the model is either fixed or set to a given horizontal displacement, depending on whether or not the model includes far-field tectonic strains. (b) Example finite element model mesh, and an inset showing details of the mesh in the region of the lava tube.

We simulate lava tubes which have formed in either a lithostatic or Poisson stress state, representing two end-member cases of how stresses in the emplaced and cooled lava could be distributed. The lithostatic stress state is one where the horizontal stresses at depth are equal to the overburden (vertical) stress, a state which would arise if all of the materials comprising the lava tube and its surroundings were able to relax differential stresses completely after emplacement; in geotechnical engineering terms, the lithostatic state is defined as one where the coefficient of earth pressure at rest, k_0, is equal to unity. The Poisson stress state represents the material's direct elastic response to overburden, where horizontal stresses at depth are some fraction (usually on the order of ⅓, given a typical basaltic Poisson ratio of 0.25 as used here; see Table 1) of the vertical stress and are controlled by the material's Poisson ratio. To obtain our results for the Poisson stress state, we simply allow the structure to self-compress under lunar gravity with zero-horizontal-motion (and free vertical motion) boundary conditions at the lateral edges of the model. This is the only model run necessary to initiate a Poisson stress state. In contrast, the development of an initial lithostatic stress state requires an iterative process that balances gravity loads with applied stresses such that no significant gravitational self-compression occurs in regions far from the lava tube. We accomplish this by running a version of the self-compression simulation that only includes elastic material properties, retrieving only the final vertical stresses from each element in the model, and assigning that vertical stress value to all three Cartesian stress components for that element in a second elastic simulation in which the elements again start at their original, undeformed positions. After running this second simulation, we typically still observe some far-field motion in the model, and so we repeat the process until far-field displacements vary by less than 1% between two successive models, typically through the 3rd or 4th iteration.

Table 1
Model parameters.

Symbol	Description	Value	Units
ρ_b	Density[a]	3100	$kg\,m^{-3}$
ν	Poisson's ratio	0.25	
σ_{ci}	Unconfined compressive strength	100	MPa
m_i	Material constant[b]	20	
GSI	Geological Strength Index[b]	70	
φ	Friction angle[c]	43	°
ψ	Dilation angle	29	°
E	Young's modulus[c]	30	GPa
c	Cohesive strength	7.2	MPa
g_{Moon}	Lunar gravity	1.662	$m\,s^{-2}$

[a] after Kiefer et al. (2012);
[b] value from Marinos and Hoek (2000);
[c] calculated using method described in Marinos and Hoek (2000).

We also consider regional-scale tectonic strains that may affect the stability of a lava tube. To simulate these strains, we modify our models so that the edge farthest from the plane of symmetry is forced to move laterally during the simulation by an assigned percentage of the total width of the model (not of the lava tube) which varies between model runs. Edge motion towards the plane of symmetry places the model into contraction, simulating the flexural compression and subsidence associated with the emplacement of the mare which may have led to the formation of features like mare ridges. Edge motion away from the plane of symmetry places the region into extension, which might be expected if the region is undergoing flexural uplift. We vary the magnitude and sign of the tectonic strains to examine the effects of various amounts and types of tectonic deformation, since the regional strain conditions of the lunar maria are poorly constrained. These tectonic strains are superimposed onto the gravity loading described above.

The material comprising our model is assigned a Mohr–Coulomb plastic failure envelope in order to simulate stresses and strains in a way that incorporates rock failure. The parameters for the material's plasticity are chosen to represent a slightly fractured rock body as opposed to a pristine sample of intact rock so as to make our results both more realistic and more conservative, as fractures (e.g. due to cooling; see Discussion) are likely present and would make the rock body weaker than intact rock. We do this using the Geological Strength Index (GSI) method of Marinos and Hoek (2000), choosing parameter ranges appropriate to lunar basalts and then choosing the weakest values where a range is given; we assume that the rock mass forming the lava tube and its surroundings has an unconfined compressive strength σ_{ci} of 100 MPa (from a 100 to 250 MPa range given for basalt, and equivalent to sandstone), a material constant m_i of 20 (from a typical basaltic m_i range of 25 ± 5), and a GSI value of 70 (corresponding to "blocky" rock structure and zero aqueous weather-

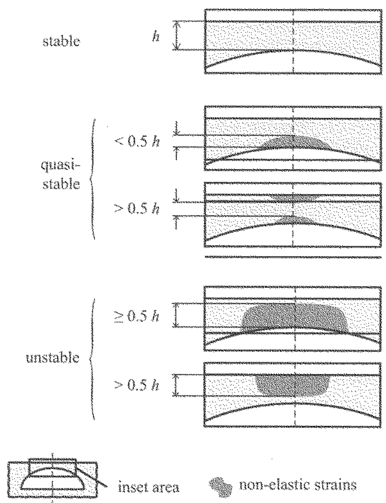

Fig. 2. Model outcome designations. We deem a tube "stable" (top) when there are no non-elastic strains in the lava tube's roof; "quasi-stable" when there are non-elastic strains in less than half of the roof's total thickness (middle); and "unstable" when non-elastic strains are present in more than half of the roof's thickness (bottom). In the latter two cases, we do not distinguish based on the location of the non-elastic strains, instead considering only their total prevalence in the roof. Illustration roughly to scale.

ing). From these, we calculate a friction angle φ of 43°, a dilation angle ψ of 29°, a deformation (Young's) modulus E of ~30 GPa, and a cohesive strength c of 7.2 MPa, using the method outlined in Marinos and Hoek (2000). In addition, we assume a basalt density of 3100 kg m^{-3}, a rough median value of the basalt densities found in a recent re-analysis of lunar samples by Kiefer et al. (2012). All of our material parameters are summarized in Table 1. This is a "continuum" approach to modeling the material, where the influence of individual fractures is ignored in favor of distributed plastic (e.g. cataclastic) deformation; this assumption becomes less reasonable with thinner lava tube roofs, as structurally critical areas represent a larger portion of the model, meaning that randomly distributed unmodeled fractures are more likely to exist in critical areas (e.g. through the apex of the roof). Nevertheless, in absence of such fractures, this approximation of the material behavior is substantially more realistic for our purposes than assuming that the rock behaves elastically.

We infer the structural stability or failure of a lava tube by calculating what proportion of the thickness of the lava tube's roof has exceeded the Mohr-Coulomb failure envelope at the end of our model simulation (Fig. 2). The rationale for this approach lies in the observed tendency of terrestrial caves to fail at the apex of the roof, progressing upwards layer by layer as the cave fails (e.g. Ford and Williams, 1994; Palmer, 2007); as stated previously, our roof thicknesses can thus be thought of as representing either the thickness of the thinnest layer in the roof or the thickness of a single but more voluminous volcanic deposit. Any amount of plastic strain in our model output is taken to indicate complete local material failure; we are not claiming that the rock body undergoes gross plastic deformation, only that it has ceased to behave elastically and is therefore likely to fail. If there are no plastic strains in the lava tube's roof, we deem the tube stable. If plastic deformation (either contractional or extensional) is present in less than 50% of the total thickness of the lava tube's roof, the structure is considered 'quasi-stable'; this could represent either the failure of several layers within the roof, or the failure of some portion of a single-layer roof. Finally, if our model indicates plastic strains in the majority (50% or more) of the roof's thickness, we conclude that this lava tube would be unstable under lunar conditions. In the latter two cases, we do not distinguish based on the location of failure zones at either the top or bottom of the roof, and instead examine the total thickness that they occupy. The choice of a cut-off point of 50% of the roof thickness is arbitrary, but having two distinct degrees of failure allows us to note both lava tubes that are beginning to fail and those in which total roof failure is more likely.

3. Results

We find that the maximum size of a stable or quasi-stable empty lunar lava tube depends strongly on both the thickness of the tube's roof and the assumed pre-existing stress state (Fig. 3). Without considering the effects of regional tectonics, our results indicate that a lava tube buried 50 m under the lunar surface can remain fully stable at a width of up to 3.5 km; if some portion of the roof is allowed to fail as in our "quasi-stable" results, both pre-existing stress state cases allow a tube 5.25 km across with a roof 200 m thick. This means that regardless of the gravitational stress state assumed to exist in the structure or the degree of local failure which is permitted (i.e. none in the stable outcomes or < 50% in the quasi-stable outcomes), our results support the interpretation of Chappaz et al. (2014a,b, 2016) that GRAIL gravity observations may represent very large vacant sublunarean lava tubes, although the question of initially forming a lava tube of this scale is a separate matter (see the Discussion). The largest possible stable or quasi-stable lava tube changes depending on our stress state assumptions, however, as does the relationship between lava tube roof thickness and stability. These differences are discussed in more detail below, along with the results of our models testing the influence of far-field tectonic strains and the cooling of the lava tube.

Assuming a lithostatic state of stress in the material, the maximum size of a stable lava tube increases with the thickness of the roof (Fig. 3, top). With our maximum tested roof thickness of 500 m, a lava tube as large as 5 km across (Fig. 4) experiences no plastic strains under lunar conditions, and lava tubes up to 6.75 km across may remain stable if they are able to survive failure occurring in a portion of the roof's thickness. Lava tubes 1 km wide as inferred from GRAIL data (Chappaz et al., 2014a,b; 2016) can remain stable given a roof at least 1 m thick, given our material assumptions and the modeled roof shape. In all cases, a lithostatic stress state leads to stresses in the roof of the lava tube that are compressional throughout its thickness (e.g. Fig. 5, color contours) similar to the designed behavior of masonry keystone arches, and when failure occurs it does so in absolute contraction (i.e. with negative lateral plastic strains) progressing from the surface of the lava tube downwards.

Lava tubes beginning in a Poisson stress state cannot remain stable at sizes quite as large as those in an initial lithostatic stress state, and the relationship between roof thickness and tube stability is more complex (Fig. 3, bottom). The largest fully stable tube in this case is found to be 3.5 km across, with a 50–100 m thick roof (e.g. Fig. 5, model D); if some plastic failure is allowed, that maximum size increases to 5.25 km with a roof thickness of 200–500 m.

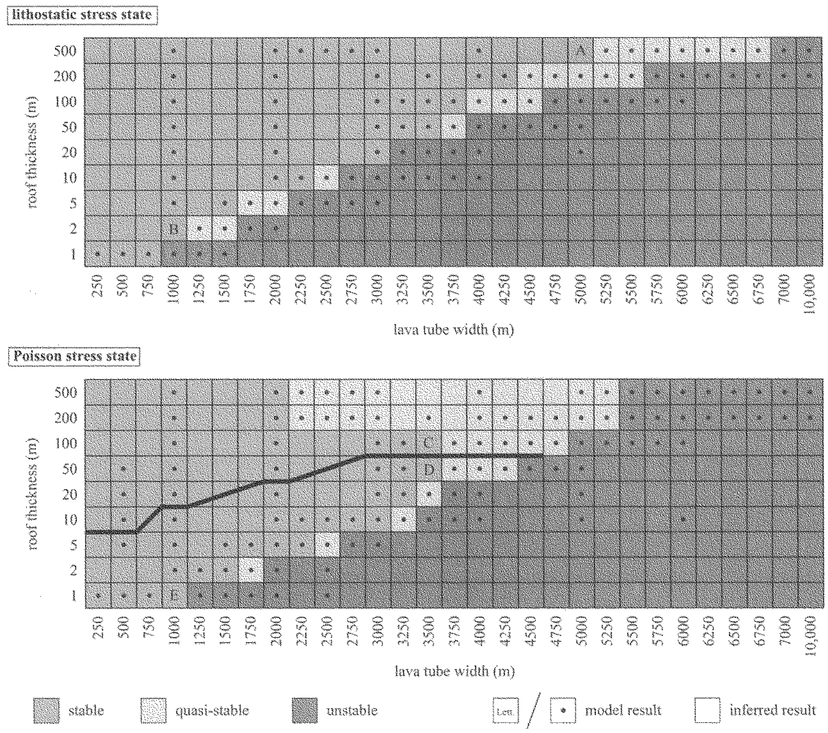

Fig. 3. Lava tube stability results from this study for an assumed lithostatic (top) and Poisson (bottom) state of stress in the material comprising the lava tube and its surroundings, and for a variety of combinations of lava tube width and roof thickness (with height fixed at ⅓ of the width). A lava tube is deemed stable when there are no plastic strains present in the roof, quasi-stable when plastic strains are present in < 50% of the roof's thickness, and unstable when plastic strains are found over ≥ 50% of the roof's thickness. The bold line in (b) indicates a division between two modes of failure in the Poisson models, with models below that line (and all models in the lithostatic stress state case) failing in contraction, and models above that line failing in extension due to downwards flexure of the roof. See the text for more details. Dots or letters indicate performed simulations, blank boxes indicate interpolated results; the letters correspond to models shown in Figs. 4–6.

We also find that tubes 1 km wide or wider can remain stable even with a roof thickness of only 1 m given an initial Poisson stress state and our assumptions regarding the material properties of the rock (i.e the GSI parameters and density as described in the Modeling Techniques section). However, unlike the lithostatic stress state, increasing roof thickness does not uniformly lead to larger possible tube sizes. Below a certain thickness (below the bold line in Fig. 3), the roof is entirely in compression (Fig. 5, model E), leading failure to occur in compression and at the surface, as is the case with our lithostatic stress state models. In thicker-roofed tubes (above the bold line in Fig. 3), however, the tendency of the roof to flex downwards under its own weight, combined with the lower horizontal stresses present in this stress state compared to the lithostatic stress state, leads to extension at the base of the roof (Fig. 5, model D). As rock is much weaker in tension/extension than in compression, this causes local material failure at the base of the roof, similar to the failure pattern observed in terrestrial caves in bedded deposits. The presence of this second failure mode leads to both smaller possible lava tube sizes and the observed nonlinear relationship between roof thickness and lava tube stability in our models with an initial Poisson stress state.

The failure mode of a given lava tube also affects its ability to withstand far-field tectonic strains. Fig. 6 shows a selection of models under both the lithostatic and Poisson stress states which were subjected to both contractional and extensional far-field strains (shown on the horizontal axis) until the point of failure; failure states are the same as in Fig. 3. Models that fail in contraction with no imposed far-field strains (e.g. models A, B, D, and E in Fig. 6) can be subjected to comparatively large amounts of extensional strain before failing. A small amount of imposed far-field

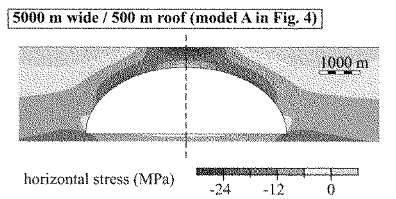

Fig. 4. The largest lava tube found to be theoretically stable, indicated as model A in Fig. 3. The lava tube is 5 km wide, has a roof 500 m thick, and begins in a lithostatic stress state. Color contours show the horizontal stress component with negative (compressional) stresses throughout the roof of the tube.

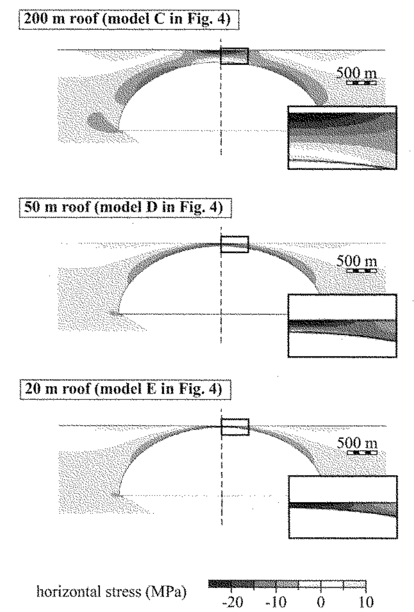

Fig. 5. Models of a 3500 m wide tube with an initial Poisson stress state, showing how varying roof thickness results in different final stress states, failure modes, and stability outcomes. The model with a 200 m roof (model C here and in Fig. 3) fails in extension at the apex of the tube; with a 50 m roof (model D) is stable and shows uniformly compressional horizontal stresses; and with a 20 m roof (model E) fails in compression from the surface downwards. Color contours show the horizontal stress in the model, with positive stress corresponding to tension. Inset boxes show the central portion of the roof magnified for clarity, and the vertical dashed lines represent the plane of symmetry. Shown to scale.

extension (up to +0.03%) combined with a strongly ($\lesssim -20$ MPa) compressional stress state in the roof due to gravity actually serves to bring the lava tube's roof back towards a more neutral stress state, such that several models (B and E) showed an ability to remain stable under more extensional strain than contractional. Models A, B, D, and E (see Fig. 6) also show a rough inverse proportionality between the thickness of a lava tube's roof and the amount of strain that it is able to withstand before failing. Those models which before failed via downwards flexure of the roof (e.g. model C in Fig. 6), however, are far more susceptible to failing when extensional far-field strains are superimposed as opposed to contractional strains, as the addition of still more extensional strain to the system causes the lava tube's roof to sag even farther and quickly leads to pervasive failure at the base of the roof.

4. Discussion

Our results show that lava tubes up to 5 km wide can remain stable under lunar gravity, which is a much larger width than previously expected. Even the smaller stable tubes in our results, such as the 1.5 km wide tube with a 5 m thick roof, which is possible in both the lithostatic and Poisson stress state cases, are several times larger than the 385–500 m stable size calculated by Oberbeck et al. (1969). This is due to the simplification in that analysis where lava tubes are approximated as having a flat roof which acts as a beam, whereas we find that beam-like extensional stresses only occur in the thicker-roofed Poisson-stress-state models (above the dashed line in Fig. 3b). Oberbeck et al. (1969) hypothesized that arched roofs would allow thinner roofs for a given size of lava tube or a larger tube width for the same roof thickness. Our models confirm this hypothesis by showing that with an arched roof lava tubes are more likely to fail in compression rather than tension, which takes advantage of the rock's much higher strength in compression and enables larger lava tubes to remain stable compared to Oberbeck et al. (1969). The fact that an arched roof can allow wider roof spans in masonry structures has been well known since antiquity, so this general result is not in itself surprising.

What may be surprising, however, is the tremendous size (up to 5 km wide) of the largest stable lava tubes in this study, or how thin a roof may be possible while still supporting lava tubes more than a kilometer across. These structures are indeed very large—the lunar horizon lies ~2.4 km away, so in many of the stable tubes modeled here one side of the lava tube's floor would not be visible from the opposing side. For comparison, the largest terrestrial lava tubes are ~30 m in width (e.g. Greeley, 1971), although cave or tunnel chambers formed by other means (such as erosion by subterranean rivers) have been found with widths of several hundred meters (e.g. Ford and Williams, 1994). The larger stable sizes of lava tubes on the Moon can be explained partly by the lower gravity (1/6 that of Earth), which will lead to proportionally lower stresses in the roof in cases where the entire roof is driven into compression by gravity; a cavern 200 m across on Earth could potentially survive at 1200 m acrôss on the Moon for this reason alone assuming linear scaling with overburden pressure. Gravity is only a contributing factor, however, as we find caverns much larger than 1200 m to be stable in these cases. Furthermore, lava tubes which fail due to downwards flexure of the roof which might be expected to follow scaling more like the $g^{1/2}$ factor given by beam theory such that a 200 m terrestrial cavern would correspond to a ~490 m lunar one (closely in line with the value given in Oberbeck et al. (1969)), whereas we find that lava tubes ~2–7 times larger are possible even under flexure, again indicating scaling in excess of that explainable by gravity. Another contributing factor to increased lava tube stability on the Moon may be the almost total lack of aqueous erosion and the assumed "blocky" texture of lunar rocks (i.e. having widely-spaced fractures), which may lead lunar

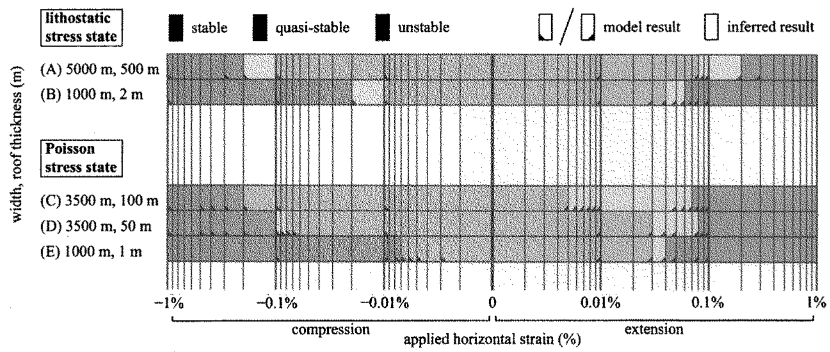

Fig. 6. Stability of various models subjected to far-field tectonic strains. Models are lettered A–E to correspond to those in Figs. 3–5. The amount of contractional or extensional strain is noted on the horizontal axis, with the column of boxes next to 0% strain representing ±0.001%, the next column out representing ±0.002%, and so on. Triangles in the corner of boxes indicate a performed simulation, with results for intermediate amounts of strain inferred from these simulations. Colors and failure states for each model are as in Fig. 3 and explained in the text.

basalts to be stronger (higher cohesion and internal friction angles) than their terrestrial counterparts (after Marinos and Hoek, 2000). In thinner roofs it is also more likely that our continuum assumption is incorrect due to pre-existing fractures in the lava tube's roof. Altering our material parameters to more Earth-like values or changing our continuum approach would thus likely reduce our resulting lava tube sizes, possibly bringing them closer to the size expected from pure gravitational scaling.

Our results also raise the question of whether lava tubes larger than a kilometer across are likely to form under lunar conditions. Although the mechanics of lava tube formation on the Moon are poorly understood, there are several lines of evidence suggesting that tubes several kilometers across may be able to form under lunar conditions. The first of these is the very large, sinuous mass deficits observable in GRAIL gravity data, which indicate some sort of void under the lunar surface—although not necessarily lava tubes—on the order of one kilometer across (Chappaz et al., 2014a; b; 2016). The size of lunar sinuous rilles is also illustrative: Rima Sharp is ~840 m wide on average, Vallis Schröteri ~4.3 km, and there are numerous other rilles with widths over 1 km (e.g. Hurwitz et al., 2013; Garry and Bleacher, 2011). These rilles are generally interpreted to be volcanic in origin, suggesting very high eruption volumes on the Moon. It is possible that among features this size, those with thinner roofs collapsed to form open channels in the form of the observed sinuous rilles, and others with thicker roofs were stable enough to persist as sublunarean lava tubes. Even the global median sinuous rille width, 480 m (Hurwitz et al., 2013), is an order of magnitude larger than known terrestrial examples. This disproportionately larger size of lunar sinuous rilles clearly indicates a different volcanic environment on the two bodies, caused by some combination of factors like crustal stress states, material differences, lava production, or cooling rates. Factors such as the lower viscosity and higher density of lunar lavas, the higher eruption rates inferred at the Moon from observed sinuous rilles, or the absence of convective or advective cooling may also allow the formation of much larger lava tubes on the Moon than on Earth (Cruikshank and Wood, 1971) by enabling more voluminous flows, more cohesive roofs, or thicker chilled lava flow margins, respectively. It is worth noting, however, that air-cooled lava tubes cool more slowly than might be expected due to the insulating effect of gases (Sakimoto and Zuber, 1998), so a radiation-only environment inside a lava tube may not cool at a meaningfully different rate; this question requires further investigation.

The cooling process of a lava tube in an environment such as a lunar mare is also poorly understood, and may have other effects on the stress state and long-term stability of the tube. Cooling of lava during the initial formation process likely does not lead to the development of stresses in the structure, as these will instead be accommodated by pervasive cracking. These cracks will then fill in with subsequent flows, altering the structural properties of the rock as a whole in complex ways. While we attempt to simulate the pervasive weakening through our use of the Geological Strength Index (Marinos and Hoek, 2000), it is possible that subsequent flows may also lead to further cycles of heating and cooling of in-place material, which are not modeled here. These thermal effects would depend on the exact volcanic history of a lava tube, the thicknesses and temperatures of subsequent flows, and, as mentioned above, the specifics of the cooling environment. While this is an admittedly complex parameter space, and is outside the scope of the present study, the complete formation-to-present thermal history of lava tubes does likely play a role in their long-term stability.

Lava tubes ~100–150 m tall (300–450 m wide) that could potentially underlie observed skylights are found to be stable in our calculations even with the very thin (~1 m) roof layer thicknesses observed in the skylights. With both the lithostatic and Poisson initial stress states, there are also models several times larger than this which we find to be stable, so we might not expect structures of these proportions to be particularly "close" to failure; in other words, changes of a factor of two or more in roof thickness or tube width would not affect their stability. This may indicate that, if the skylights are in fact openings into lava tubes, they represent some sort of local failure of otherwise stable structures and not gravitational collapse of fundamentally unstable structures. Meteorite impacts, local concentration of pre-existing fractures, regionally thinner roofs or roof layers, or local material differences could all lead to the formation of skylight-like collapses. Different mechanisms for the formation of the lunar skylights may also be distinguishable by the observed shape of the hole, with irregularly shaped holes representing structural failure instead of an impact origin (e.g. Martellato et al., 2013). It is worth noting, however, that a skylight could easily form due to a combination of factors, with a nearby meteorite impact triggering the collapse of an already anomalously weak part of the tube or a small but non-penetrating impact creating a weak area which later fails for some other reason. The relative influence of these processes likely varies between individual skylights.

Regional tectonics may also play a role in the location of stable lava tubes. Our results show that lava tubes near the maximum stable size are able to withstand far-field strains between -0.2% and +0.08%, depending on the initial stress state, lava tube size, and roof thickness (see Fig. 6). The presence of any nearby tectonic features (e.g. mare ridges, graben) should thus be carefully considered when attempting to locate or characterize potential lava tubes, as large amounts of regional strain will lead to smaller local maximum lava tube sizes and/or thicker minimum roof thickness than in less tectonically active regions.

Due to their higher gravity, we would expect that similar lava tubes on either Mars or Mercury (both with surface gravity g of $\sim 3.7\,N\,kg^{-1}$) may be able to remain stable at sizes ~44% as large as presented here ($\lesssim 2.2$ km wide), or for terrestrial lava tubes ($g \sim 9.8\,N\,kg^{-1}$) to be able to remain stable when they are ~16% as large ($\lesssim 800$ m wide), since gravity has a linear effect on the stresses experienced at depth due to overburden. The size of stable lava tubes on a given body would be further reduced by weakening the material comprising the tube either by weathering or the more rapid advective cooling possible in the Martian or terrestrial atmospheres. It is also possible that lava tube aspect ratios other than the 3:1 width-to-height ratio used here could produce different results for stability, and that this ratio may differ between bodies. The exact ways in which lava tube stability is affected by these various factors remains to be investigated. It is important to note, however, that calculations such as those in the present study only represent the sizes at which lava tubes may remain structurally stable; lava tubes 800 m wide are not found on Earth, and so it is entirely possible that lava tubes do not exist at these maximum sizes on the Moon, Mars, or Mercury. The maximum size of extant (as opposed to structurally possible) lava tubes may thus be controlled more by the properties of the source of the tube-forming lava flow than by the stability of the formed lava tube.

5. Conclusions

We use finite element models to test the stability of lava tubes of various sizes and burial depths under a variety of conditions appropriate to the lunar maria. By calculating material failure in the lava tubes' roofs, we conclude that large (kilometer scale) vacant sublunarean lava tubes may be able to remain stable on the Moon under a wide range of possible conditions. Our results suggest that a lava tube ~5 km wide can remain stable given that it formed in sufficiently voluminous lava flows that it possesses a thick (500 m) roof, and given a near-lithostatic initial stress state and a comparatively quiescent regional tectonic environment. Lava tubes ~1 km wide may be able to remain stable with a roof only ~2 m thick, given similar initial and regional stress conditions. Both of these results assume a set of Geological Strength Index parameters and a rock density appropriate to the lunar maria, an unconfined compressive strength of 100 MPa, and a lava tube with an assumed 3:1 width-to-height ratio. These results indicate that the interpretation of Chappaz et al. (2014a,b, 2016) that GRAIL data suggests the presence of several-kilometer-wide voids buried beneath the lunar surface is within the realm of mechanical plausibility.

The primary factor which allows large lava tubes to remain stable is the arched shape of the roof, which leads to a compressional stress state throughout the roof under gravitational loading. This result, when scaled for gravity, leads to stable lava tube sizes on Earth much larger than known examples. The size of the largest extant vacant lava tube on a given body may thus be limited not by stability issues, but by the manner and scale of their formation or by erosional processes that decrease the durability of larger tubes. Therefore, while both this study and gravitational evidence from GRAIL (Chappaz et al., 2014a,b, 2016) support the possibility that lava tubes several kilometers across may exist under the lunar surface, further proof of their existence gathered by methods such as ground-penetrating RADAR (e.g. Sood et al., 2016c), gravimetry (e.g. Urbancic et al., 2015) or seismic studies will be needed before their existence can be confirmed.

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Responses by Dr. Sandra Magnus

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"An Update on NASA Exploration Systems Development"

Dr. Sandra Magnus, Executive Director, American Institute of Aeronautics and Astronautics (AIAA)

Questions submitted by Ranking Member Ami Bera, House Committee on Science, Space, and Technology

1. How important is the role of component and system suppliers in meeting SLS, Orion, and ground system production milestones?

   Answer: A well-functioning and well-integrated supply chain is vital for the successful execution of any production activity, especially for the manufacture of complex hardware. In addition, in particular for human spaceflight hardware, quality and attention to detail is imperative to ensure that the exacting standards for safety and reliability are met. Our nation's aerospace component and system suppliers form the backbone and foundation of our capabilities to produce advanced space hardware. Each component or system, no matter the size, embodies some level of technical expertise and knowledge, whether that is related to a particular design that produces the appropriate functionality or to a specific manufacturing technique or skill. Maintaining a healthy supplier base, with constancy of orders and work, keeps this corporate knowledge intact, while also ensuring that important delivery milestones are met. Moreover, with enough resources and certainty in their business environment the individuals and companies that comprise the nation's supply chain have the capacity to innovate and experiment. These are critical activities for national competitiveness and technical evolution.

2. In your prepared statement, you state that uncertain and improperly passed budgets, including the regular usage of continuing resolutions and threat of government shutdowns, have resulted in inefficiencies and higher long-term operational costs. Is this a challenge that is particularly harmful to development activities in NASA's human spaceflight program, and if so, why?

   Answer: Large, complex human spaceflight programs require a systematic planning and execution approach that includes the definition for the concept of operations and the overall systems architecture, the corresponding hardware design and development, and the operational process and procedures. It is not uncommon when determining operational safety, efficiency, and cost-effectiveness that substantial up-front investment is required to optimize design and/or manufacturing technologies to achieve these long-term goals. One-year budget allocations or, worse, uncertainty and limitations in resource availability resulting from continuing budget resolutions put constraints on designs and force a short-term decision-making mindset, regardless of the long-term consequences of potentially increased operational costs. While the NASA authorization is often multiyear, the appropriations are done annually. And even though there is often a multiyear budget projection, these funds are not assured. Having assured capital at the beginning of a program, during the development phase, to allow the most efficient trade-offs between near-term and long-term cost drivers is imperative to ensure the highest quality, safety, and efficiency in operations. In addition, when faced with insufficient funds or uncertain budgets, programs are forced to slow down design, development, or manufacturing activities. Consequently, important skill sets are at risk as people are sometimes forced to work elsewhere or leave the field entirely. Once important knowledge and technical skills are lost, a program cannot simply start again where things had left off. Inevitably, there is a re-learning phase that requires time, and this can potentially lead to costly mistakes. Adequately phased and sufficient funds with constancy of commitment are key to a safe, reliable, and cost-effective program.

3. How would a return to the Moon, including potentially establishing a human presence there, impact the goal of sending humans to Mars in the 2030s, as directed in the 2017 NASA Transition Act? How do we prevent a return to the Moon from becoming the de facto end point of the human space exploration program for the foreseeable future?

   Answer: As the government prepares to embark on sending humans beyond low Earth orbit, it must do so with a long-term vision and goals along with the plan for executing those goals. Most importantly, there must be a long-term commitment to the plan and adequate resources must be provided to execute the plan. For example, if we decide, as has been stated, that Mars is the long-term goal for human expansion then the plan we build must reflect this. Any activity that the government engages within the vicinity of and on the moon must be targeted at what is required to build and test the necessary equipment, gather the necessary operational experience, and mitigate all known risks required to travel to Mars. A clear set of milestones for activities around the moon, once executed, signals the moment when the journey to Mars should be implemented. Staying focused on these goals will ensure that the moon is not a de facto termination of human activity, but rather an expansion point for human activity in space beyond low Earth orbit. The investment in the infrastructure required to realize the goal of returning humans to the moon should also address the requirements for the commercial exploitation (nongovernmental-funded independent interests) of cislunar space and should be adequate to support future missions to Mars, whether robotic, human, or a combination thereof. Designing into the program how to leave behind a healthy economic ecosystem, or at least the start of one, gives the government more freedom to continually expand its activities over time. Under these conditions our outward expansion will not "stall" on the moon unless the nation so chooses.

4. Beyond SLS and Orion,

   a. Where would international and commercial partner participation in the human space exploration make the most sense?

      Answer: To answer this question we first need to define what our national priorities are related to how the United States wants to lead in space. It is safe to say that we value having our own independent launch capability, for example, as well as setting the mark for state-of-the-art space propulsion. Deep space communication capability is also a key technology in which the United States should remain a leader, as is the ability to produce a habitable, closed system vehicle. What other capabilities or technologies do we, as a nation, want to ensure that we maintain? The answer to this question will drive how we approach our international partners for teaming arrangements and collaboration. Once we have identified the capabilities and technologies that are important to us as a nation, an analysis can be done to determine the state of development of those assets and whether it makes sense for government to invest in their maturation—making the resultant knowledge available to industry at large, or deciding to invest in companies to develop the key capabilities, which leads to economic expansion as opposed to shared knowledge. Such considerations will drive how and where to engage with private companies.

   b. What would be the role of academia?

      Answer: Academia plays two very important roles in this area. The first, and more important role, is attracting and training a pipeline for the highly-skilled technical workforce that is needed to execute a complex and expanding human spaceflight program successfully. Second, the nation's universities conduct government-funded basic and, to some extent, applied research that is foundational for our continuing space exploration efforts. Academic research can play a complementary role to the more applied and integrated research and development that occurs at NASA. As basic science and engineering research activities mature concepts and ideas, this information can be transferred to NASA, and potentially industry, for application development.

   c. What impact would instilling greater international and commercial partner participation have on our ability to maintain the vitality and relevance of the Nation's industrial base and domestic academic institutions?

      Answer: Done correctly, partnering with commercial entities and international space agencies could have a positive impact on our nation's industrial base and academic institutions. Done haphazardly, without a larger vision, these same partnerships could be a detriment. The key, again, is understanding what our strengths are, what strengths we want to develop and instill, and how we want to deal with areas we consider our weaknesses, or areas that we are not interested in developing. The latter are the areas where partnerships could be of benefit to both industry and academia.

5. What should a meaningful roadmap contain to ensure that it provides the constancy of purpose needed to provide stability and maintain the Nation's commitment to NASA's human space exploration program? How can we avoid the human tendency toward short-term thinking and focusing on near-term objectives?

   Answer: Please refer to my response to question three. The plan should be long term in nature—defining that Mars is the long-term goal and including activities that we hope to accomplish once getting there. The plan should also identify the necessary milestones and risk mitigation activities that have to take place on and around the moon. Finally, the plan should have a coherent approach for how to leverage government investment in the achievement of the milestones for the benefit of establishing a lasting infrastructure in the lunar neighborhood independent of government support. The milestones should be built in such a way that progress can be illustrated on a short-term basis, but always in the context of where on the roadmap the program is. The plan cannot be changed substantially every two, four, or six years. It must be allowed to be executed coherently over a decade or two. Most importantly, the plan needs the appropriate long-term financial commitment and backing from both political parties and must be reaffirmed regularly by both the executive and legislative branches.

Appendix II

ADDITIONAL MATERIAL FOR THE RECORD

STATEMENT SUBMITTED BY RANKING MEMBER
EDDIE BERNICE JOHNSON

OPENING STATEMENT
Ranking Member Eddie Bernice Johnson (D-TX)

Committee on Science, Space, and Technology
Subcommittee on Space
"An Update on NASA Exploration Systems Development"
November 9, 2017

Good morning. Welcome to our panelists and thank you for your service. I look forward to your testimony on the status of NASA's Exploration Systems Development programs, namely the Space Launch System—or SLS—the Orion crew vehicle, and the Exploration Ground Systems.

Mr. Chairman, earlier this year, the Congress passed and the President signed the NASA Transition Authorization Act of 2017. Among other things, the Act gives clear direction that NASA manage human space flight programs, including the SLS and Orion "to enable humans to explore Mars and other destinations". It is important that we keep our eye on that goal. It will require focus, commitment, stable funding, and support over several Congresses and Administrations. It is why we are here today.

We cannot get to Mars without a heavy-lift rocket, a crew vehicle that can transport our astronauts to deep space and return them safely, and a ground infrastructure that can support the multiple launches that will be needed to meet the Mars goal. I look forward to hearing about what steps NASA is taking to develop innovative and efficient manufacturing processes that will establish an affordable and sustainable capability for human exploration of deep space for the decades ahead. While progress towards the initial test flights of SLS and Orion is critical towards meeting the eventual Mars goal, we must ensure that safety remains at the forefront.

Trying to meet deadlines at the cost of compromising long-term safety practices will not advance a sustainable program. We learned that hard lesson after the Challenger and Columbia accidents, and I know that NASA will not knowingly do anything that could compromise safety in its exploration program. Nor can we allow the fits and starts caused by lack of stability in funding or changes in goals and directions. That is why, Mr. Chairman, we must ensure a "constancy of purpose" as recommended by the Aerospace Safety Advisory Panel. I hope, as the ASAP has encouraged, that we can do so in partnership with the Administration. We need to be on the same page.

The Human Exploration Roadmap that the NASA Transition Act directed NASA to develop is due to this Committee by December 1, 2017. I hope, Mr. Chairman, that this Committee will hold hearings to review the Roadmap, and to consider the implications of the Vice President's proposal to send humans to the lunar surface, in the context of that plan.

Thank you, and I yield back.

STATEMENT SUBMITTED BY
REPRESENTATIVE BILL POSEY

Statement of Representative Bill Posey (R-FL)
To the House Science, Space, and Technology - Space Subcommittee
Concerning the Hearing: "An Update on NASA Exploration Systems Development"

November 9, 2017
10:00 a.m.

Mr. Chairman, Ranking Member, and Members of the Subcommittee,

I appreciate the efforts of my colleagues on the House Science, Space, and Technology – Space Subcommittee in holding a hearing on the program of exploration systems development at NASA. Thank you for your leadership on this important issue.

Maintaining American leadership in human space exploration is a key concern for me and for the Members on this committee. Foreign competitors are closing the gap year by year as we wait for our flagship exploration systems, such as the Space Launch System (SLS) and the Orion crew capsule, to come online.

Expanding the frontiers of American space faring capability and keeping our lead in cutting edge space exploration technology are national priorities. Investments into in-space refueling, and using resources harvested from celestial bodies such as asteroids and the moon, are a key part of keeping our human spaceflight program moving forward. Additionally, with NASA leading the way toward the moon and Mars, we must enable and unleash the vast potential of the private sector as we move toward a permanent commercial and human presence.

Thank you again for holding this important hearing.

Sincerely,

Bill Posey
Member of Congress