PURDUE UNIVERSITY

Resilient ExtraTerrestrial Habitats

2018 International Workshop

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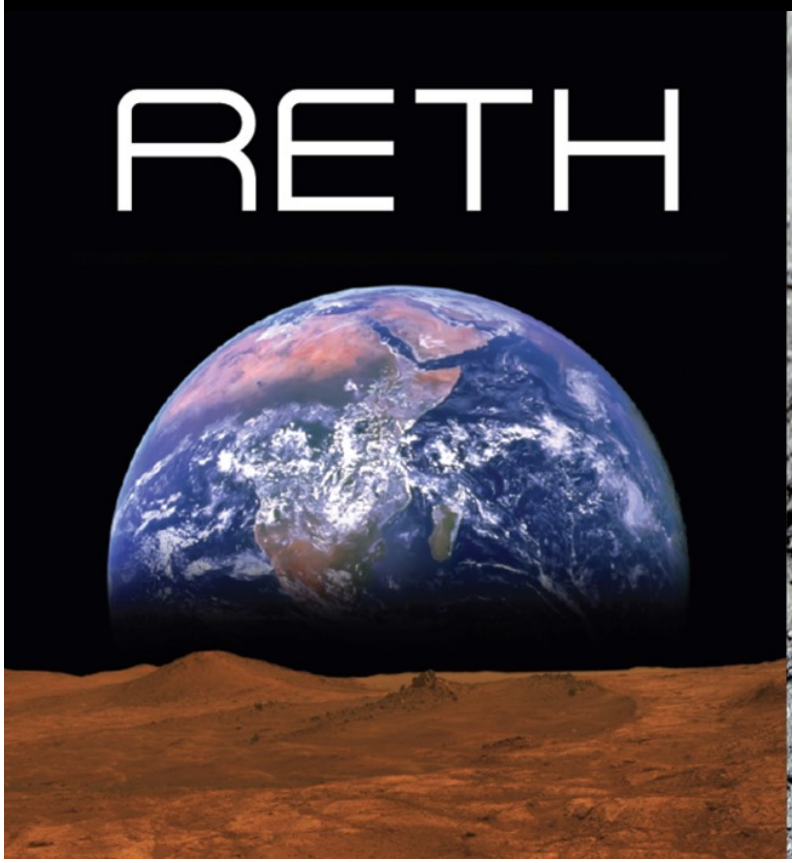
Purdue University, West Lafayette, IN



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RESILIENT EXTRATERRESTRIAL HABITATS PROJECT

The first New Horizons grant was awarded by the Provost's Office at Purdue University to the team of Resilient ExtraTerrestrial Habitats (RETH) researchers proposing to create a program in Resilient ExtraTerrestrial Habitats – the first such university program (https://www.purdue.edu/reth). The creation of resilient and comfortable habitations is one of humankind's oldest activities. Millennia of experimentation and planning have brought the creation and maintenance of habitats on Earth to a high degree of sophistication. However, humankind is now faced with new challenges as we begin to move beyond the Earth's relatively benign surface and out into Space. Beyond the protection of Earth's atmosphere, future space explorers and colonists face new challenges stemming from the lack of air pressure and oxygen, wild temperature fluctuations and hazards such as meteoroid impacts and intense particle radiation. Countering these challenges to provide livable conditions in extraterrestrial environments will require the most advanced applications of engineering and technology.

Any human settlement in space will require excavation, construction and transportation of large masses of material from one place to another. Accomplishing these tasks in extraterrestrial environment, on nearly or completely airless bodies with less gravity than the Earth such as the Moon, Mars or asteroids is not beyond our current capabilities, but will require extensive planning combined with both theoretical

and experimental studies long before we even begin to construct in situ pilot projects.

Purdue offers one of the most favorable venues for the creation of a program in Extraterrestrial Habitat Engineering. In addition to our fame as the home of more astronauts than any other institution in the world, including the first and last men on the Moon, we are also home of one of the top five USA Civil Engineering programs, the Lyles School of Civil Engineering, with its expertise in habitats in extreme environments. Purdue is also home to a highly-ranked School of Aeronautical and Astronautical Engineering and a new, but now highly visible, program in Planetary Science in the Department of Earth, Atmospheric, and Planetary Sciences. Members of the Aeronautical and Astronautical Engineering and Earth, Atmospheric and Planetary Sciences programs have recently been active as part of NASA's GRAIL mission, which mapped the Moon's gravity field to unprecedented precision. One of the Purdue-centered discoveries from this mission was the existence of a network of large, empty caves in the lunar lava flows. These lava tubes are breached to the surface in several locations to form so-called "lunar skylights". Similar skylights have also been detected on Mars. The lava tubes may form the basis for ideal habitats on the Moon or Mars, offering instant protection to astronauts from temperature variations, radiation and meteorite impacts. The RETH project is fully aligned with the core mission of Purdue University to offer world-class transformative education.

PREFACE

One of the important tasks in the RETH project is to elucidate the grand challenges and key research questions which, if answered, will address the grand challenges of achieving resilient habitats on extraterrestrial bodies. In the execution of this task, the RETH project team convened the 11-member committee to organize a workshop with participation of Purdue faculty and invited national and international engineering and scientific leaders from other research institutions, industry and government agencies. The objective of the workshop is to discuss challenges, potential solutions, and research needs for the establishment of resilient extraterrestrial habitats. The committee met several times during the Spring of 2018.

ACKNOWLEDGEMENT OF SUPPORT

The support to make this workshop possible from the Purdue Office of the Provost, College of Engineering, Department of Earth, Atmospheric, and Planetary Sciences and Schools of Civil and Mechanical Engineering is deeply appreciated by the RETH team and all participants.

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SUMMARY

The United States has been at the forefront of human space exploration throughout history in government and industry sectors. Key factors for this leadership are the basic research and engineering developments associated with these efforts.

In response to this directive, the New Horizons project RETH team convened a committee of Purdue faculty to organize the workshop held at Purdue University on October 22-23, 2018. On January 19, 2018, a group of members of the RETH team and the workshop organizing committee consisting of Professors A. Bobet, S. Dyke, K. Howell, J. Melosh and J. Ramirez visited NASA and met with top administrators. Key topics of discussion were the RETH program and the upcoming workshop at Purdue University. The team had a very productive meeting with William H. Gerstenmaier, Associate Administrator, Human Exploration and Operations, Steve Jurczyk, Associate Administrator for the Space Technology Mission Directorate, and Dennis Andrucyk, Science Mission Directorate, and extended invitations to join the workshop at Purdue.

During the organizational phase of the workshop, information was distributed across the Purdue campus and to the local community. Speakers were identified, in consultation with NASA, for their visionary concepts and technical expertise related to space hazards. Individuals on campus were personally invited. During this phase, a wealth of relevant research needs was uncovered involving many potential collaborators across the Purdue campus.

The objectives of the workshop were to discuss the challenges associated with establishing and operating permanent habitats outside Earth, and explore potential solutions to address the challenges. The workshop was organized under five themes:

1. Hazards (Events)
    a. Science and current state of the art in space extreme environment and hazards (e.g. radiation, meteorite impacts, extreme temperatures, seismicity, etc.)
    b. Technology to quantify and qualify hazards
    c. Impacts of hazards on human exploration and survival
    d. Hazard mitigation
2. Resources (Harvesting and Utilization)
    a. Resources and supplies needed for permanent habitats, e.g. food, water, energy, construction materials
    b. Sources of resources and supplies
    c. Mining, harvesting methods and technologies
    d. Reutilization
    e. Current state of the art in manufacturing and construction technologies (Robotics and Automation, Additive Manufacturing, 3D Printing, etc.)
    f. Improvements to manufacturing and construction for hazardous environments
3. Habitats (Preparation and Architecture)

    a. Habitation: mission, vision, and current state of the art
    b. Function and requirements
    c. Structural design parameters (robustness, performance and recovery, resiliency)
    d. Lunar and Martian habitats: surface vs. underground (Lava Tubes)
    e. Size and stability of natural lava tubes
4. Partnering Nationally and Internationally: Industry, Facilities and Research (collaborations, access)
    a. Requirements to make successful team collaborations
    b. Suggestions for resources of funding and partners (names and works)
    c. Approaches to make nationally and internationally collaborations
    d. Industry needs from academia
5. Forming the Right Research Team for Project Scope: Expertise, Interdisciplinary, Expected Contributions
    a. Priorities in research objectives
    b. Research approaches
    c. Required expertise and networking to accomplish research objectives

There were 63 workshop participants. They were distributed among the themes 1-3 on Day 1 of the workshop. On Day 2, the participants were distributed among themes 4 and 5. Under Themes 1, 2 and 3, the participants discussed the state of the art, gaps in knowledge, and key research questions that, if answered, would fill in the knowledge gaps. Under Themes 4 and 5, the focus was the identification of the success factors in research campaigns. In the final session of the workshop agenda (Appendix A), the participants came together to identify the overall workshop resolutions and next steps.

The main findings from the workshop, as they pertain to the session themes, were:

Hazards: It should be a priority to extensively study in advance any potential future habitat sites to better understand the characteristics of the most damaging hazards affecting those sites. Some regions of space, the Moon, or Mars may be more inherently safe or dangerous for various reasons, which could be discovered studying the regions with our current means in a more sustained fashion. For instance, our current understanding of lunar seismicity is lacking, or that certain regions of the surface of extraterrestrial bodies may be more likely to suffer asteroid impacts.

Resources: An important aspect of optimizing utilization of any available resource will be prioritizing requirements and comparing them to availability, purity and ease of processing for each resource in question. Several large knowledge gaps exist in this area, such as soil interaction with mechanical components and sensors, radiation interactions with materials in question, and energy requirements related to the possibility of water harvesting from permanently shaded poles of the moon. Other important gaps have to do with finding efficient and sustainable ways of clearing water contaminants, transfer and storage logistics for energy, water and minerals; along with understanding the extent to which these processes can be automated. For longer, sustained missions that occur more frequently, finding ways to cut down cost via

reusing and recycling things will be paramount.

Habitats: There is a clear link between habitat system's lifecycle requirements and system resilience. Several significant knowledge gaps are identified in this area, such as habitat system robustness, rapid recovery, resourcefulness, redundancy, human factors and operations, habitat construction, structural aspects, radiation protection, and hypervelocity impacts. 3D printing is expected to be an important construction method for habitats for deep space exploration. Some major knowledge gaps related to the 3D printing of habitats using in-situ materials are scalability, limited understanding of printing with extraterrestrial based materials, multi-scale mechanical behavior of materials, difference between the mechanical properties of the interface and bulk. Finally, as an alternative to surface habitats, lava tubes could be considered as potential safe havens for permanent settlement and life support equipment. In this area, major gaps are: assessing the stability of these underground tunnels, evaluating methods for entry/exit considering hardware reliability and redundancy, in addition to the variety of terrain, and assessing methods for supplying power and light during exploratory missions into the lava tubes.

Partnering Nationally and Internationally: Industry, Facilities and Research: Extraterrestrial habitats for deep space exploration creates an exceptional opportunity for civil, architectural and construction companies to innovate on Earth applications which are also applicable to extraterrestrial habitation. The most important challenges are developing common research goals and agendas, providing transparent access to all the regulations associated with export controlled information, and developing mechanisms to engage universities and define research problems aligned with the objectives of industrial institutions.

Forming the Right Research Team for Project Scope: To establish a right research team, it is important to know that the team members will be diverse in terms of experience, region of expertise and language. Important factors to consider with regards to team composition are interpersonal relationships, funding context, sector context and organizational context. It will be beneficial for industry and government agencies to establish university-industry-government cooperation since working with academic institutions usually leads to the investigation of a wider variety of possible methods and more innovative solutions due to the availability of greater manpower with more flexible time resources. While the government may focus on determining what topics of research are important to the project at hand, ultimately it should also focus on facilitating the contact between industry and academia. Industry has an upper hand in being able to provide resources and equipment; although industry ideally should strive to be more flexible when comes to sharing intellectual property.

INTRODUCTION

A 1.5-day workshop was held October 22 and 23, 2018. The workshop agenda is included in Appendix A. In addition to engineering and planetary science issues, recent research into human factors involved in planning for resilience were integrated. Twenty-one invited speakers, including 2 international, and 19 from the U.S., participated. The speakers represented engineering and science academic programs, industry and two government space agencies from the USA and Japan. In total, 63 attendees including the invited speakers participated in the workshop. Purdue University had a strong participation of faculty, graduate researchers, and students. The full list of participants is given in Appendix B. Purdue students had the opportunity to showcase a number of research activities in a Poster Session at the end of Day-1. Appendix C lists the posters presented during the session.

List of Invited Speakers: Lindsay Aitchison (NASA Headquarters); Hunain Alkhateb (University of Mississippi); Jared Atkinson (Honeybee Robotics and Colorado School of Mines); Ernie Bell (University of Maryland, Department of Geology); Charles Dischinger (NASA); Dan Dumbacher (Executive Director, American Institute of Aeronautics and Astronautics, AIAA); Barry Finger (Paragon Space Development Corporation); Anita Gale (Co-Founder, Space Settlement Design Competitions); Michael Grichnik (Caterpillar); Junichi Haruyama (Japan Aerospace Exploration Agency, JAXA); Ramesh Mall (University of Connecticut); William O'Hara (Sierra Nevada Corporation, SNC); Tatjana Paunesku (Northwestern University); Riccardo Pozzobon (University of Padova); Monsi Roman (NASA); Nicholas Schmerr (University of Maryland); Elizabeth Silber (Defence Research and Development Canada, DRDC); Larry Toups (NASA/Johnson Space Center); Justin Werfel (Harvard University); Glenn White (Construction Robotics); Kelsey Young (NASA Goddard Space Flight Center).

This workshop report contains a summary of the discussions in the breakout sessions, links to presentations and research questions identified.

SUMMARY OF BREAKOUT SESSIONS

Hazards (Events)

Moderator:
Tatjana Paunesku, Research Associate Professor of Radiation Oncology, Northwestern University

Coordinators and Recorders:
Daniel Gomez, Graduate Research Assistant of Civil Engineering, Purdue University
Anthony Boener, Undergraduate Researcher, Department of Earth, Atmospheric and Planetary Sciences, Purdue University

Panelists:
Karen Marais, Associate Professor of Aeronautics and Astronautics, Purdue University
Jay Melosh, Distinguished Professor of Earth, Atmospheric, and Planetary Sciences, Purdue University
Julio Ramirez, Kettelhut Professor of Civil Engineering, Purdue University
Nicholas Schmerr, Assistant Professor, Department of Geology, University of Maryland
Elizabeth Silber, Defence Scientist, Defence Research and Development Canada (DRDC)
Michelle Thompson, Assistant Professor, Department of Earth, Atmospheric and Planetary Sciences, Purdue University
Kathleen Vander Kaaden, Research Scientist, Jacobs, NASA Johnson Space Center

Zackary Burman, Undergraduate Researcher of Planetary Geomorphology, Purdue University
Jory Lyons, Undergraduate Researcher of Aeronautics and Astronautics, Purdue University

Goals:

The purpose of this breakout session was to delve into the state of the art and the research gaps in:

- Science and current state of the art in space extreme environment and hazards (e.g. radiation, meteorite impacts, extreme temperatures, seismicity, etc.)
- Technology to quantify and qualify hazards
- Impacts of hazards on human exploration and survival
- Hazard mitigation

Presentation:

- “Challenges to Living on the Moon and Mars” - Jay Melosh, Purdue University

The presentation is available at https://www.purdue.edu/reth/workshop.html.

Gaps in Knowledge:

The following is a list of gaps in knowledge identified by the participants in this breakout session:

- Reaction of human biology to long-term exposure to space environments (i.e. radiation or the sterile environment of a habitat)
- Lack of hazard forecast system (i.e. solar storms or asteroids)
- Effects of cosmic ray (high Linear Energy Transfer, LET) radiation on health of humans
- Effect of long-term low dosage radiation
- Methods of mitigation or healing of radiation exposure
- Forms of shielding from radiation which are feasible for the development of space vessels and extraterrestrial habitats
- Presence of carcinogenic components in Lunar/Martian soils or subsurface layers
- Effect of radiation exposure on the equipment
- More detailed knowledge of safer or more dangerous zones for certain hazards due to the terrain characteristics of the Moon/Mars
- General understanding of Lunar/Martian seismology
- Short and long-term properties of 3D printed materials (i.e. mechanical failure, radiation shielding and degradation, etc.)
- Anthropogenic hazards inherent with human settlement

Summary:

The discussion focused on the hazards that potential extraterrestrial habitats face including physical threats such as asteroid impacts, biological threats posed by the harsh environment, and even psycho-socio threats associated with human habitation. The session started with a discussion about the important distinction between human-centric hazards, that is, hazards which threaten the safety of human life, and general threats to the habitat. Many of the most obvious and difficult hazards to overcome are those which pose some direct threat to human life as these are most pervasive in the extraterrestrial environment, but many threats, including some of the former, could also jeopardize the functionality of the habitat as a whole.

One of the first major points addressed in the discussion was the importance of the duration or dosage of the threat. Even long-term living in a nearly sterile environment could have health effects on humans which have not been sufficiently studied. Radiation is a pervasive space hazard, which may be greatly augmented by both dosage amount and duration. It was also mentioned that the specific nature of radiation in space, particularly cosmic ray radiation, and its effect on human health is not well understood and is one of the most prevalent threats humans will encounter. Dr. Jay Melosh's presentation about challenges to living on the Moon and Mars helped focus the

discussion. His presentation showed data on the radiation endured by an average space flight to Mars compared to the typical values experienced on the International Space Station, and the average on Earth: A trip to Mars receives around 500 mSv of radiation compared to about 50 mSv for the ISS and 20 mSv on Earth; see Figures 1 and 2. However, it was mentioned that the duration of the dose may be an important factor in how damaging it would be to human health.

The issue of radiation shielding in general was also a prominent topic of the discussion. Shielding against cosmic ray radiation in particular presents a particular difficulty to extraterrestrial habitats: It requires more shielding than the lower energy radiation typically encountered on Earth. Dr. Schmerr mentioned that lower mass methods of electromagnetic shielding, a sort of artificial magnetosphere, are a potential future solution. After further discussion, the participants concluded that current shielding against radiation is primarily a mass issue.

A health risk caused by lower energy radiation, which may be present naturally as on Earth, or induced at least at the surface through cosmic radiation was also discussed in the session. Our current understanding of the threats of radiation exposure is based primarily on extrapolation from data on higher exposures. It was concluded that there was a paucity of data to verify if this is a valid assumption, especially for the long-term exposure to low radiation levels.

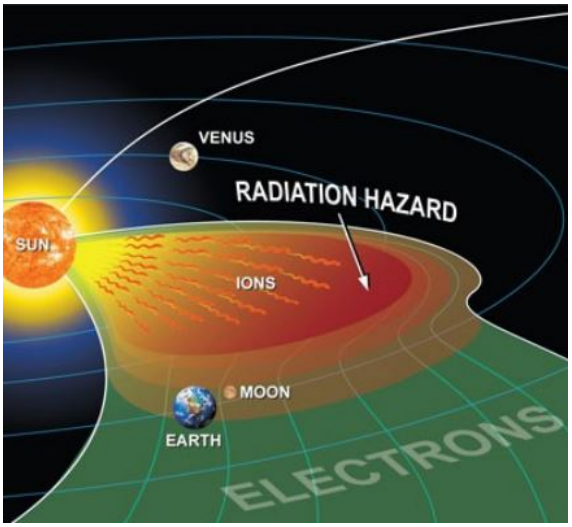

Figure 1. Solar Energetic Particles

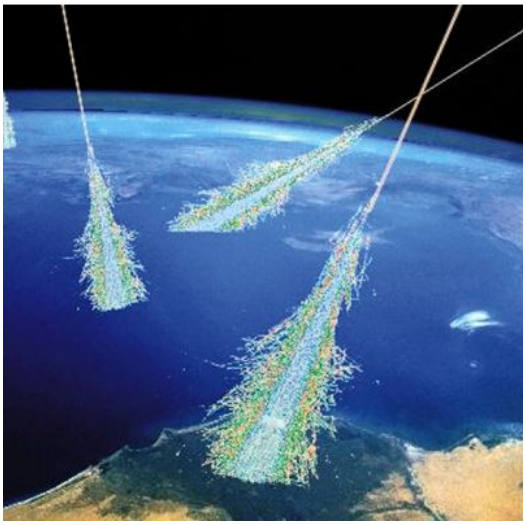
Figure 2. Galactic Cosmic Rays

The discussion turned to the effects of hazards on the habitat itself. The participants mentioned that many of the hazards may not as readily pose health risks for the inhabitants of a facility but rather threaten disruption of the function of the habitat itself. It was pointed out that radiation has already caused electronic and computer issues for space agencies' probes. If a habitat's electronics are not appropriately shielded, radiation may induce failures in systems essential to the operation of the facility, jeopardizing the safety of the inhabitants. However, far more mundane features of an

extraterrestrial environment can pose significant technological hurdles to design a habitat which can withstand them. Dr. Melosh's presentation featured dust as a prominent hazard, as he mentioned that lunar dust was found to be a particularly problematic substance. The participants agreed that it will be important to have means to prevent the introduction of significant quantities of dust into the interior of a habitat to prevent it from degrading all the systems within.

Another hazard discussed was asteroid impacts. Outside of Earth's protective atmosphere, hypervelocity impacting becomes a far more prevalent and dangerous threat. It was postulated that the rate of impacting on the lunar surface, in comparison to Earth, is likely very similar. On Earth, any impactor smaller than tens of meters in diameter will likely completely disintegrate or otherwise be decelerated by the atmosphere before it reaches the surface, while on bodies with little to no atmosphere even millimeter scale objects with tens of kilometers per second velocities present a very real threat. The high risk of secondary impacts on low atmosphere bodies was also observed. This would then greatly increase the probability of impact-related hazards to an extraterrestrial habitat compared to Earth. It was pointed out that the average secondary impact velocity was still higher than the muzzle velocity of a rifle, presenting a very real threat to astronauts on the surface of the Moon or even Mars.

Several of the participants noted the issue of having some manner of forewarning or forecasting threats and the potential necessity of having this ability before sending humans into any region of space. Certain threats such as radiation from Solar activity or possibly even asteroids could be detected before they would reach a habitat if the infrastructure for doing so existed. The group decided that it may even be necessary to have at least some elements of this sort of warning system in place before attempting to settle on other bodies.

The participants also discussed the potential for some threats to the habitat to be inherent with a human population. Anthropogenic threats will likely follow mankind anywhere it goes and must be prepared for and hopefully mitigated though they cannot ultimately be prevented. The group mentioned various historical psycho-sociological studies into how humans handle the sorts of extreme confinement and isolation in extraterrestrial travel and the problems exposed therein. Behavioral issues stemming from the psychological duress of space travel must be expected. The risk of illness and the handling of waste products, which cannot readily be recycled, were also discussed. Earth quasi-analogues to extraterrestrial habitats such as Antarctic research stations may help, given they are realistic case studies on how human settlement can be successful even under extreme conditions.

In conclusion, it was agreed that it would be necessary to extensively study any potential future habitat sites to better characterize the hazards with the largest effects at those sites. Some regions of space, the Moon, or Mars may be more inherently safe or dangerous for various reasons which could be discovered studying the areas with our current means in a more sustained fashion. For example, it was discussed that our current understanding of lunar seismicity is lacking, or that certain regions of the surface

of extraterrestrial bodies may be more likely to suffer asteroid impacts. Better understanding of the more damaging characteristics of the hazards will be invaluable in deciding where and how to build habitats in the future.

Resources (Harvesting and Utilization)

Moderator:
Cary Mitchell, Professor of Horticulture, Purdue University

Coordinators and Recorders:
Audai Theinat, Graduate Research Assistant of Civil Engineering, Purdue University
Ajay Radhakrishnan, Undergraduate Researcher of Mechanical Engineering, Purdue Student

Panelists:
Hunain Alkhateb, Assistant Professor of Civil Engineering, University of Mississippi
Jared Atkinson, Senior Geophysical Engineer, Honeybee Robotics
David Cappelleri, Associate Professor of Mechanical Engineering, Purdue University
Dan Dumbacher, Executive Director, American Institute of Aeronautics & Astronautics (AIAA)
Shirley Dyke, Professor of Mechanical and Civil Engineering, Purdue University
Mike Grichnik, Emerging Technologies Program Leader, Caterpillar
Ibrahim Emre Gunduz, Research Assistant Professor of Mechanical Engineering, Purdue University
Robert Haddon, Program Director, Aerospace Medicine Fellowship, Mayo Clinic
Briony Horgan, Assistant Professor, Department of Earth, Atmospheric, and Planetary Sciences, Purdue University
Jan Olek, Professor of Civil Engineering, Purdue University
Florence Sanchez, Associate Professor of Civil and Environmental Engineering, Vanderbilt University
Justin Werfel, Senior Research Scientist, Harvard's Wyss Institute for Biologically Inspired Engineering
Glenn White, Sr. Software and Controls Engineer Lead, Construction Robotics
Jeffrey Youngblood, Professor of Materials Engineering, Purdue University

Leon Brendel, Graduate Research Assistant of Mechanical Engineering, Purdue University
Michael Kosson, Graduate Student of Chemical and Biomolecular Engineering, Vanderbilt University
Kinsey Larson, Undergraduate Student, Purdue University
Aryan Noroozi, Graduate Research Assistant of Civil Engineering, Purdue University
Babajide Onanuga, Graduate Research Assistant, Department of Chemical Engineering, Tennessee Technological University
Josh Panos, President of Lunabotics, Purdue University

Goals:

The purpose of this breakout session was to delve into the state of the art and research gaps in:

- Resources and supplies needed for permanent habitats, e.g. food, water, energy, construction materials
- Sources of resources and supplies
- Mining, harvesting methods and technologies
- Reutilization
- Current state of the art in manufacturing and construction technologies (Robotics and Automation, Additive Manufacturing, 3D Printing, etc.)
- Improvements to manufacturing and construction for hazardous environments

Presentation:

- "Planetary Potential Construction Material" – Hunain Alkhateb, University of Mississippi

The presentation is available at https://www.purdue.edu/reth/workshop.html.

Gaps in Knowledge:

The following is a list of gaps in knowledge identified by the participants in this breakout session:

- Available materials, requirements, material consideration and implementation, environmental challenges such as high temperature and radiation
- Construction with in-situ resources
- Soil (regolith) and dust interaction with mechanical components and sensors
- Energy sources and requirements
- Poles as regions to harvest possible solid water in dark moon areas
- Water contamination
- Mineral processing techniques for various in situ resources
- Automation in construction (the feasibility to program to one task but the possibility of need for autonomy for each unit)
- Use of robots in construction and cross robot communication
- Robot operation using simple basic rules
- Programming based on functions (applications of these autonomous swarms can vary greatly – mining, construction, processing)
- Economical solution (current solutions cannot be perfectly autonomous – but can be partly autonomous)
- Inefficiencies of current robotics and materials
- 3D printing (3D printers are viable if and only if using in-situ resources)
- Using earth disasters to measure viability of current prototypes such as seismic test on a 3D printed building - not enough data, but missing data has been identified to an extent
- Rheological properties of involved sedimentatious material at different scales

- Reinforcement between 3D printed material layers and their interfaces
- Improving toughness of printed systems in additive manufacturing (AM) - such as by rotating filaments geometrically which can cause any fault lines to appear in predetermined locations
- Current AM methods used - Direct Wire and Extrusion methods, and Powder Bed method, and Hybrid solutions
- Earth based AM research in a vacuum
- Assembly and repairs
- Function: resilience, radiation protection, pressure
- Inflatable structures
- Resources to prevent sneaking of some bacteria/microbes into the habitation ecology
- Physical accessibility of all parts of habitation so that all the ecology can be accessible
- Resources to prevent easy spread of infectious diseases in habitats, especially since the same bacteria may affect different people differently
- Resources to prevent microbe growth in any component that can support it when exposed to excess heat
- International investing to help with costs - international partnerships might cost more money wise in short-term, but spreading costs internationally keeps things to float longer

Summary:

This breakout session focused on the primary problems encountered when attempting to find and utilize resources in an extraterrestrial setting such as the lunar surface. Several key concerns were brought up, some of which include absence of certain minerals leading to the impossibility of traditional constructive material mixtures, the lack of knowledge of interactions of lunar conditions (such as regolith and radiation) with contemporary machinery, amongst other important topics that require more research. Any construction material used will be required to be resistant to impact, temperature variation, pressure and provide radiation shielding. Additionally, these materials must not use much water in production or maintenance, nor consume much power in production, withstand tension, and not age to other external forces.

If utilizing resources present on the lunar environment, these in-situ resources will be site dependent – thus a habitation site will have to be gauged for availability of material of note. The absence of some minerals such as calcium carbonate means standard composites such as cement cannot be made. Thus, the minerology of regolith applies and affects available options. An important part of optimizing utilization of any available resource will be ranking requirements and comparing them to availability, purity and ease of processing for each resource in question.

Several large knowledge gaps exist such as soil interaction with mechanical components and sensors, radiation interactions with materials in question, energy requirements related to the possibility of water harvesting from permanently shaded poles of the moon, etc. Other important gaps have to do with finding efficient and

sustainable ways of clearing water contaminants, transfer and storage logistics for energy, water and minerals, along with the understanding of the extent to which these processes can be automated.

One method for potentially sustainable construction is 3-D printing. There are multitudes of ways to enhance this process to better accommodate the requirements of lunar construction (see Figure 3). Some of these include increasing toughness of printed structures via rotation of filaments to make failure lines more predictable, reinforcement between layers of printed matter, utilizing specifics of the rheological properties involved of the sedimentatious material, utilizing additive manufacturing and vibration assisted printing along testing these enhancements on analogues back on earth to verify their practicality.

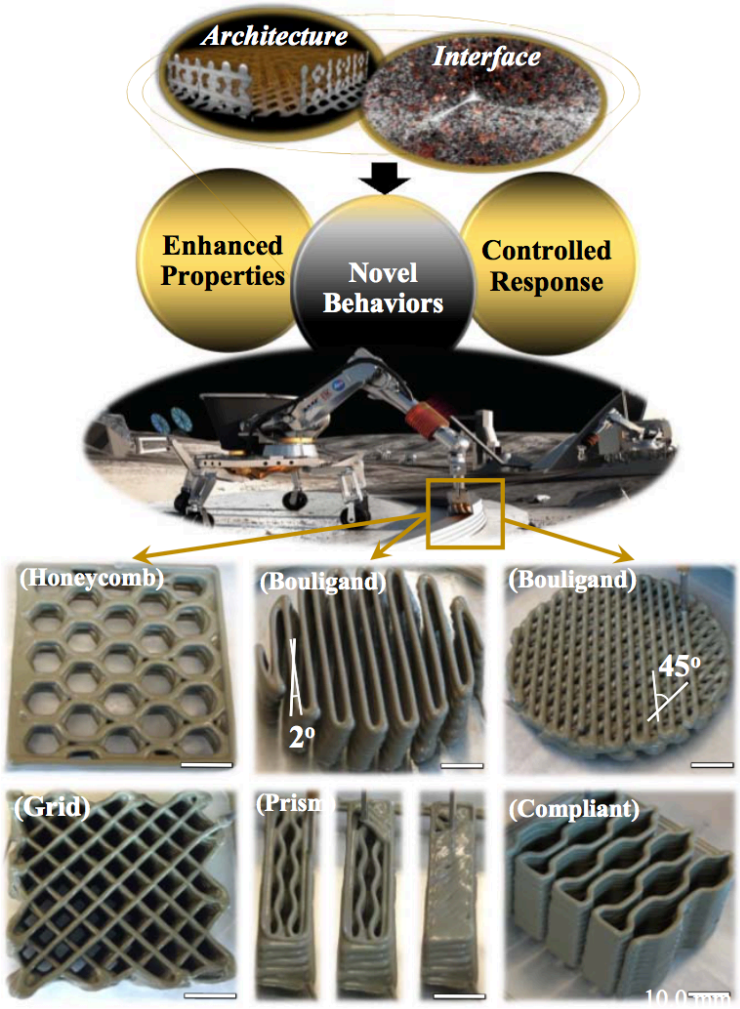

Figure 3. Additive manufacture architecture cement-based materials (see Moini et al. (2018) poster at https://www.purdue.edu/reth/workshop.html)

An ecological analysis of any human habitation is an important part of any long-term mission. “How many occupants” is the most important variable for viability analysis of

any human habitation. Since it will be impossible to completely avoid microbes from becoming part of the habitation ecology, all parts of the habitation should be physically accessible for maintenance of the whole ecology. Maintenance is vital as infectious diseases spread easily in habitats, especially since the same bacteria may affect different people differently.

For longer, sustained missions that occur more frequently, finding ways to cut down cost via reusing and recycling will be paramount. This is primarily because budgets allocated for these projects have no projected growth of any kind – thus having more projects more often is more realistic of a goal than bigger and more costlier projects; something that happens when these projects are more economically viable.

Habitats (Preparation and Architecture)

Moderator:
Barry Finger, Chief Engineer/Director of Life Support Systems, Paragon Space Development Corporation

Coordinators and Recorders:
Amin Maghareh, Postdoctoral Research Assistant of Civil Engineering, Purdue University
Anahita Modiriasari, Postdoctoral Research Assistant of Civil Engineering, Purdue University

Panelists:
Lindsay Aitchison, Program Executive, Life Support and EVA, NASA Headquarters
Ernie Bell, Graduate Research Assistant, Department of Geology, University of Maryland
Antonio Bobet, Professor of Civil Engineering, Purdue University
Joseph Biernacki, Professor of Chemical Engineering, Tennessee Technological University
Charles Dischinger, Discipline Deputy for Human Factors, NASA
Anita Gale, Co-Founder, Space Settlement Design Competitions
Junichi Haruyama, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (JAXA)
Mohammad Jahanshahi, Assistant Professor of Civil Engineering, Purdue University
Ben Kosbab, Principal Engineer, SC Solutions
Ramesh Malla, Professor of Civil and Environmental Engineering, University of Connecticut
William O'Hara, Principal Systems Engineer, Sierra Nevada Corporation
Riccardo Pizzobon, Postdoctoral Researcher in Planetary Geology, University of Padova
Monsi Roman, Program Manager – Centennial Challenges, NASA
Larry Toups, Systems Engineer, NASA/Johnson Space Center

Haiyan Wang, Professor of Materials Engineering, Purdue University
Dawn Whitaker, Indiana Space Grant Consortium Associate Director, Purdue University
Kelsey Young, Research Space Scientist, NASA Goddard Space Flight Center
Pablo Zavattieri, Professor of Civil Engineering, Purdue University

Mark Gee, Undergraduate Researcher of Biological Engineering, Biochemistry, and Agronomy, Purdue Student
Yonggang Luo, Graduate Research Assistant of Physics, Purdue Student
Abdul Salam Mohammad, Post Graduate Research Assistant, Tennessee Technological University
Mohammadreza Moini, Graduate Research Assistant of Civil Engineering, Purdue Student
Danielli Moura, Graduate Research Assistant of Civil Engineering, Purdue Student
Yunlan Zhang, Graduate Research Assistant of Civil Engineering, Purdue Student

Goals:

The purpose of this breakout session was to delve into the state of the art and research gaps in:

- Habitation: mission, vision, and current state of the art
- Function and requirements
- Structural design parameters (robustness, performance and recovery, resiliency)
- Lunar and Martian habitats: surface vs. underground (Lava Tubes)
- Size and stability of natural lava tubes

Presentations:

- "Additive Manufacturing for Habitats" – Joseph Biernacki, Vanderbilt University
- "Human Considerations for Resilient Habitation Systems" – Charles Dischinger, Marshall Space Flight Center and NASA Discipline Deputy for Human Factors
- "Building Structures on the Moon and Mars: Engineering Challenges and Structural Design Parameters for Proposed Habitats" – Ramesh Malla, University of Connecticut
- "The Huge Size of Lunar and Martian Lava Tubes Revealed by Comparative Planetology" – Riccardo Pozzobon, University of Padua, Padova
- "Centennial Challenges, Daring You to Ask: What If?" – Monsi Roman, NASA
- "Science Operations Concepts" – Kelsey Young, NASA Goddard Space Flight Center

The presentations are available at https://www.purdue.edu/reth/workshop.html.

Gaps in Knowledge:

The following is a list of gaps in knowledge identified by the participants in this breakout

session:

- Scale additive manufacturing from lab scale to large scale
- Lack of understanding to print with extraterrestrial based materials (transferring from terrestrial based materials to extraterrestrial ones) - cannot get Portland cement on the Moon
- Multi-scale mechanical behavior of material (fundamental understanding of material properties)
- Habitat lifecycle requirements
- Repairability with the technology
- Structural aspects (shape of structures and stress concentrations)
- Regolith sufficiency for radiation protection
- Micro meteorite impact (material to resist the impact)
- Extensibility of Moon testing to Mars for habitats (not only structures)
- Impact of habitats on the local environment
- Psychological impact of no windows (or distance views)
- Habitat construction (in situ construction vs assembling)
- What is truly meant by resilience and how is it defined
- Adequate human factors and operations understanding and requirements at the outset of the mission
- Human is not being looked at as part of the dissimilar redundancy of the system
- Comprehensive Controlled and Accessible knowledge-base of habitat problem solutions
- Accessible and affordable test facilities
- The use of microorganism to make useful products
- Planetary protection
- Behavior of humans and fluids/solids in low gravity
- Bring scientists and engineers to planetary surface to formally assess the lava tube environments
- Supplying power and light during exploratory missions into the lava tubes
- How to get into a lava tube
- Robotic Long-term characterization of the lunar environment
- In-situ analytical capabilities (i.e. a complete lab)
- Characterizing suit-rover-habitat interfaces
- EVA technology as it related to science
- Identification of optimum gaps- lava tubes candidates for habitation
- Moving habitat system into the infusion path (how to build and test hardware earlier)

Summary:

The objective of this breakout session was to identify and discuss challenges and knowledge gaps on permanent extraterrestrial habitation and issues related to mission, vision, and the state of the art, habitat system function and requirements, habitat system design parameters (system robustness, performance and resilience) and natural lava tubes.

Several issues/challenges regarding 3D printing of habitats using in-situ materials were discussed. A number of knowledge gaps towards this topic were identified. Some of the most significant ones are: (1) scalability issues (additive manufacturing) from lab scale to large scale; (2) limited understanding of printing with extraterrestrial-based materials (transferring from terrestrial-based materials to extraterrestrial ones); (3) multi-scale mechanical behavior of materials (fundamental understanding of material properties); and (4) difference between the mechanical properties of the interface and bulk. In addition, Dr. Joseph Biernack from the department of chemical engineering, Tennessee Technological University, made a presentation on Additive Manufacturing for Habitats. In the presentation, he discussed some important issues regarding combining bioinspired architectures in design along with introduced flaws during 3D-printing process which allows for (1) flaw-tolerant properties and resilient structures, and (2) enhanced toughness and inelastic deformation in materials with brittle characteristics. He also discussed: (1) the impacts of printing paste formulation, additive chemistry, rheology, printability and flow modeling on the uniformity of printed paste across various length scales and the predictability of paste design and print outcomes as a function of print scale and (2) characterization of interfaces between layers of 3D printed cement paste for different printed patterns and the effects of interfaces on the bulk material properties of 3D printed cement pastes.

In this breakout session, participants discussed different habitat lifetime requirements and highlighted that system resilience should be integral to the design process of a habitat system. Two definitions were provided with regards to system resilience. In the first one system resilience was defined as the “minimization of direct and indirect losses from hazards through enhanced resistance and robustness to extreme events, as well as more effective recovery strategies” by Dr. Ramesh B. Malla from the Department of Civil and Environmental Engineering, University of Connecticut. The second one, by Dr. Charles Dischinger, the team lead for human factors engineering at Marshall Space flight Center, referred to system resilience as “the ability of a system to sustain required operations under both expected and unexpected conditions by adjusting its functioning prior to, during, or following changes, disturbances, and opportunities.” In the first definition, system resilience is characterized by four features, (1) robustness (i.e., the systems’ ability to maintain critical functions in crisis); (2) resourcefulness (i.e., the ability to effectively manage crisis as it unfolds); (3) rapid recovery (i.e., the systems’ ability to reconstitute normal operations quickly and effectively); and (4) redundancy (i.e., the systems’ ability to backup resources). The second definition characterizes resilience by the following system properties: Anticipate: Knowing what to expect, or being able to anticipate developments further into the future, e.g. potential disruptions, novel demands or constraints, new opportunities, changing operating conditions; Monitor: Knowing what to look for, or being able to monitor that which is or could seriously affect the system’s performance in the near term; Respond: Knowing what to do, or being able to respond to regular and irregular changes, disturbances, and opportunities by activating prepared actions or by adjusting current mode of functioning; Learn: Knowing what has happened, or being able to learn from experience, in particular to learn the right lessons from the right experience.

Participants also discussed some other gaps and design requirements related to habitat design; for instance, adequate human factors and operations understanding and

requirements at the outset of the mission, human not being looked at as part of the dissimilar redundancy of the system, robotic long-term characterization of the lunar environment, psychological impacts of no windows (or distance views), habitat construction (in situ construction and assembling), comprehensive controlled and accessible knowledge-base of habitat problem solutions, structural aspects (e.g., shape of structures and stress concentrations), regolith sufficiency for radiation protection, and micro meteorite impact (required material to resist the impact).

Data from the Gravity Recovery and Interior Laboratory (GRAIL) supports the presence of a network of large, empty tubes in the lunar lava flows. The concept of lava tubes has long been discussed as potential safe havens for permanent settlement and life support equipment. In this session, participants discussed that: (1) only recently has work begun on how to explore lava tubes on planetary surfaces; (2) lava tubes provide shielding from radiation, surface temperature fluctuations, impact events, etc.; and (3) it is not possible to map out from a pit to determine the size, shape, geometry, and therefore the habitability from orbit. Participants discussed different strategies to investigate the modes of exploration (e.g., flying explorers, smaller robots, etc.) and highlighted that Space agencies need to find a way to characterize the important features of lava tubes (e.g., shapes, sizes, and geometries) from the ground without endangering human or robotic assets. In addition, participants underlined the need to: (1) evaluate methods for entry/exit considering hardware reliability and redundancy, in addition to the variety of terrain; and (2) assess methods for supplying power and light during exploratory missions into the lava tubes, see Figure 4.

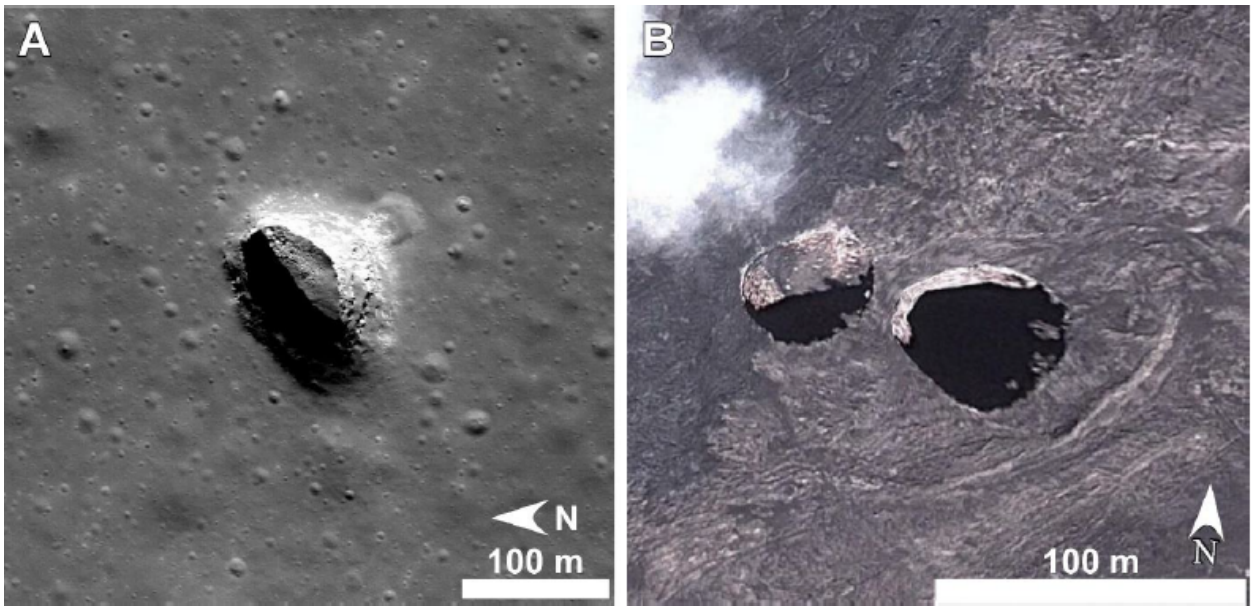

Figure 4. A: Mare Ingenii Lunar Pit LROC Image, B: Two Pits on Kilauea Google Earth. Courtesy of NASA TubeX Project, Presented by Kesley Young, PhD

Partnering Nationally and Internationally: Industry, Facilities and Research (collaborations, access)

Moderator:
William O'Hara, Principal Systems Engineer, Sierra Nevada Corporation

Coordinators and Recorders:
Daniel Gomez, Graduate Research Assistant of Civil Engineering, Purdue University
Anahita Modiriasari, Postdoctoral Research Assistant of Civil Engineering, Purdue University

Panelists:
Jared Atkinson, Senior Geophysical Engineer, Honeybee Robotics
David Cappelleri, Associate Professor of Mechanical Engineering, Purdue University
Charles Dischinger, Discipline Deputy for Human Factors, NASA
Dan Dumbacher, Executive Director, American Institute of Aeronautics & Astronautics (AIAA)
Barry Finger, Chief Engineer/Director of Life Support Systems, Paragon Space Development Corporation
Mike Grichnik, Emerging Technologies Program Leader, Caterpillar
Ben Kosbab, Principal Engineer, SC Solutions
Ramesh Malla, Professor of Civil and Environmental Engineering, University of Connecticut
Karen Marais, Associate Professor of Aeronautics and Astronautics, Purdue University
Jay Melosh, Distinguished Professor of Earth, Atmospheric, and Planetary Sciences, Purdue University
Jan Olek, Professor of Civil Engineering, Purdue University
Julio Ramirez, Kettelhut Professor of Civil Engineering, Purdue University
Monsi Roman, Program Manager – Centennial Challenges, NASA
Nicholas Schmerr, Assistant Professor, Department of Geology, University of Maryland
Michelle Thompson, Assistant Professor, Department of Earth, Atmospheric and Planetary Sciences, Purdue University
Kathleen Vander Kaaden, Research Scientist, Jacobs, NASA Johnson Space Center
Haiyan Wang, Professor of Materials Engineering, Purdue University
Justin Werfel, Senior Research Scientist, Harvard's Wyss Institute for Biologically Inspired Engineering
Glenn White, Sr. Software and Controls Engineer Lead, Construction Robotics
Kelsey Young, Research Space Scientist, NASA Goddard Space Flight Center
Jeffrey Youngblood, Professor of Materials Engineering, Purdue University

Leon Brendel, Graduate Research Assistant of Mechanical Engineering, Purdue University
Yonggang Lou, Graduate Research Assistant of Physics, Purdue Student
Danielli Moura, Graduate Research Assistant of Civil Engineering, Purdue University
Aryan Noroozi, Graduate Research Assistant of Civil Engineering, Purdue University

Babajide Onanuga, Graduate Research Assistant, Department of Chemical Engineering, Tennessee Technological University
Josh Panos, President of Lunabotics, Purdue University

Goals:

The purpose of this breakout session was to delve into challenges and research gaps in:

- Requirements to make successful team collaborations
- Suggestions for resources of funding and partners (names and works)
- Approaches to make nationally and internationally collaborations
- Industry needs from academia

Presentations:

- "Industry Outreach and Relationship Potential for Space Habitats" – Ramesh Malla, University of Connecticut
- "Lunar Resource Characterization Mission(s?)" – Jay Melosh, Purdue University

The presentations are available at https://www.purdue.edu/reth/workshop.html.

Gaps in Knowledge:

The following is a list of what is missing in this field and the key research questions to answer that were identified in this breakout session:

- Not addressing the questions that industry really needs (academia focuses on a much smaller scale)
- Intellectual property rights conflicts
- Lack of mechanism to negotiate and communicate the objectives and industry needs (having a good communication team)
- Lack of meetings with companies and individuals from different areas and listening to the needs
- Not approaching the right expertise in academia and trust issues
- Clear and accessible decisions on export controlled information
- Export restrictions in partnership and international cooperation
- Language and communication
- Lack of long-term plan to build partnerships and lack of setting clear goals
- International conference on habitat development and analogue testing (approach AIAA for this purpose)
- Taking the leadership and a proposal from Purdue or other institutions to form a community with a big picture
- Who are the industry partners to approach?
- Bringing people from energy and mining companies to make big international partnerships and also market analysis companies for investments
- Investigate potential for technology/process spin offs from Earth application to Space habitats instead of the other way around

- Academia and industry advertising of habitat development challenges and benefits

Summary:

The session focused on fostering relationships between academia, industry and space agencies. It highlighted the importance of improving partnering actions to bridge the gap between academic interests and companies' actual requirements. The session explored the necessity to strengthen leadership and form a scientific community with a common objective in resilient extraterrestrial habitation. A diverse organization (industry, academia and space agencies) needs to be included in the grand challenge of an extraterrestrial habitat program. Furthermore, the technologies emerging from such partnerships can be used on Earth (e.g., 3D printing), with the potential of creating spin-offs for Earth applications due to advances in Space habitats. The following reasons for creating nationally and internationally partnerships were discussed in the session:

- Takes time to build the partnership and associated trust. There is a gap to connect these partnerships. One reason is the lack of set clear goals.
- Addressing the questions that industry really needs is vital to academia to go through regional and international cooperation. Universities could help industries with innovation; however, academia sometimes tends to focus on a much smaller scale.
- The cooperation between academia, industry and space agencies needs to make clear and accessible decisions on export controlled information.
- Share the expenses across multiple space agencies should be clearly stated to split the cost of the investigation.
- Strengthening the mechanism to engage universities in the objectives of industries
- Developing common research goals and agendas.
- Communication and language gap. This can be a problem to decisions. It is a good suggestion to learn other languages and cultural perspectives.
- Big opportunity to civil, architectural and construction companies to innovate on Earth applications and process that might be applied on extraterrestrial habitations.
- Big opportunity for civil, architectural and construction companies to innovate on extraterrestrial habitation application and process that might be applied on infrastructure on Earth.
- Industry outreach and potential relationships for leveraging capabilities and resources, sharing the laboratories and data resources for space habitats investigations.
- Distribute costs and liabilities
- Creates momentum and interdependencies
- Accessing new markets in and outside of the US
- Different skill sets and approaches

Forming the Right Research Team for Project Scope: Expertise, Interdisciplinary, Expected Contributions

Moderator:
Dawn Whitaker, Indiana Space Grant Consortium Associate Director, Purdue University

Coordinators and Recorders:
Amin Maghareh, Postdoctoral Research Assistant of Civil Engineering, Purdue University
Audai Theinat, Graduate Research Assistant of Civil Engineering, Purdue University

Panelists:
Lindsay Aitchison, Program Executive, Life Support and EVA, NASA Headquarters
Hunain Alkhateb, Assistant Professor of Civil Engineering, University of Mississippi
Ernie Bell, Graduate Research Assistant, Department of Geology, University of Maryland
Antonio Bobet, Professor of Civil Engineering, Purdue University
Joseph Biernacki, Professor of Chemical Engineering, Tennessee Technological University
Shirley Dyke, Professor of Mechanical and Civil Engineering, Purdue University
Anita Gale, Co-Founder, Space Settlement Design Competitions
Ibrahim Emre Gunduz, Research Assistant Professor of Mechanical Engineering, Purdue University
Robert Haddon, Program Director, Aerospace Medicine Fellowship, Mayo Clinic
Junichi Haruyama, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (JAXA)
Briony Horgan, Assistant Professor, Department of Earth, Atmospheric, and Planetary Sciences, Purdue University
Mohammad Jahanshahi, Assistant Professor of Civil Engineering, Purdue University
Cary Mitchell, Professor of Horticulture, Purdue University
Riccardo Pizzobon, Postdoctoral Researcher in Planetary Geology, University of Padova
Florence Sanchez, Associate Professor of Civil and Environmental Engineering, Vanderbilt University
Elizabeth Silber, Defence Scientist, Defence Research and Development Canada (DRDC)
Larry Toups, Systems Engineer, NASA/Johnson Space Center
Tatjana Paunesku, Research Associate Professor of Radiation Oncology, Northwestern University
Pablo Zavattieri, Professor of Civil Engineering, Purdue University

Anthony Boener, Undergraduate Researcher, Department of Earth, Atmospheric and Planetary Sciences, Purdue University

Zackary Burman, Undergraduate Researcher of Planetary Geomorphology, Purdue University
Mark Gee, Undergraduate Researcher of Biological Engineering, Biochemistry, and Agronomy, Purdue Student
Michael Kosson, Graduate Student of Chemical and Biomolecular Engineering, Vanderbilt University
Kinsey Larson, Undergraduate Student, Purdue University
Jory Lyons, Undergraduate Researcher of Aeronautics and Astronautics, Purdue University
Abdul Salam Mohammad, Post Graduate Research Assistant, Tennessee Technological University
Mohammadreza Moini, Graduate Research Assistant of Civil Engineering, Purdue Student
Ajay Radhakrishnan, Undergraduate Researcher of Mechanical Engineering, Purdue Student
Yunlan Zhang, Graduate Research Assistant of Civil Engineering, Purdue Student

Goals:

The purpose of this breakout session was to delve into challenges and research gaps in:

- Priorities in research objectives
- Research approaches
- Required expertise and networking to accomplish research objectives

Presentation:

- "Forming the Right Research Team" – Anita Gale, Boeing Space Vehicle Cargo Integration (retired) and Co-Founder of Space Settlement Design Competitions

The presentation is available at https://www.purdue.edu/reth/workshop.html.

Gaps in Knowledge:

The following is a list of what is missing in this field and the key research questions to answer that were identified in the breakout session:

- Intended outcomes: customer needs, expected results, purpose, expectations, address unclear details
- How to meet constrains, conditions, infrastructure: knowledgeable team, budget and time schedule, cost.
- Facility that gets all agencies together to study: field data, time frame, environment, enhance partnership
- Flexibility to combine different fields, reconfiguring accosting to needs
- Unique skills: innovations, building a team with different skills, how to publish, mutual benefits
- Lack of communication
- Facilitating the contact between industry and academia

- Innovations: academic partnership and involving graduate students
- Training of students
- Intellectual property
- Right research
- Choice of team leader
- Expectations to assure success
- What topics related to different agencies, and the influences related with those topics
- Mission contacts and requirements
- Physical: labs and technology
- Space gateways and resources: such as equipment
- Data: such as earthquakes and impacts

Summary:

The session focused on primary questions that need to be answered when attempting to build a team: What is the research goal? What is the form of the expected research result? Who are the customers for the product (research, in this context) made by this team? What are the technological and economic constraints in place? What is the infrastructure already in place with regards to the project? What are the requirements for each team member?

Almost all team scenarios that arise after these questions are satisfactorily answered do require a team leader to be selected. One of the many duties of this team leader will be to ensure that communication occurs among the team members. Other duties include ensuring no hidden agendas are put into motion and keeping the team on a timeline while utilizing a strategic process.

It is important to realize that the team members will be diverse in terms of experience, region of expertise, language, and other skills such as management, funding, equipment, relationship, etc. Four factors that lead to a particular team composition – interpersonal relationships, funding context, sector context and organizational context.

In government and academic cooperation, the main advantage is that working with a university usually leads to investigating a wider variety of solutions that tend to be more creative due to the larger manpower amount with more flexible time resources. Other academia related advantages include an interdisciplinary outlook to the problem statement, without interference from any individual career ambitions. Important components of thought for assembling a team is to think about the outcomes based on: customer needs, expected results, purpose and expectations of the project in question.

It is of paramount importance to meet different constraints and conditions with available infrastructure and funds. This can be done with a team that is able to build a long-term schedule that takes budgeting as a primary part of their schedule design. An important consensus reached was that to enhance the effectiveness of a long-term project, the communication and the partnership between government, industry and

academia need to be strengthened.

While the government may focus on determining what topics of research are important to the project at hand, ultimately it should also focus on facilitating the contact between industry and academia. Industry has an upper hand in being able to provide resources, and equipment; although they will need to be more flexible when comes to sharing intellectual properties.

At the end, networking was discussed as a means to connect researchers and lead to stronger and more integrated teams. Branching out to find resources and expertise outside of a researcher's focus area was a topic, including reaching outside of the typical publication venues. For example, the NASA Techport database was discussed. This is a website which contains goals, progress and knowledge gaps on most of the projects undertaken by NASA that are related to similar pursuits. This can be used as a resource to find related regions of knowledge, find what research has been completed, and enhance the progress of a balanced team.

NEXT STEPS

The major resolutions of the workshop were:

***Partnership Development*:** Purdue is well positioned to meet the challenge of building resilient extraterrestrial habitats. Furthermore, the strengths of Purdue support this objective with world-renown researchers experienced in remote sensing and full-scale experimentation. Collaborators will be engaged with complementary expertise in cyber-physical systems, additive manufacturing, embedded systems, robotics, materials engineering, and energy systems.

Success cannot be achieved in such a complex initiative without collaboration among all stakeholders. Academics, professionals and industry partners will be engaged, from both inside and outside Purdue, and beyond those directly involved in the project, as well as the agencies that will be implementing the findings from the research. Federal agencies such as NASA, European Space Agency, as well as Japan Aerospace Exploration Agency (JAXA) should be involved.

***Publication*:** A white paper about resilient extraterrestrial habitation should be published in a well-known aerospace magazine.

***Technical Session*:** A technical session should be organized at one (or more) of the upcoming conferences in aerospace engineering (e.g. 2019 AIAA Propulsion and Energy Forum and Exposition), or space section of well-known conferences in civil engineering (e.g. American Society of Civil Engineers (ASCE) conferences) or mechanical engineering, which could include 5-6 presentations and major conclusions about resilient extraterrestrial habitations reached by the participants.

Dissemination: The excitement of space exploration is contagious, attracting numerous interested students and faculty, inspiring youth, and capturing the imagination of the world. To both engage the broad Purdue community and workshop participants and publicly disseminate information about this exciting new direction, one of our first steps in the RETH project was to develop a dynamic web page dedicated to the project: https://www.purdue.edu/reth.

The website is evolving over the project period and is updated each quarter to provide information on goals, new curricular directions being pursued, seminars, activities, and the results of research studies conducted by the team, as they become available. The RETH team will continue to work with Purdue Media to strategically publicize the project and in particular this workshop. All keynote lectures have been videotaped and will be posted on the RETH website and YouTube, and it is expected that this will generate widespread excitement on this novel program.

APPENDIX A

WORKSHOP AGENDA

Agenda Day 1

7:30 am — Breakfast and Registration (*Stewart Center, room 218*)

8:15 — Welcome and Opening Remarks (*Stewart Center, room 218*)
Moderator: Julio Ramirez, Kettelhut Professor of Civil Engineering, Purdue University
Speakers: Peter Hollenbeck, Vice Provost for Faculty Affairs, Purdue University
Melba Crawford, Associate Dean for Research in the College of Engineering, Purdue University
Elizabeth Taparowsky, Associate Dean for Research and Graduate Education in the College of Science, Purdue University

8:50 — Agenda and Objectives of the Workshop (*Stewart Center, room 218*)
Moderator: Shirley Dyke, Professor of Mechanical and Civil Engineering, Purdue University

9:00 — Plenary Session Invited Talks (*Stewart Center, room 218*)
Moderator: Shirley Dyke, Professor of Mechanical and Civil Engineering, Purdue University
Coordinator: Anahita Modiriasari, Postdoctoral Research Assistant of Civil Engineering, Purdue University
Speakers: Dan Dumbacher, Executive Director, American Institute of Aeronautics & Astronautics (AIAA)
Junichi Haruyama, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (JAXA)
Larry Toups, Systems Engineer, NASA, Johnson Space Center

10:00 — Q/A Session (*Stewart Center, room 218*)
Moderator: Shirley Dyke, Professor of Mechanical and Civil Engineering, Purdue University

10:20 — Break (*Stewart Center, room 218*)

10:40 — Joint Session – Panel Session (*Stewart Center, room 218*)
Moderator: Antonio Bobet, Professor of Civil Engineering, Purdue University
Coordinator: Anahita Modiriasari, Postdoctoral Research Assistant of Civil Engineering, Purdue University
Panelists: Lindsay Aitchison, Program Executive, Life Support and EVA, NASA Headquarters
William O'Hara, Principal Systems Engineer, Sierra Nevada Corporation
Mike Grichnik, Emerging Technologies Program Leader, Caterpillar
Anita Gale, Co-Founder, Space Settlement Design Competitions
Barry Finger, Chief Engineer/Director of Life Support Systems, Paragon Space Development Corporation
Jay Melosh, Distinguished Professor of Earth, Atmospheric, and Planetary Sciences, Purdue University

11:40 — Joint Session – Expectation and Organization of Afternoon Breakout Sessions (*Stewart Center, room 218*)
Moderator: Antonio Bobet, Professor of Civil Engineering, Purdue University

12:00 pm — Group Picture (*Purdue Memorial Union)*

12:15 — Lunch (*Purdue Memorial Union, West Faculty Lounge*)

1:15 — Breakout Sessions – I *(The breakout sessions are concurrent. The scope of each breakout session includes (but is not limited to) the following subjects.)*

Theme A – Hazards (Events) (*Stewart Center, room 278*)
Session Scope:
- ✓ *Science and current state of the art in space extreme environment and hazards (e.g. radiation, meteorite impacts, extreme temperatures, seismicity, etc.)*
- ✓ *Technology to quantify and qualify hazards*
- ✓ *Impacts of hazards on human exploration and survival*
- ✓ *Hazard mitigation*

Moderator: Tatjana Paunesku, Research Associate Professor of Radiation Oncology, Northwestern University
Coordinators and Recorders: Daniel Gomez, Graduate Research Assistant of Civil Engineering, Purdue University
Anthony Boener, Undergraduate Researcher, Department of Earth, Atmospheric and Planetary Sciences, Purdue University
Panelists: Karen Marais, Associate Professor of Aeronautics and Astronautics, Purdue University
Jay Melosh, Distinguished Professor of Earth, Atmospheric, and Planetary Sciences, Purdue University

Julio Ramirez, Kettelhut Professor of Civil Engineering, Purdue University
Nicholas Schmerr, Assistant Professor, Department of Geology, University of Maryland
Elizabeth Silber, Defence Scientist, Defence Research and Development Canada (DRDC)
Michelle Thompson, Assistant Professor, Department of Earth, Atmospheric and Planetary Sciences, Purdue University
Kathleen Vander Kaaden, Research Scientist, Jacobs, NASA Johnson Space Center

Zackary Burman, Undergraduate Researcher of Planetary Geomorphology, Purdue University
Jory Lyons, Undergraduate Researcher of Aeronautics and Astronautics, Purdue University

Theme B – Resources (Harvesting and Utilization) (*Stewart Center, room 279*)

Session Scope:

- ✓ *Resources and supplies needed for permanent habitats, e.g. food, water, energy, construction materials*
- ✓ *Sources of resources and supplies*
- ✓ *Mining, harvesting methods and technologies*
- ✓ *Reutilization*
- ✓ *Current state of the art in manufacturing and construction technologies (Robotics and Automation, Additive Manufacturing, 3D Printing, etc.)*
- ✓ *Improvements to manufacturing and construction for hazardous environments*

Moderator: Cary Mitchell, Professor of Horticulture, Purdue University
Coordinators and Recorders: Audai Theinat, Graduate Research Assistant of Civil Engineering, Purdue University
Ajay Radhakrishnan, Undergraduate Researcher of Mechanical Engineering, Purdue Student
Panelists: Hunain Alkhateb, Assistant Professor of Civil Engineering, University of Mississippi
Jared Atkinson, Senior Geophysical Engineer, Honeybee Robotics
David Cappelleri, Associate Professor of Mechanical Engineering, Purdue University
Dan Dumbacher, Executive Director, American Institute of Aeronautics & Astronautics (AIAA)
Shirley Dyke, Professor of Mechanical and Civil Engineering, Purdue University
Mike Grichnik, Emerging Technologies Program Leader, Caterpillar
Ibrahim Emre Gunduz, Associate Professor of Mechanical and Aerospace Engineering, Naval Postgraduate School
Robert Haddon, Program Director, Aerospace Medicine Fellowship, Mayo Clinic
Briony Horgan, Assistant Professor, Department of Earth, Atmospheric, and Planetary Sciences, Purdue University
Jan Olek, Professor of Civil Engineering, Purdue University
Florence Sanchez, Associate Professor of Civil and Environmental Engineering, Vanderbilt University
Justin Werfel, Senior Research Scientist, Harvard's Wyss Institute for Biologically Inspired Engineering
Glenn White, Sr. Software and Controls Engineer Lead, Construction Robotics
Jeffrey Youngblood, Professor of Materials Engineering, Purdue University

Leon Brendel, Graduate Research Assistant of Mechanical Engineering, Purdue University
Michael Kosson, Graduate Student of Chemical and Biomolecular Engineering, Vanderbilt University
Kinsey Larson, Undergraduate Student, Purdue University
Aryan Noroozi, Graduate Research Assistant of Civil Engineering, Purdue University
Babajide Onanuga, Graduate Research Assistant, Department of Chemical Engineering, Tennessee Technological University
Josh Panos, President of Lunabotics, Purdue University

Theme C – Habitats (Preparation and Architecture) (*Stewart Center, room 218*)

Session Scope:

- ✓ *Habitation: mission, vision, and current state of the art*
- ✓ *Function and requirements*
- ✓ *Structural design parameters (robustness, performance and recovery, resiliency)*
- ✓ *Lunar and Martian habitats: surface vs. underground (Lava Tubes)*
- ✓ *Size and stability of natural lava tubes*

Moderator: Barry Finger, Chief Engineer/Director of Life Support Systems, Paragon Space Development Corporation

Coordinators and Recorders: Amin Maghareh, Postdoctoral Research Assistant of Civil Engineering, Purdue University
Anahita Modiriasari, Postdoctoral Research Assistant of Civil Engineering, Purdue University
Panelists: Lindsay Aitchison, Program Executive, Life Support and EVA, NASA Headquarters
Ernie Bell, Graduate Research Assistant, Department of Geology, University of Maryland
Antonio Bobet, Professor of Civil Engineering, Purdue University

Joseph Biernacki, Professor of Chemical Engineering, Tennessee Technological University
Charles Dischinger, Discipline Deputy for Human Factors, NASA
Anita Gale, Co-Founder, Space Settlement Design Competitions
Junichi Haruyama, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (JAXA)
Mohammad Jahanshahi, Assistant Professor of Civil Engineering, Purdue University
Ben Kosbab, Principal Engineer, SC Solutions
Ramesh Malla, Professor of Civil and Environmental Engineering, University of Connecticut
William O'Hara, Principal Systems Engineer, Sierra Nevada Corporation
Riccardo Pozzobon, Postdoctoral Researcher in Planetary Geology, University of Padova
Monsi Roman, Program Manager – Centennial Challenges, NASA
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Pablo Zavattieri, Professor of Civil Engineering, Purdue University

Mark Gee, Undergraduate Researcher of Biological Engineering, Biochemistry, and Agronomy, Purdue University
Yonggang Luo, Graduate Research Assistant of Physics, Purdue University
Abdul Salam Mohammad, Post Graduate Research Assistant, Tennessee Technological University
Mohammadreza Moini, Graduate Research Assistant of Civil Engineering, Purdue University
Danielli Moura, Graduate Research Assistant of Civil Engineering, Purdue University
Yunlan Zhang, Graduate Research Assistant of Civil Engineering, Purdue University

3:15	Break *(Stewart Center, room 218)*
3:30	Joint Session: Report- Results of Breakout Sessions – I (*Stewart Center, room 218*) *Moderator:* Anita Gale, Co-Founder, Space Settlement Design Competitions
5:30	Joint Session: Expectation and Organization of Day 2 (*Stewart Center, room 218*) *Moderator:* Antonio Bobet, Professor of Civil Engineering, Purdue University
5:45	Break
6:00 – 8:00	Reception with Poster Session *(Stewart Center, room 279)* *Coordinators:* Daniel Gomez, Graduate Research Assistant of Civil Engineering, Purdue University Audai Theinat, Graduate Research Assistant of Civil Engineering, Purdue University

Agenda Day 2

7:30 am	Breakfast (*Stewart Center, room 218*)
8:15	Agenda and Objectives of the Workshop (*Stewart Center, room 218*) *Moderator:* Jay Melosh, Distinguished Professor of Earth, Atmospheric, and Planetary Sciences, Purdue University
8:30	Breakout Sessions – II Theme D – Partnering Nationally and Internationally: Industry, Facilities and Research (collaborations, access) (*Stewart Center, room 278*) *Session Scope:* ✓ *Requirements to make successful team collaborations* ✓ *Suggestions for resources of funding and partners (names and works)* ✓ *Approaches to make nationally and internationally collaborations* ✓ *Industry needs from academia* *Moderator:* William O'Hara, Principal Systems Engineer, Sierra Nevada Corporation *Coordinators and Recorders:* Daniel Gomez, Graduate Research Assistant of Civil Engineering, Purdue University

Anahita Modiriasari, Postdoctoral Research Assistant of Civil Engineering, Purdue University

Panelists: Jared Atkinson, Senior Geophysical Engineer, Honeybee Robotics
David Cappelleri, Associate Professor of Mechanical Engineering, Purdue University
Charles Dischinger, Discipline Deputy for Human Factors, NASA
Dan Dumbacher, Executive Director, American Institute of Aeronautics & Astronautics (AIAA)
Barry Finger, Chief Engineer/Director of Life Support Systems, Paragon Space Development Corporation
Mike Grichnik, Emerging Technologies Program Leader, Caterpillar
Ben Kosbab, Principal Engineer, SC Solutions
Ramesh Malla, Professor of Civil and Environmental Engineering, University of Connecticut
Karen Marais, Associate Professor of Aeronautics and Astronautics, Purdue University
Jay Melosh, Distinguished Professor of Earth, Atmospheric, and Planetary Sciences, Purdue University
Jan Olek, Professor of Civil Engineering, Purdue University
Julio Ramirez, Kettelhut Professor of Civil Engineering, Purdue University
Monsi Roman, Program Manager – Centennial Challenges, NASA
Nicholas Schmerr, Assistant Professor, Department of Geology, University of Maryland
Michelle Thompson, Assistant Professor, Department of Earth, Atmospheric and Planetary Sciences, Purdue University
Kathleen Vander Kaaden, Research Scientist, Jacobs, NASA Johnson Space Center
Haiyan Wang, Professor of Materials Engineering, Purdue University
Justin Werfel, Senior Research Scientist, Harvard's Wyss Institute for Biologically Inspired Engineering
Glenn White, Sr. Software and Controls Engineer Lead, Construction Robotics
Kelsey Young, Research Space Scientist, NASA Goddard Space Flight Center
Jeffrey Youngblood, Professor of Materials Engineering, Purdue University

Leon Brendel, Graduate Research Assistant of Mechanical Engineering, Purdue University
Yonggang Lou, Graduate Research Assistant of Physics, Purdue Student
Danielli Moura, Graduate Research Assistant of Civil Engineering, Purdue University
Aryan Noroozi, Graduate Research Assistant of Civil Engineering, Purdue University
Babajide Onanuga, Graduate Research Assistant, Department of Chemical Engineering, Tennessee Technological University
Josh Panos, President of Lunabotics, Purdue University

Theme E – Forming the Right Research Team for Project Scope: Expertise, Interdisciplinary, Expected Contributions (*Stewart Center, room 218*)

Session Scope:

- ✓ *Priorities in research objectives*
- ✓ *Research approaches*
- ✓ *Required expertise and networking to accomplish research objectives*

Moderator: Dawn Whitaker, Indiana Space Grant Consortium Associate Director, Purdue University
Coordinators and Recorders: Amin Maghareh, Postdoctoral Research Assistant of Civil Engineering, Purdue University
Audai Theinat, Graduate Research Assistant of Civil Engineering, Purdue University

Panelists: Lindsay Aitchison, Program Executive, Life Support and EVA, NASA Headquarters
Hunain Alkhateb, Assistant Professor of Civil Engineering, University of Mississippi
Ernie Bell, Graduate Research Assistant, Department of Geology, University of Maryland
Antonio Bobet, Professor of Civil Engineering, Purdue University
Joseph Biernacki, Professor of Chemical Engineering, Tennessee Technological University
Shirley Dyke, Professor of Mechanical and Civil Engineering, Purdue University
Anita Gale, Co-Founder, Space Settlement Design Competitions
Ibrahim Emre Gunduz, Associate Professor of Mechanical and Aerospace Engineering, Naval Postgraduate School
Robert Haddon, Program Director, Aerospace Medicine Fellowship, Mayo Clinic
Junichi Haruyama, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (JAXA)
Briony Horgan, Assistant Professor, Department of Earth, Atmospheric, and Planetary Sciences, Purdue University
Mohammad Jahanshahi, Assistant Professor of Civil Engineering, Purdue University
Cary Mitchell, Professor of Horticulture, Purdue University
Riccardo Pozzobon, Postdoctoral Researcher in Planetary Geology, University of Padova
Florence Sanchez, Associate Professor of Civil and Environmental Engineering, Vanderbilt University
Elizabeth Silber, Defence Scientist, Defence Research and Development Canada (DRDC)
Larry Toups, Systems Engineer, NASA/Johnson Space Center

Tatjana Paunesku, Research Associate Professor of Radiation Oncology, Northwestern University
Pablo Zavattieri, Professor of Civil Engineering, Purdue University

Anthony Boener, Undergraduate Researcher, Department of Earth, Atmospheric and Planetary Sciences, Purdue University
Zackary Burman, Undergraduate Researcher of Planetary Geomorphology, Purdue University
Mark Gee, Undergraduate Researcher of Biological Engineering, Biochemistry, and Agronomy, Purdue Student
Michael Kosson, Graduate Student of Chemical and Biomolecular Engineering, Vanderbilt University
Kinsey Larson, Undergraduate Student, Purdue University
Jory Lyons, Undergraduate Researcher of Aeronautics and Astronautics, Purdue University
Abdul Salam Mohammad, Post Graduate Research Assistant, Tennessee Technological University
Mohammadreza Moini, Graduate Research Assistant of Civil Engineering, Purdue University
Ajay Radhakrishnan, Undergraduate Researcher of Mechanical Engineering, Purdue University
Yunlan Zhang, Graduate Research Assistant of Civil Engineering, Purdue University

10:00 Break (*Stewart Center, room 218*)

10:20 Joint Session: Report- Results of Breakout Sessions – II (*Stewart Center, room 218*)
Moderator: Larry Toups, Systems Engineer, NASA/Johnson Space Center

12:00 pm Summary and Closing Session- Expanding the vision of science and engineering to achieve resilient long-term extraterrestrial habitats (*Stewart Center, room 218*)
Moderator: Dan Dumbacher, Executive Director, American Institute of Aeronautics & Astronautics (AIAA)
Julio Ramirez, Kettelhut Professor of Civil Engineering, Purdue University

1:00 – 2:00 Lunch (*Purdue Memorial Union, East Faculty Lounge*)

APPENDIX B

LIST OF PARTICIPANTS

Over 60 people registered and attended the 2018 RETH workshop. Participants represented a variety of domestic and international sectors including universities, NASA, and private firms. The list of participants with their affiliations is:

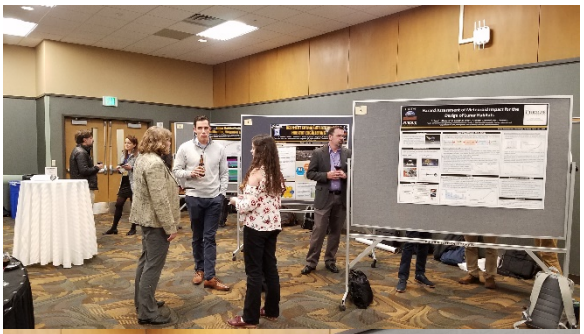
First Name	Last Name	Title	Company
Lindsay	Aitchison	Program Executive, Life Support and EVA	NASA Headquarters
Hunain	Alkhateb	Assistant Professor of Civil Engineering	The University of Mississippi
Jared	Atkinson	Senior Geophysical Engineer	Colorado School of Mines
Ernie	Bell	Graduate Research Assistant	University of Maryland, Department of Geology
Joseph	Biernacki	Professor of Chemical Engineering	Tennessee Technological University
Antonio	Bobet	Professor of Civil Engineering	Purdue University
Anthony	Boener	Undergraduate Researcher of Earth, Atmospheric, and Planetary Sciences	Purdue University
Leon	Brendel	Graduate Research Assistant of Mechanical Engineering	Purdue University
Zachary	Burman	Undergraduate Researcher of Planetary Geomorphology	Purdue University
David	Cappelleri	Associate Professor of Mechanical Engineering	Purdue University
Charles	Dischinger	Discipline Deputy for Human Factors	NASA
Daniel	Dumbacher	Executive Director	American Institute of Aeronautics & Astronautics
Shirley	Dyke	Professor of Mechanical and Civil Engineering	Purdue University
Barry	Finger	Chief Engineer/Director of Life Support Systems	Paragon Space Development Corporation
Anita	Gale	Co-Founder	Space Settlement Design Competitions
Mark	Gee	Undergraduate Researcher of Biological Engineering	Purdue
Daniel	Gomez	Graduate Research Assistant of Civil Engineering	Purdue University
Michael	Grichnik	Emerging Technologies Program Leader	Caterpillar
Ibrahim Emre	Gunduz	Associate Professor of Mechanical and Aerospace Engineering	Naval Postgraduate School
Robert	Haddon	Program Director, Aerospace Medicine Fellowship	Mayo Clinic
Junichi	Haruyama	Institute of Space and Astronautical Science	Japan Aerospace Exploration Agency (JAXA)

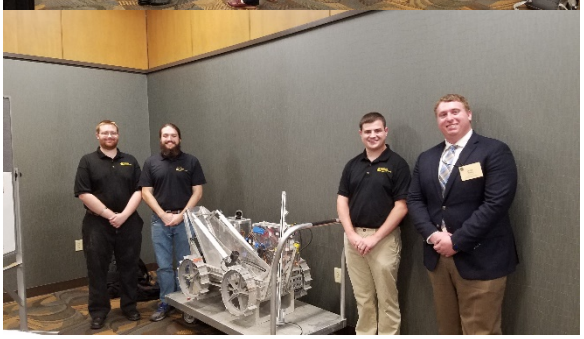
Briony	Horgan	Assistant Professor of Earth, Atmospheric, and Planetary Sciences	Purdue University
Mohammad	Jahanshahi	Assistant Professor of Civil Engineering	Purdue University
Ben	Kosbab	Principal Engineer	SC Solutions
Michael	Kosson	Graduate Student of Chemical and Biomolecular Engineering	Vanderbilt University
Kinsey	Larson	Undergraduate Student	None
Yonggang	Luo	Graduate Research Assistant of Physics	Purdue University
Jory	Lyons	Undergraduate Researcher of Aeronautics and Astronautics	Purdue University - RETH
Amin	Maghareh	Postdoctoral Research Assistant of Civil Engineering	Purdue University
Ramesh	Malla	Professor of Civil and Environmental Engineering	University of Connecticut
Karen	Marais	Associate Professor of Aeronautics and Astronautics	Purdue
Jay	Melosh	Distinguished Professor of Earth, Atmospheric, and Planetary Sciences	Purdue University
Cary	Mitchell	Professor of Horticulture	Purdue
Anahita	Modiriasari	Postdoctoral Research Assistant of Civil Engineering	Purdue University
Abdul Salam	Mohammad	Post Graduate Research Assistant	Tennessee Technological University
Mohamadreza	Moini	Graduate Research Assistant of Civil Engineering	Purdue University
Danielli	Moura	Graduate Research Assistant of Civil Engineering	Purdue University
Aryan	Noroozi	Graduate Research Assistant of Civil Engineering	Purdue University
William	O'Hara	Principal Systems Engineer	Sierra Nevada Corporation
Jan	Olek	Professor of Civil Engineering	Purdue University
Babajide	Onanuga	Graduate Research Assistant of Chemical Engineering	Tennessee Technological University
Josh	Panos	President of Lunabotics	Purdue Lunabotics
Tatjana	Paunesku	Research Associate Professor of Radiation Oncology	Northwestern University
Mark	Pollard	Undergraduate Student	Purdue Lunabotics
Riccardo	Pozzobon	Postdoctoral Researcher in Planetary Geology	University of Padova
Ajay	Radhakrishnan	Undergraduate Researcher of Mechanical Engineering	Purdue University
Julio	Ramirez	Kettelhut Professor of Civil Engineering	Purdue University
Monsi	Roman	Program Manager – Centennial Challenges	NASA

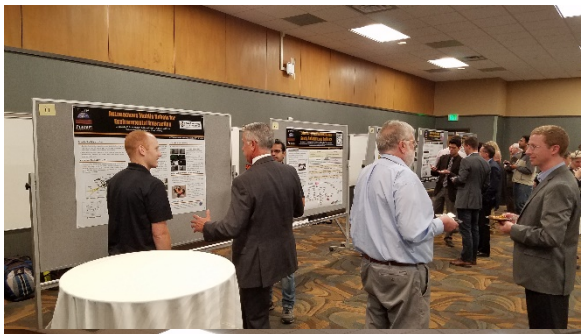
Florence	Sanchez	Associate Professor of Civil and Environmental Engineering	Vanderbilt University
Nicholas	Schmerr	Assistant Professor of Geology	University of Maryland
Elizabeth	Silber	Defence Scientist	Defence Research and Development Canada (DRDC)
Ed	Theinat	Graduate Research Assistant of Civil Engineering	Purdue University
Michelle	Thompson	Assistant Professor of Earth, Atmospheric and Planetary Sciences	Purdue University
Larry	Toups	Systems Engineer	NASA/Johnson Space Center
Kathleen	Vander Kaaden	Research Scientist	Jacobs, NASA Johnson Space Center
Haiyan	Wang	Professor of Materials Engineering	Purdue University
Justin	Werfel	Senior Research Scientist	Harvard's Wyss Institute for Biologically Inspired Engineering
Dawn	Whitaker	Indiana Space Grant Consortium Associate Director	Purdue University - INSGC
Glenn	White	Sr. Software and Controls Engineer Lead	Construction Robotics
Kelsey	Young	Research Space Scientist	NASA Goddard Space Flight Center
Jeffrey	Youngblood	Professor of Materials Engineering	Purdue University
Pablo	Zavattieri	Professor of Civil Engineering	Purdue University
Yunlan	Zhang	Graduate Research Assistant of Civil Engineering	Purdue University

APPENDIX C

POSTER PRESENTATIONS







- "Magnetically Mapping Lava Tubes (Part of the TubeX Project)" – Ernie Bell, Department of Geology, University of Maryland.
- "Vapor Compression Refrigeration for Cold Storage on Spacecraft" – Leon Brendel, School of Mechanical Engineering, Purdue University.
- "Autonomous Mobile Robots for Environmental Interaction" – David Cappelleri, School of Mechanical Engineering, Purdue University.
- "Resilient Agriculture in Space: Microgreens and the Microbiome" – Mark Gee, Department of Agriculture and Biological Engineering, Purdue University.
- "Interlayer Interface Characteristics in 3D Printed Cement Paste" – Michael Kosson, Department of Chemical and Biomolecular Engineering, Vanderbilt University.
- "Scaling Smart Autonomous Construction" – Abdul S. Mohammad, Department of Chemical Engineering, Tennessee Technological University.
- "Performance of Additively Manufactured Architectured Cement-based Materials" – Mohammadreza Moini, Lyles School of Civil Engineering, Purdue University.
- "NASA's Robotic Mining Competition" – Purdue Lunabotics
- "Evacuation and Deposition" – Purdue Lunabotics
- "Chassis Design and Modeling" – Purdue Lunabotics
- "Risk Assessment" – Purdue Lunabotics

The presentation will soon be available at https://www.purdue.edu/reth/workshop.html.